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Road Deterioration in Developing Countries and Low-Volume Road Engineering

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1 highway transportation

subject areas
11 administration
12 planning
14 finance
15 socioeconomics
24 pavement design and performance
25 structures design and performance
40 maintenance

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Contents

Foreword

This Record should be of interest to anyone responsible for design, construction, operation, and maintenance of low-volume roads. Concern about the deteriorating state of roads in many developing countries prompted the World Bank to conduct a major policy study. The first four papers in this Record are on the deterioration of roads in developing countries; the remaining six papers are on low-volume road engineering.

Faiz et al. present an overview of the status of the road networks in 85 developing countries. They use the condition of main roads and factors contributing to regional differences to understand the cause of the road deterioration. Bhandari et al. report on the basic issues concerning road maintenance. They use the World Bank's Highway Design and Maintenance Model (HDM-III) to obtain life-cycle cost analysis. Smith and Harral report on estimates of the aggregate cost of rehabilitating and maintaining the main road networks. They classify the 85 countries included in the study in two groups according to the rehabilitation and maintenance needs relative to gross national product. They also review options for finding the funds needed. In a separate paper, Harral discusses the factors that affect efficacy and efficiency of public road authorities. He recommends a number of reforms to improve efficiency.

Rwebangira et al. have developed guidelines on spring load restriction for local roads. The guidelines are based on a survey of current practices in the United States and Canada. This paper received the 1987 K. B. Woods Award for outstanding paper in the field of design and construction of transportation facilities. Riverson et al. report on the evaluation of a subjective rating of unpaved roads in Indiana. They show regression relationships between panel condition ratings and several road characteristics and suggest a basis for selection of maintenance activity.

Eck has developed an interactive microcomputer program to assist in making decisions on rehabilitation needs of a particular roadway link in the Appalachian region. The program is compatible with both the Apple and IBM PC computers and could be modified to make it applicable to any other region. Kurt reports on the software system that he has developed for use with microcomputers to rate simple and continuous-span girder-type and simple-truss bridges on low-volume roads. The program follows AASHTO rating procedures and is indicated to provide improvements in productivity and rating options. Pautsch and Baumel describe a microcomputer program designed to enable county personnel to estimate the change in travel and investment costs from alternative strategies on local rural roads. The program also computes benefit-cost ratios for the alternative investment strategies. Potter et al. consider the U.S. Army Corps of Engineers' pavement design procedure appropriate for low-volume road applications. The corps design method is applicable to thin asphalt concrete pavements on granular base courses and subbases, and rigid low-volume pavements construction using roller compaction techniques. They indicate that these design procedures have been computerized.

State of the Road Networks in Developing Countries and a Country Typology of Response Measures

ASIF FAIZ, CLELL HARRAL, AND FRIDA JOHANSEN

An overview of the status of the road networks in 85 developing countries is presented. A broad-brush assessment of the condition of main roads in these countries is followed by an analysis of regional differences and the factors contributing to these differences. These factors have been grouped into country typology consisting of six categories. Although it is not scientifically precise, this classification is useful in explaining the regional and country differences in road condition, understanding the causes of the road deterioration problem in developing countries, and formulating appropriate responses to the problem. This paper is the first of four papers in this Record on "Road Deterioration in Developing Countries."

The road-building boom in developing countries during the 1960s and 1970s has not been matched by a comparable investment in follow-up maintenance and restoration, and the debilitation as a result of neglect has been aggravated by increasing and heavier traffic use. Much too small a share of resources available for roads has been used for maintaining existing roads, and even that small share has seldom been applied effectively. The result today in many developing countries is a network of deteriorating roads, many of them beyond the stage at which normal maintenance measures can be effective, and rehabilitation or reconstruction is required at a cost three to five times what it would have been if preventive maintenance and strengthening had been done in time. A much larger mileage will soon reach that stage if not maintained better than in the past. For many countries, it may already be well beyond their financial means to correct the deficiencies in their road infrastructure. The growing problems of road deterioration, functional obsolescence, and insufficient capacity to serve future growth have converged at a time when severe budgetary constraints are forcing governments to reassess spending priorities and make difficult investment and expenditure choices from among the many competing claims on available resources.

The increase in costs to the road authorities is only a fraction of the overall burden resulting from deteriorating roads. Vehicle operating costs on properly maintained roads account for some 80 to 90 percent of the total road transport cost except in extremely low traffic. On bad roads, vehicle operating costs (largely in foreign exchange) can easily double, imposing a heavy burden on road users. The higher road haulage costs can constrain the location of economic activities, hamper the integration of economic markets, limit the gains from specialization, and render many transport-intensive activities nonviable. Continued deterioration of road networks can lead to chronic transportation bottlenecks that inevitably erode the productive base of the economy and result in major economic dislocation (see box "Consequences of Road Neglect in Ghana").

Consequences of Road Neglect in Ghana

Road deterioration can make an economic crisis worse. In Ghana a good road network was built before 1970, but it later suffered from serious neglect. By 1984, about 60 percent of the main paved roads were in a state of moderate to severe deterioration. Important sections have become almost impassable, and access to some interior areas has been severely curtailed. Transporters refuse to go there because they do not want their vehicles to break down.

Transport costs have increased in real terms by about 50 percent on main roads and by more than 100 percent on rural roads that have suffered even greater neglect. In many areas, the market rate for transporting fertilizer is as high as a dollar per ton-mile. These high transport costs have cut deeply into farm returns, particularly for poor farmers in areas away from main roads: some villagers can no longer move their cocoa stocks to regional depots. During the 1982–1983 famine, poor roads prevented the transport of food from surplus areas to areas facing starvation. The high transport costs have also hit the timber industry. Logs moving from the Kumasi area for export through the Takoradi port are trucked over a 500-km route because the direct road, which is about half as long, is broken down and the rail services are unreliable. The detour adds $15 to $20 (U.S. dollars) for each ton of logs exported.

The prospects are not encouraging. Road resurfacing and strengthening covers only about 20 percent of estimated annual needs of about $47 million, mainly for resealing 1100 km of paved roads and regraveling 1600 km of unpaved roads. Even with a recent road maintenance project supported by the World Bank, maintenance will increase to only about 30 percent of that needed by 1989. Unless more resources can be put into road maintenance—and applied effectively—deterioration will continue. Ultimately the network will require far more costly rehabilitation, if financed, or result in an almost total collapse of road transport.

Although neglect of maintenance may be commonplace in other sectors of the economy and in other transport modes, it is particularly acute for roads for at least three reasons:

- Because of the large magnitude of the costs and financial requirements involved, the expenditures now needed to make

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up for past omissions of preventive maintenance in sub-Saharan Africa are at least 10 times as much as would be needed to provide a continuing supply of textbooks for all elementary school children in the region until year 2000.

- The nonlinear progression of deterioration on roads renders it difficult to recognize the need for preventive maintenance before it is too late to avoid more expensive corrective measures;
- The agency responsible for road maintenance is usually not directly exposed to, and hence is unlikely to be sensitive to, the economic consequences of undermaintenance of roads or organized pressure for better roads.

The purpose of this paper is to provide an overview of the status of roads in 85 developing countries that have received World Bank assistance for roads ($9.4 billion during 1974–1985). Following a discussion of the general characteristics of the road networks, regional differences in road condition are analyzed and factors contributing to these differences are grouped into a country typology to (a) help explain the differences in road condition across countries, (b) understand the causes of the road deterioration problem, and (c) identify appropriate responses to the problem as discussed by Bhandari et al., Smith and Harral, and Harral elsewhere in this Record.

ROAD NETWORKS

The main roads in the 85 developing countries comprise the primary and secondary road systems as defined or enumerated in government road classifications. The aggregate length of the main road systems in the 85 countries is about 1.8 million km, of which slightly more than 1.0 million km are paved. The main roads carry about 70 to 80 percent of the interurban traffic.

The tertiary network and all unclassified roads are not included, because road classification practices differ considerably from country to country and data on the geographical distribution and condition of these lower-order roads are less reliable. Much of the tertiary network in developing countries consists of unpaved roads with light, low-volume traffic. The ratio of maintenance to construction costs on these roads is fairly high, and neglect of maintenance has an immediate and more severe impact on service performance (user costs) than on the physical condition of the road. Urban road systems are also excluded because their traffic and maintenance characteristics and related deterioration problems are of a different nature.

Without detailed road inventories and country-specific construction costs, it is difficult to assess the value of the road stock with precision. Value assessments of national road stocks are not commonly available. In a report prepared by the U.K. National Development Office *(1)*, the gross replacement value of the entire U.K. road stock in 1982, including the plant and equipment owned by central and local road authorities, was estimated at about £38 billion ($50 billion, U.S. dollars). The deficiencies in the system as compared with a brand new system were estimated at about £10 billion ($13 billion, U.S. dollars) or 26 percent of the replacement value.

The replacement value of the main roads in the 85 developing countries is estimated at about $300 billion, excluding the value of land, major earthworks, and bridges. (This estimate is based on generalized average costs per kilometer presented in Table A-1 in the Appendix). This is roughly the same asset base as that for electric power generation and distribution in these countries.

In addition, there are another 5 to 6 million km of mostly unpaved, low-volume local roads and tracks (the tertiary system) with a replacement value of perhaps $75 to $100 billion. This overview deals primarily with main road networks, partly because they comprise the most important and valuable roads, and partly because information on other roads is too fragmentary.

There are significant differences in the coverage and quality of the road networks across the 85 countries. To illustrate, the coverage of main roads ranges from some 250 000 km in China to 760 km in Comoros, and four countries—China, India, Brazil, and Mexico—account for 51 percent of the total road kilometerage, 40 percent of main roads and 45 percent of paved roads. The differences emerging from aggregating the country data by geographic regions are equally striking as summarized in Table 1. The regional classification used in this paper reflects the geographic grouping of countries by the six operational regions of the World Bank, namely Eastern and Southern Africa (ESA); Western Africa (WA); East Asia and Pacific (EAP); South Asia (SA); Europe, Middle East, and North Africa (EMENA); and Latin America and Caribbean (LAC). See Figure 1 for a geographical demarkation of the regions. More detailed regional data are presented in Table A-1 and country-specific information is presented in Table A-2 in the Appendix.

Sub-Saharan Africa has the lowest area density km/100 km^2 of roads—about one-half of the global average for developing countries—whereas road length per 1,000 persons is about twice that for Asia. The ratio of road kilometers per million dollars of gross national product (GNP) (the market value of the final output of goods and services claimed by the residents of a country in a year) is the highest of all regions. The World Bank uses estimates of GNP as the main yardstick of economic activity in a country *(2, 3)*. These figures reflect the vast distances, the dispersed settlement patterns, and the smaller economic base of sub-Saharan Africa. Compared with other regions, a smaller proportion of main roads in sub-Saharan Africa is paved, but this is a reflection of lower traffic volumes on sub-Saharan road networks. In terms of the total road network, however, Latin America and Caribbean is observed to have a similar proportion of paved roads as Western Africa, suggesting that roads in sub-Saharan Africa may have been paved at lower traffic thresholds than in LAC. The Asian regions have the lowest road length per 1,000 population, reflecting the high population densities and spatial concentration of economic activity. These regions (except India) also have the lowest road density per million dollars of GNP, pointing to the hitherto less dominant role of modern road transport and the comparatively less developed state of roads relative to income levels. The Europe, Middle East, and North Africa region (which excludes all European countries except Hungary, Poland, Portugal, Romania, Turkey, and Yugoslavia) has the highest area density of main roads, a high ratio of road length per 1,000 population, a low road density per million dollars of GNP, and the highest percentage of paved roads, reflecting the relatively mature development of road networks relative to characteristics of the road networks in LAC are similar to their economies, in most countries of this region. The aggregate characteristics of the road networks in LAC are

TABLE 1 REGIONAL AND ROAD NETWORK CHARACTERISTICS, 1984

	Sub-Saharan Africa		Asia		Other	
	Eastern and Southern Africa	Western Africa	East Asia and Pacific	South Asia	Europe, Middle East, and North Africa	Latin America and Caribbean
Population and Economic Activity						
No. of countries	19	20	7	6	14	19
Area (million km^2)	11.1	8.9	13.2	5.1	6.5	18.9
Population (million)	201	186	1,350	1,008	232	350
Population density (persons/km^2)	18	21	102	197	36	19
GNP (1984 billion U.S. dollars)	51	105	600	258	338	583
GNP/capita (1984 U.S. dollars)	310	290	710	220	1,795	1,190
Growth in GNP/capita (1975–1985), percent	–0.1	–1.0	3.4	2.4	3.1	–0.03
Road Network (thousand km)						
All roads	588	430	1,540	1,681	1,051	2,212
Main roads	191	145	451	217	304	512
Replacement Value of Main Roads						
(1984 billion U.S. dollars)	18	17	90	33	66	76
Percent of GNP	35	16	15	13	20	13

similar to those of EMENA, except for one major difference: about 11 percent of the total road network in LAC is paved compared with 29 percent in EMENA and 31 percent in South Asia (although much of the road network in the Indian subcontinent is not suitable for modern road transport).

The regional differences in road density also reflect other factors: evidence suggests that some roads in sub-Saharan Africa have been expanded for social and political reasons beyond the levels needed to sustain economic growth. In East Asia and Pacific, motorized road transport is only now beginning to emerge as a dominant transport mode, and the extensive South Asian networks represent a legacy of road building spanning centuries.

CONDITION OF THE MAIN ROAD NETWORKS

In this study the basic information on road networks and their condition was pieced together from more than 150 internal World Bank documents (e.g., transport sector reviews, project appraisal reports, and consultant studies), which are classified and not available for general public distribution. This information was supplemented by data from standard references on road statistics *(4–6)*. Although the assessment of road conditions is subject to considerable error because of lack of reliable data, available evidence is good enough to gauge the broad dimensions of the problem. On the basis of information from recent surveys *(7, 8)*, supplemented as necessary by the judgment of World Bank highway engineers, the conditions of the main road of a country have been categorized as good, fair, and poor. A road in good condition requires only normal maintenance in the short term. Fair condition connotes the need for early resurfacing or strengthening. A road in poor condition has already deteriorated to the point that reconstruction, either partial or extensive, is required.

Road conditions in different countries (Table A-2) assessed in the preceding terms were combined into regional averages, weighted by network lengths. The regional figures (Table 2) are

TABLE 2 CONDITION OF MAIN ROADS

	Paved			Unpaved		
Region	Good	Fair	Poor	Good	Fair	Poor
Eastern Africa	42	32	26	42	30	28
Western Africa	52	23	25	20	36	44
East Asia	20	59	21	41	34	25
South Asia	18	45	36	6	39	55
Europe, Middle East, and North Africa	40	35	25	30	46	24
Latin America and Caribbean	44	32	24	24	43	33
Average	32	42	26	31	36	32
United States [federal-aid network, 1981 (*10*, pp. 20–21)][a]	31	57	12	–	–	–
United Kingdom (trunk road system, 1983)[b]	85	12	3	–	–	–

NOTES: As reported in an internal World Bank survey of 85 countries based as far as possible on published pavement condition information (60 countries) and supplemented where necessary by the judgment of bank highway engineers. *Paved roads* were assessed as follows: good—substantially free of defects and requiring only routine maintenance; fair—significant defects, requiring resurfacing or strengthening; and poor—extensive defects, requiring reconstruction or major rehabilitation. *Gravel roads* were assessed as follows: good—needing only routine grading or spot regraveling; fair—needing regraveling or reshaping, and spot repair of drainage; and poor—needing reconstruction and major drainage works.

[a]The condition data are based on serviceability ratings and qualitative definitions used by the Federal Highway Administration. A poor road is one that requires immediate resurfacing or complete reconstruction, a road in fair condition suggests the need for resurfacing in the near future, and a good road is one that does not require immediate resurfacing or reconstruction.

[b]Based on residual life concept—15 percent with a residual life of less than 5 years (before strengthening is likely to be needed), 25 percent with a residual life of less than 10 years, and 60 percent with a residual life of more than 20 years (*1*, p. 9). Assuming a uniform age distribution, these data would roughly conform to 85 percent good, 12 percent fair, and, at most, 3 percent poor, using the qualitative definitions employed by the FHWA and assuming that the near future is within the next 5 years.

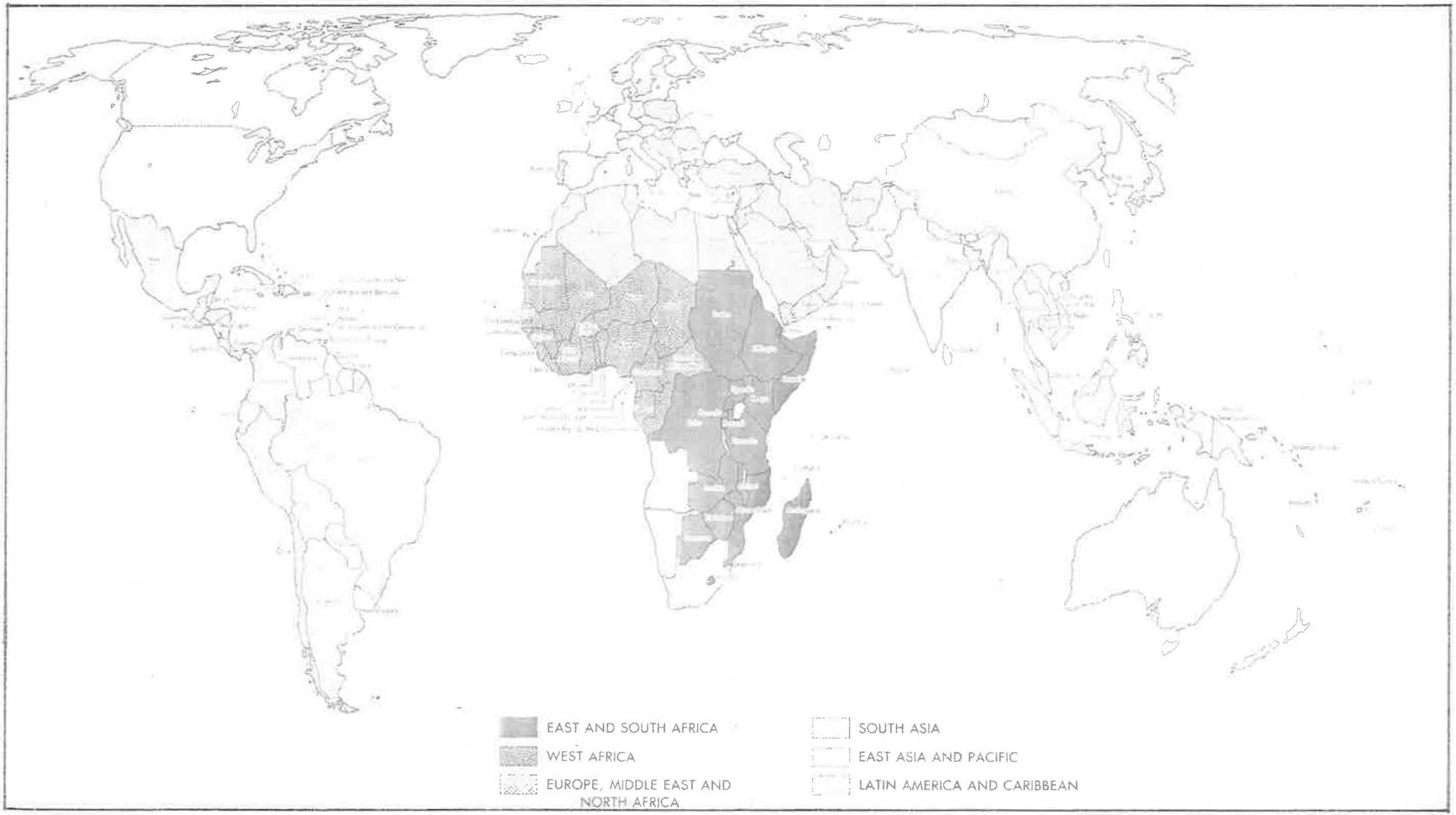

FIGURE 1 Geographical demarkation of World Bank's operational regions.

alarming on two counts. First, more than one-fourth of paved roads (some 267 000 km) are already in poor condition and a majority of these need rehabilitation or reconstruction. Second, and of even greater concern, the heavy concentration (42 percent) of paved roads in the fair category (about 430 000 km) foreshadows a crisis of major proportions, unless concerted efforts are made soon to prevent the descent of these roads into poor condition. For comparison, less serious levels of deterioration on the federal-aid highway network in the United States during the 1970s (12 percent poor as opposed to 26 percent in developing countries) prompted widespread alarm, the introduction of new legislation, new user taxes, and a large infusion of federal and state resources in the 1980s to remedy the situation *(9-11)*. In Maryland and Virginia at that time all road funds were required to be used for maintenance to the exclusion of new construction (see box "U.S. Experience During the 1970s").

The condition of unpaved roads in the main networks in developing countries is even worse *(12)*. In terms of road authority finances, the timing of maintenance for unpaved roads is less critical because the costs of restoration are, within rather broad limits, less sensitive to the timing of intervention. However, the aggregate effect of deterioration on vehicle operating costs can be quite large. Although unpaved roads normally carry less traffic, the riding condition of an unpaved road that is not maintained deteriorates much faster than a paved road. Deferral of simple maintenance measures (e.g., routine blading) on unpaved roads results in a rapid increase (as much as 100 percent) in vehicle operating costs.

Considerable variation exists in the conditions of roads in different regions and countries, which is explained by differences in the past maintenance needs of individual networks on the one hand and in the countries' responses to those needs on the other. A regional overview of the road conditions is presented in the following section.

U.S. Experience During the 1970s

The consequences of neglecting road maintenance are demonstrated by the U.S. experience during the 1970s. Needed maintenance on the federal-aid highway system was deferred or canceled by state agencies faced with budget constraints arising from the energy crisis and sharp recession beginning in 1974–1975. Because federal funds were not available for maintenance and rehabilitation, many states chose to let their roads, bridges, and highways deteriorate until they became eligible for capital federal aid for reconstruction. By 1982, the escalating deterioration of the federal aid highways, particularly the Interstate system, required a 44 percent increase in annual federal authorizations from $9 billion (in 1982) to $13 billion over the 1983–1990 period to help finance the repair and replacement of various components of the federal-aid system. The total cost of this restoration was estimated at $104.8 billion: Interstate highways, $19.6 billion; primary, secondary, and urban systems, $44.7 billion; and bridges, $40.5 billion. Although the United States may be able to mobilize such a massive level of resources to rehabilitate its road infrastructure, the less developed countries can ill afford this type of response.

Sub-Saharan Africa

At present, paved roads in Western Africa are generally found to be in better condition than in most other regions: 52 percent are considered good, 23 percent fair, and 25 percent poor. In Eastern and Southern Africa conditions are more typical: 42 percent good, 32 percent fair, and 26 percent poor. The relatively better condition of the paved roads in Western Africa is largely due to the rapid expansion of the paved networks during the last 10 years—about 50 percent of the paved road network in Western Africa was newly constructed, upgraded, or reconstructed during the last decade. Ivory Coast and Nigeria (see box "Nigeria's New Roads and the Risk of Massive Deterioration") substantially rebuilt their paved networks after 1975. Nigeria financed the effort by increased income from oil revenues. Even in less-endowed countries there has been a rapid improvement of road networks in the past decade financed by external-aid agencies. In Burundi, an Eastern African example, the length of the paved network has increased by more than 50 percent since 1979, whereas gravel roads have increased fourfold. Of 20 Western African countries for which information is available, 15 have networks with relatively new roads. The proportion at 10 out of 16 is not significantly lower for Eastern and Southern Africa. Many African countries are still enjoying an initial grace period during which maintenance requirements are minimal for much of their paved networks.

Nigeria's New Roads and the Risk of Massive Deterioration

The Nigerian Federal Trunk Road System, which has a total length of 29 000 km, has been largely rebuilt since 1975 in response to the explosive growth in road traffic following the economic expansion triggered by the increase in oil prices in 1973–1974. Traffic increases of 15 to 35 percent per annum were not uncommon on the federal network until 1978. Of the 21 000 km of paved roads, about 7600 km (36 percent) were constructed or rehabilitated during 1975–1980 and another 5000 km (24 percent) during 1981–1985. As a result, 62 percent of the paved network has been virtually abandoned because of ineffective maintenance, and an estimated 90 percent is in poor condition.

Despite the remarkable expansion and improvement of the Nigerian trunk road system during the last 10 years—at an estimated expenditure of about $8 billion—its condition is still precarious. The design standards used in road improvement and construction works have tended to encourage the use of generous geometric features but weak pavements, which require substantial strengthening within 3 to 4 years after initial construction to ensure continued use of the roads. In addition, a substantial part of the network has been improved under short-term emergency rehabilitation programs, which consist of a minimum of works necessary to make the roads serviceable. Without an extensive pavement strengthening program covering about 2000 to 3000 km a year at an estimated annual expenditure of $150 to $200 million and a concerted effort to improve maintenance, the Nigerian trunk road system may deteriorate rapidly, requiring massive rehabilitation and reconstruction in the next 10 to 15 years.

The continuous expansion and upgrading of the networks has masked serious weaknesses in road maintenance in many African countries; this holds serious portent. Gravel and earth roads deteriorate more quickly from maintenance neglect than paved roads; this is already reflected in the relatively poor condition of the main unpaved networks, particularly in Western Africa, with 20 percent good, 36 percent fair, and 44 percent poor.

East Asia and Pacific

The relatively poor state of East Asian paved networks (20 percent good, 59 percent fair, and 21 percent poor) primarily reflects conditions in three large countries: Indonesia, the Philippines, and China. China has not neglected maintenance; rather the existing 173 000-km paved network is woefully inadequate for the current demands placed on it, not only in terms of low spatial road density in the country's more densely populated regions, but also in terms of the structural and traffic-handling capacity of the network. Because of the expansion of the network in the 1970s, and also because many roads were built with inferior materials as a result of earlier difficulties in obtaining good quality bitumen in China, currently 70 percent of the existing main paved network is in need of resurfacing or strengthening. A substantial portion of the network requires not only structural strengthening but also substantial geometric improvements to cope with anticipated traffic growth. Other countries in East Asia, particularly Korea, Thailand, and Malaysia, have also experienced high growth, and have invested heavily in the expansion and improvement of their road networks. They are still enjoying the initial period when paved road maintenance demands are minimal, but will require a substantial expansion of road maintenance capacity to cope with future needs. The unpaved main roads in East Asia are in relatively better condition (41 percent good, 34 percent fair, and 25 percent poor) compared with other regions, possibly because of the higher traffic on these roads and consequently more intensive levels of maintenance.

South Asia

Current road conditions are by far the worst in South Asia. Only 18 percent of the paved main network is rated in good condition whereas 36 percent is in poor condition. Unpaved roads are in worse shape: no more than 6 percent are in good condition, and fully 55 percent are in poor condition. The regional aggregates are dominated by the large Indian networks (federal and state) of some 127 000 km, but conditions are not too dissimilar in other countries in the region, except Nepal whose small network is still relatively new. The pronounced deterioration in the South Asian networks is a result of the sustained growth in road transport over the last decade (without a commensurate level of investments in road infrastructure) and a shift of passenger and goods traffic from other modes to roads. The road networks consist mainly of aging and obsolete roads that have neither the geometric capacity nor the structural strength to carry the increasing traffic and vehicle loads. Poor quality construction and outmoded maintenance methods have not helped the situation. The critical need at this time is not so much restoration and maintenance as it is replacement and upgrading of an antiquated road infrastructure. To sustain its recent rate of economic growth, South Asia now faces the need for a large road-building program (see box "Pakistan's Deficient Road Infrastructure").

Pakistan's Deficient Road Infrastructure

The main road network in Pakistan comprising the national and provincial highways amounted to some 45 000 km in 1983. Nearly 30 000 km are now paved compared with 8000 km at the time of independence in 1947. The main road network, together with about 49 000 km of district roads and 11 000 km of municipal roads, provides extensive coverage, but the quality of roads is deficient and in need of substantial improvement. Most of the paved road system has inadequate geometric characteristics, particularly road width, and only 1500 km of national and provincial highways have two lanes or more. The structural condition of the roads is no better. Nearly 32 percent of the paved main roads and 70 percent of unpaved roads were estimated to be in poor condition in 1984.

The rapid growth in traffic (averaging about 11 to 13 percent per annum during the past 10 years), the high proportion of heavy-laden trucks, inadequate planning and management of highway development, insufficient road maintenance, deficient design and construction standards, and obsolete construction technology have all contributed to the poor and deteriorating condition of roads in Pakistan.

To cater to the growing demand for road transport, which has now replaced rail as the dominant transport mode and accounts for 80 to 90 percent of nonurban passenger traffic and 70 percent of freight traffic, Pakistan now needs to undertake a major program of road modernization and upgrading. This will not be an easy task, because the domestic road-building capacity using modern road construction technology amounts to about 15 to 25 km of highway per month. Bad roads are likely to impede the introduction of efficient and economical road transport technology in Pakistan. Eventually they could seriously constrain the country's development and economic growth prospects.

Europe, Middle East, and North Africa

In this region the main networks are well developed and, for the most part, so are maintenance institutions. However, the mature age profile of the networks implies higher maintenance requirements, which, combined with budgetary constraints in some countries (e.g., Yugoslavia and Morocco), has resulted in a road condition mix of 40 percent good, 35 percent fair, and 25 percent poor, with corresponding values for the unpaved network of 30 percent good, 46 percent fair, and 24 percent poor, respectively. Although conditions have improved for the region as a whole, the situation in some countries has deteriorated over the past 5 years. Most conspicuous is Yugoslavia, whose paved network, formerly one of the better maintained of the developing countries, has slipped because of unusually severe budgetary constraints to 30 percent good condition, 41 percent fair, and 29 percent poor. In the Republic of Croatia, for example, the periodic maintenance backlog was estimated at 40 percent of the network in 1985–1986 and was growing at the rate of about 13 percent (700 km) annually. Morocco's paved network is in even worse condition, with a current condition distribution of 20 percent good, 44 percent fair, and 36 percent poor. The need for immediate action is particularly striking in Yemen People's Democratic Republic where fully 69 percent of the paved network is now in fair condition.

Latin America and Caribbean

On average, current road conditions in the Latin American Region are still relatively good (44 percent good, 32 percent fair, and 24 percent poor for paved roads), but striking variations across countries and across time are concealed. Latin America contains two countries in which the condition of the paved networks approaches the condition distribution of well-maintained networks: Paraguay (with an estimated 73 percent of roads in good condition, 22 percent fair and 5 percent poor), and, most important, the Mexican federal network of more than 40 000 km (85 percent good, 10 percent fair, and 5 percent poor). However, the region also has countries (Bolivia, Costa Rica, Guatemala, Haiti, Jamaica, and Peru) where only one-fourth or less of main paved roads are in good condition. The condition of main paved roads are especially bad in Guatemala (7 percent in good condition, 50 percent fair, and 43 percent poor) and Jamaica (10 percent good, 75 percent fair, and 17 percent poor). Unpaved roads, which constitute about 51 percent of the main roads in Latin America, are worse than the average in Peru, Haiti, Belize, Bolivia, Jamaica, Argentina, and Costa Rica. Traffic levels on some of these roads, however, are quite low (10 to 20 vehicles per day) and substantial improvements in road conditions may not be warranted.

Road conditions in Latin America and the Caribbean as a whole have recently worsened quite rapidly, mirroring the general economic downturn and accompanying financial stringencies over the past 5 years—this illustrates how quickly roads can deteriorate once they reach the critical stage in their life cycle. Brazil with by far the largest network in Latin America has seen serious erosion despite substantial maintenance efforts. In 1984, 28 percent of the network was reported in poor condition compared with 18 percent in 1979 (see box "A Case of Undermaintenance: Brazil's Federal Highway Network"). In Honduras, which in the past had devoted an adequate level of effort and resources to road maintenance, the deterioration has been even more dramatic, with the percentage of the paved road network in good condition dropping from 82 percent in 1981 to 50 percent in 1984, largely because of financial constraints. The large decline in road condition may partly reflect differences in condition measurement and evaluation over the 2 years.

A Case of Undermaintenance: Brazil's Federal Highway Network

A 1979 survey of Brazil's federal highway network showed the following distribution of road conditions:

Condition	*km*	*%*
Good	10 000	24
Fair	23 000	58
Poor	7 000	18
Total	40 000	

Restoring all roads at that time would have cost $1.8 billion (1985 prices). A repeat survey in 1984 rated the network as follows:

Condition	*km*	*%*
Good	14 000	30
Fair	19 000	42
Poor	13 000	28
Total	46 000	

The increase in the percentage of roads in good condition resulted from new construction not good maintenance: 6000 km of new paved roads were constructed, whereas 2000 km of those formerly in good condition declined to fair condition. Nor did the massive backlog of roads in fair condition receive the resurfacing and strengthening that was needed. Some 6000 km of that group deteriorated to poor condition, greatly increasing the number of kilometers and the percentage of roads needing rehabilitation rather than just maintenance. The cost of this rehabilitation is estimated at $1.7 billion, and the cost of preventive maintenance needed to save the roads in fair condition is estimated at about $750 million (1985 prices). Thus, the federal rehabilitation and maintenance backlog increased to $2.4 billion, a one-third increase in 6 years.

The portent is clear, as shown by the extremely high proportion of roads in fair condition—on a regional basis ranging from 23 to 59 percent for paved and 30 to 46 percent for unpaved main networks.

DETERMINANTS OF ROAD CONDITIONS

The condition of road networks, at both global and regional levels, point to a serious neglect of maintenance in all but a handful of countries. Most countries that currently enjoy relatively good road conditions—particularly within the sub-Saharan Africa, Latin America, and East Asia regions—do so largely because of recent large additions to their networks and because such roads have not yet reached the end of their design lives—older roads in their networks have already deteriorated.

A multitude of factors explain why roads have been allowed to deteriorate to such an extent. The circumstances of every country are unique in one respect or another, so that generalizations are difficult and invariably subject to many exceptions. But there are common structural and response denominators that contribute to an understanding of the road deterioration problem across countries and the policy responses needed to deal with it. The structural parameters related to physical and economic conditions help to delineate the magnitude of the problem and the room for maneuvering in dealing with it. The response parameters related to financial, management, institutional, and political conditions provide a basis for gauging the efforts made to address the problem within a country's particular circumstances.

The more important of the structural parameters relate to

- Size of the country's road network and the percentage of paved roads;

- Age distribution of the paved network (which is, of course, closely associated with the level of recent investment);
- Volume and rate of traffic growth; and
- Financial capacity.

The length of the road network and the proportion paved are major determinants of overall maintenance requirements. The age distribution of the network is important because of the particular characteristics of paved road deterioration, with typically two-thirds of pavement deterioration (and an even higher percentage of maintenance costs) being concentrated in the final one-third of the pavement design life. Where a recent boom in road construction has occurred—as in many developing countries—a grace period of several years can be expected during which roads remain in good condition and maintenance demands are minimal, followed by a period in which maintenance requirements surge dramatically. Traffic growth is also an important determinant, because sustained demand for road transport can quickly render existing road networks obsolete. The size, quality, and age of networks and the growth of traffic can thus help to explain some of the differences in the level and character of maintenance requirements.

The capacity to fund road maintenance in a given country depends on the national resources. Gross national product per capita may be a good index of the fiscal capacity of the nation, although the governments of some countries are able to capture more of it than others. Out of a given total fiscal intake, allocation of funds to highways is a political decision, reflecting a judgment about national priorities. Variations in income growth (growth rate of GNP per capita) are also important: severe setbacks in income growth clearly help explain some important instances of underfunding of maintenance and consequent road deterioration, for example, in Latin America.

A broad idea of the economic burden that road maintenance imposes on a country is to be gained from the ratio of its network length to GNP (the income-density of roads), although an allowance has to be made for aging networks and heavy traffic loading that would increase the burden, whereas lower traffic volumes in poorer countries would tend to lower the burden. Values of the ratio for main roads range from 0.3 km per million dollars of GNP for Korea and 0.4 for Nigeria to more than 8.0 for Zaire and Botswana and 14.8 for Guinea-Bissau. Of the 36 countries with the highest value of this ratio, 32 are in sub-Saharan Africa (Table A-2). Even with the best management, these countries would face the world's highest burden of road maintenance requirements relative to income.

GNP per head and its rate of change, together with network length, age distribution, and traffic do not fully explain the variations in road conditions that reflect the extent to which maintenance requirements have been met. Several higher-income developing countries have poor roads, whereas some of the lowest income countries have better ones. The capacity of a country to deal with its maintenance needs depends on how effectively and efficiently it can translate available resources into protection and rehabilitation of road infrastructure.

The response parameters are intended to gauge the size and quality of a government's efforts to address its road maintenance needs and involve a number of managerial, institutional, and political factors, collectively known as absorptive capacity.

Absorptive capacity has a number of facets. One has to do with scale—the stock of machinery and the size of the labor force that can be applied to the activity. Another is the soundness of the maintenance strategy—type, level, and timing of intervention—and still others are the managerial and operational efficiency in executing the strategy. These depend, in turn, on such factors as the institutional structure, managerial ability, staff quality, accountability, incentives, and the extent to which objectives that conflict with efficiency (such as employment generation or other objects of political patronage) are imposed on the road authority.

All of these factors can in turn be related to the level of interest and quality of public leadership not only at the road authority level but also at the political level. Often political conviction is needed to accord priority in allocation of scarce resources (human as well as financial) to maintenance rather than to other politically more popular causes. The perceived interest of high government officials in road maintenance functions can also be an important determinant of the quality and motivation of staff attracted to the task, as demonstrated in several countries.

Experience with these aspects of absorptive capacity has often been remarkably disappointing. When limited absorptive capacity cannot readily be expanded, the prospects are poor for recovering infrastructure that has already suffered degradation or for preventing heavy losses of capital when the peak of maintenance needs is yet to come.

RESPONSE TO THE PROBLEM—A COUNTRY TYPOLOGY

The countries subject to road maintenance problems are of several types. Some have backlogs of maintenance because their financial and institutional capacities have not expanded as fast as their networks. Some have built up backlogs by deferring needed maintenance during adverse economic conditions. Some do not appear to have backlogs at present, but their networks of relatively recent construction will soon greatly increase and will require systematic maintenance to prevent rapid deterioration. The road deterioration problem pervades the developing world. At the core of the problem are mainly the countries of sub-Saharan Africa and South Asia; at the hard core of the problem are sub-Saharan countries whose financial and institutional capacities are unequal to the task at hand or to the task they will soon have to face.

To differentiate responses to the road deterioration problem at the country level, a typology of cases is proposed in Table 3, for a variety of structural and response parameters influencing road conditions. The typology consists of six representative categories in which the main road networks of the 85 countries have been grouped (Table 4). The geographical distribution of the typological groups is shown in Figure 2. The quantification of response parameters in the proposed typology has been particularly difficult. Adequate data on road maintenance expenditures are available only for 18 countries. Assessing efficiency of resource utilization at either the planning or the operation level poses an even greater challenge as few developing countries possess adequate management information systems to monitor and evaluate use of resources applied to their road networks. Although no pretense to scientific precision is made, the purpose of the classification is to identify country groupings in terms of needed actions to improve the conditions of their respective main road networks.

TABLE 3 FRAMEWORK FOR A TYPOLOGY OF ROAD CONDITION DETERMINANTS

								Determinants of Road Condition									
		Condition of Main Roads						Road Network Expansion, Median Values (%)			Maintenance Backlog			GNP per Capita ($ million)		GNP per Capita Growth per Annum 1975–1985 ($)	
		Paved Networks (%)			Unpaved Networks (%)			Paved Roads		Unpaved		Replacement Value (%)					
Type	No. of Countries	Good	Fair	Poor	Good	Fair	Poor	80–84	75–79	80–84	($ million)	Range	Median	Range	Median	Range	Median
Adequately maintained networks	11	74	19	7	34	44	22	12	15	24	1,357.1	2.7–8.9	5.7	180–2,290	1,240	−1.3–5.1	0.8
Recently expanded networks, middle and upper income	21	44	31	25	34	35	31	27	19	10.5	12,240.0	2.7–28.7	13.4	540–6,490	960	−3.3–7.9	2.2
Recently expanded networks, lower income	20	41	37	22	34	28	38	23	15	10	594.1	2.4–27.3	10.5	110–530	290	−3.7–3.7	−0.15
Aging networks, middle and upper income	16	32	38	30	19	50	31	8	4.5	11	10,751.9	7.6–34.4	15.6	660–4,340	1,420	−4–7	1.4
Aging networks, low income, low growth or decline	11	23	32	45	36	32	33	6	12.5	12	1,867.0	1.8–29.6	15.9	80–540	230	−7.7–−0.	−3.35
Obsolete or inadequate networks, low income, moderate or high growth	6	14	58	28	35	30	35	8	9	NA	13,053.7	8.9–33.3	23.6	130–380	285	1.6–6.8	3.25

TABLE 4 CLASSIFICATION OF ROAD NETWORKS BY COUNTRY TYPOLOGY

Category	Regional Distribution						Average Network Condition					
	Eastern and Southern Africa (19)	Western Africa (20)	East Asia and Pacific (7)	South Asia (6)	Europe, Middle East, and North Africa (14)	Latin American and Caribbean (19)	Paved (%) Good	Paved (%) Fair	Paved (%) Poor	Unpaved (%) Good	Unpaved (%) Fair	Unpaved (%) Poor
Group 1 Networks in countries with an adequate record of road maintenance (11)	Malawi Rwanda Zimbabwe	Niger	–	–	Hungary Romania Tunisia	Hondruras Mexico Panama Paraguay	74	19	7	34	44	22
Group 2 Recently expanded networks in middle and upper income countries (21)	Botswana Swaziland	Cameroon Congo Ivory Coast Nigeria	Indonesia Korea Malaysia Papua New Guinea Thailand	–	Egypt Oman Syria Yemen, AR Yemen, PDR	Brazil Colombia Costa Rica Dominican Republic Ecuador	44	31	25	34	35	31
Group 3 Recently expanded networks in low-income countries (19)	Burundi Comoros Djibouti Ethiopia Kenya Lesotho Somalia Sudan	Benin Burkina Central African Republic Gambia, The Guinea Liberia Mali Mauritania Senegal	–	Nepal	–	Haiti	41	37	22	34	28	38
Group 4 Aging networks in middle to upper income countries (16)	Mauritius	–	Philippines	–	Algeria Cyprus Morocco Portugal Turkey Yugoslavia	Argentina Barbados Belize Chile Guatemala Jamaica Peru Uruguay	32	39	29	19	50	31
Group 5 Aging networks in low income countries with low economic growth or decline (11)	Madagascar Tanzania Uganda Zaire Zambia	Chad Equatorial Guinea Ghana Guinea-Bissau Sierra Leone	–	–	–	Bolivia	24	22	44	36	32	32
Group 6 Obsolete or inadequate networks in low income countries with moderate to high economic growth (6)	–	–	China	Bangladesh Burma India Pakistan Sri Lanka	–	–	14	58	28	35	30	35
Global average: (19)							32	43	26	31	36	32

NOTE: Figures in parentheses are number of countries.

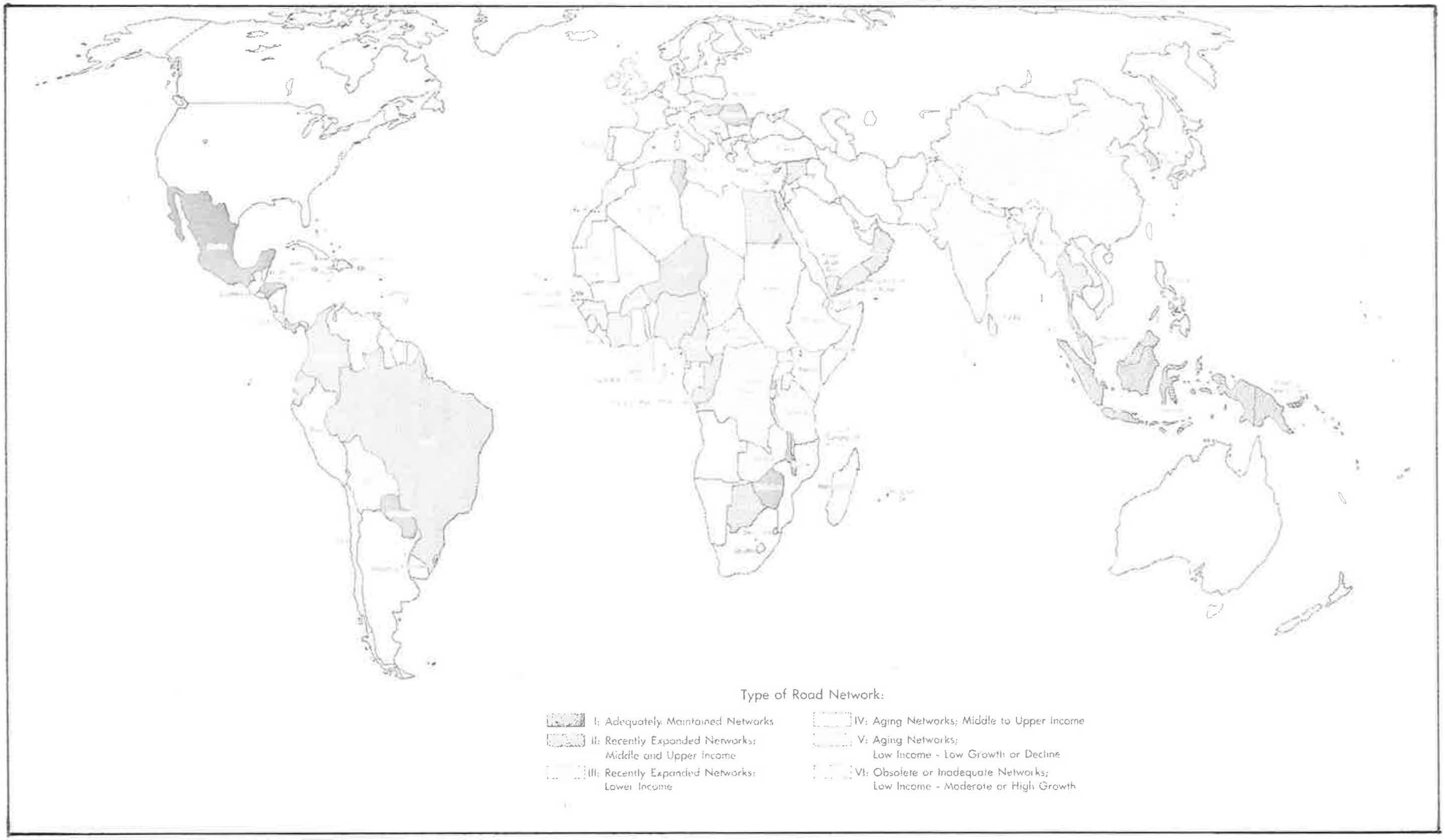

FIGURE 2 Typology of road networks in developing countries.

Group 1: Networks in Countries With an Adequate Record of Road Maintenance

This group encompasses a geographically disparate set of 11 countries (4 in sub-Saharan Africa, 1 in North Africa, 2 in Europe, and 4 in Latin America) that share the common characteristic that they have done a better job in preserving their road networks (particularly paved roads and to a lesser degree unpaved roads) than their otherwise comparable counterparts. On average 74 percent of paved roads are in good condition, 19 percent are fair, and only 7 percent are poor—not much different from the status of an optimally maintained network. Unpaved roads at 34 percent good, 44 percent fair, and 22 percent poor are well short of an optimal condition distribution, but still are generally better than in most other developing countries. The countries vary widely in economic circumstance (with per capita incomes ranging from $210 to $2,290) and in political and economic organization (from free-market to socialist). In these cases the primary advice for the future is to continue much as before with somewhat greater attention to institutional strengthening, technological improvements, and efficient operations, particularly on unpaved roads. In the two lowest income countries, Malawi and Niger, where a high proportion of the paved network is still relatively new, a swell in maintenance requirements will occur over the next several years, which might be difficult to meet without substantial external assistance.

Group 2: Recently Expanded Networks in Middle- and Higher-Income Countries

This group of 21 countries also covers a wide range of income, political and economic organization, and geographic location, although most countries in East Asia and Middle East regions are represented in this group. What they have in common is that a substantial proportion (often more than 50 percent) of their paved network has been constructed (or reconstructed) during the past 10 years, resulting in a relatively high proportion of the network being in good condition today with low current maintenance requirements but with the expectation of a surge in maintenance requirements in the future. These countries must prepare now for a major build-up in maintenance—institutionally as well as financially—well beyond their existing capabilities. A reallocation of resources from within the road sector (or from other sectors) will be needed to meet the skyrocketing road maintenance bill. Most of these countries are well placed from an absorptive capacity standpoint to institute major policy and institutional changes in their roads sector.

Group 3: Recently Expanded Networks in Lower-Income Countries

This group of 20 countries, all except 2 (Haiti and Nepal) in sub-Saharan Africa, share the characteristics of Group 2, except for the level and rate of growth of income and road networks that consist predominantly of unpaved surface. These countries, too, must prepare for the surge in road maintenance requirements ahead, but because of their low incomes, they will find it more difficult to sustain the level of expenditures needed to maintain all of their recently expanded networks to good standards. A selective road maintenance strategy that focuses on the economically and socially most important roads is indicated. Without a sustained level of continued external assistance—both financial and institutional—and improvements in the use of available resources, the maintenance requirements of their expanded road networks will heavily strain the limited financial and institutional capacities of these countries. A major shift in policy direction will be needed to deemphasize new construction and expansion of road networks in favor of maintaining existing roads.

Group 4: Aging Networks in Middle- to Higher-Income Countries

This group of 16 countries (all in LAC and EMENA regions, with the exception of Mauritius and the Philippines) shares the characteristic that there has been relatively little expansion to their networks recently (so that current maintenance requirements are a reasonably good indication of the future) and most have long-established maintenance capabilities. Maintenance needs have not been fully funded in the past, and the networks have been deteriorating. The primary constraint is additional finance. The institutional capabilities are reasonably well-established in most of these countries.

Group 5: Aging Networks in Low-Income, Low-Growth Countries

In this group of 10 sub-Saharan countries plus Bolivia, there has been relatively little expansion to the networks, but they are still struggling to establish effective road maintenance institutions, and the low incomes with either stagnant or declining economies make it difficult for these countries to maintain their existing networks, which consist mainly of unpaved roads. With future prospects even less encouraging for this group than for countries in Group 3, and on average 4 percent of paved roads in poor condition, a selective policy must be pursued to concentrate limited available resources on the most vital segments of the networks mainly for rehabilitation and periodic maintenance work. A massive dependence on external assistance is foreseen for these countries, and it is essential that appropriate, less capital-intensive road maintenance technologies be adopted by these countries to reduce this dependence locally and establish a sustainable level of maintenance.

Group 6: Obsolete or Inadequate Networks in Low-Income, and Moderate-to-High-Growth Countries

This group, composed of five South Asian countries plus China, shares the characteristic that existing networks are either largely outmoded or, in the case of China, simply not yet developed for current or readily foreseeable traffic demands. Roads in South Asia are mostly old and in an advanced state of disrepair. Because these roads do not have the traffic flow or structural capacity to meet the needs of growing economies in which the role of road transport is rapidly expanding, restoration and maintenance of the existing networks is not enough.

What is required is replacement and, like China, expansion to a modern network commensurate with the new role of road transport. A key requirement will be the adoption of modern road building and maintenance technologies in order to make the best use of available resources. The resistance to institutional and technological change is rather strong in South Asian countries despite the availability of abundant well-trained manpower. Finding innovative approaches of technology transfer and improving technical skills will prove to be a major challenge for the road administrations in these countries.

CONCLUSIONS

The developing countries are losing capital through massive deterioration of their roads. Large networks, built at great expense, have been undermaintained and more heavily used—and abused—than expected. If the decay is allowed to continue, it will accelerate, as old pavements crumble and younger ones outlive the period when neglect has little visible effect. The cost of restoring roads after they have disintegrated—three to five times the cost of preventive measures—is compounded by drastically increased vehicle operating costs. The cost in both forms would be a major drag on economic development. It is urgent to recognize the dimensions of the problem and to arrest the process while it can still be done at a reasonable cost.

The genesis of the problem lies in the rapid development of the road networks, which expanded much faster in the 1960s and 1970s than did maintenance budgets and institutional capacities. In many countries the need for expanding maintenance capacity has not been recognized or acted on early enough, further compounding the problem. The task now facing many developing countries is to salvage valuable infrastructure that has severely decayed while protecting newer vintages of roads from a similar fate. This task has major financial and institutional dimensions.

Arresting the deterioration process and repairing damage already suffered will require serious commitment by the countries concerned and by international development agencies. It will require improvements in institutions and management, good choices of technical options, and in some cases an increase in financial inputs to the roads sector. In others, the length of maintained networks may have to be reduced in order to concentrate available resources on road links with the highest social and economic priority.

In the 85 countries that receive World Bank assistance for roads, 26 percent of paved and 34 percent of unpaved main roads outside of urban areas have already decayed to the point of needing reconstruction. Of even greater concern is the large proportion (currently 42 percent) of paved roads that are now, or soon will be, in that critical phase when pavement strengthening is required if reconstruction is not also needed.

Although the circumstances of every country are unique in one respect or another, an attempt has been made to identify broad parameters of policy responses needed to halt the deteri oration of roads. The recommended policy actions are differentiated by six country types identified from a common set of characteristics related to the condition of the road networks in the 85 developing countries.

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REFERENCES

1. *Investment in the Public Sector Built Infrastructure—Report A: Roads and Bridges,* U.K. National Development Office, London, 1985.
2. A. Ray et al. *The World Development Report, 1986.* World Bank, Washington, D.C.
3. *The World Bank Atlas, 1986.* 19th edn. World Bank, Washington, D.C.
4. *World Road Statistics, 1980–84.* International Road Federation, Washington, D.C., 1985.
5. *Annual Bulletin of Transport Statistics for Europe.* United Nations, New York, 1983.
6. *World Transport Data.* International Road Transport Union, Geneva, Switzerland, 1985.
7. M. Mason. *Road Maintenance Survey for West and Central African Countries.* Paper presented at West and Central Africa Seminar on Cost-Effective Road Maintenance, Abidjan, Ivory Coast, 1985.
8. M. Mason and S. Miquel. *Results of Road Maintenance Survey for Latin American and Caribbean Countries.* World Bank, Washington, D.C., 1986.
9. M. Baker. *Rebuilding America's Infrastructure—Agenda for the 1980's.* Duke Press Policy Studies, Durham, N.C., 1984.
10. U.S. Congressional Budget Office. *Public Works Infrastructure—Policy Consideration for the 1980's,* U.S. Congress, Washington, D.C., 1983.
11. P. Choate. *Bad Roads—The Hidden Costs of Neglect.* National Asphalt Association, Riverdale, Md., 1983.
12. F. Johansen. *Deterioration of the Road Networks—An Emerging Crisis.* Transportation Department Paper, World Bank, Washington, D.C., 1984.

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APPENDIX

TABLE A-1 BASIC CHARACTERISTICS OF REGIONAL ROAD NETWORKS

REGION	NUMBER OF COUNTRIES	AREA KM2 ('000)	GNP 1984 (US$Bn)	POP. 1984 (Mn)	GNP/CAPITA MEDIAN 1984 (US$)	GNP/CAPITA GROWTH p.a.(%) 75-85	TOTAL ROAD NETWORK LENGTH KM ('000)	TOTAL ROAD NETWORK % PAVED	TOTAL ROAD NETWORK DENSITY: KM PER 100KM2	TOTAL ROAD NETWORK DENSITY: KM PER 1000P	TOTAL ROAD NETWORK DENSITY: KM PER UNIT GNP (US$Mn.)	MAIN ROADS NETWORK ('000KM)	MAIN ROADS % PAVED	MAIN ROADS DENSITY: KM PER 100KM2	MAIN ROADS DENSITY: KM PER 1000P	MAIN ROADS DENSITY: KM PER UNIT GNP (US$Mn.)	MAIN PAVED ROADS LENGTH KM ('000)	MAIN PAVED ROADS DENSITY PER 100KM2	REPLACEMENT VALUE OF MAIN NETWORK AVG.COST/KM PAVED (US$)	REPLACEMENT VALUE OF MAIN NETWORK AVG.COST/KM UNPAVED (US$)	REPLACEMENT VALUE OF MAIN NETWORK VALUE (US$Bn) PAVED	REPLACEMENT VALUE OF MAIN NETWORK VALUE (US$Bn) UNPAVED	REPLACEMENT VALUE OF MAIN NETWORK VALUE (US$Bn) TOTAL	REPLACEMENT VALUE OF MAIN NETWORK % OF GNP
EASTERN AFRICA	19	11,051	51.2	201	310	-0.1	588.3	7.7	5.3	2.9	11.5	190.5	24.6	1.7	0.9	3.7	46.9	0.8	255,000	40,000	12.0	5.7	17.7	34.6
WESTERN AFRICA	20	8,891	104.7	186	290	-1.0	430.9	12.6	4.8	2.3	4.1	144.5	37.3	1.6	0.8	1.4	53.9	0.9	245,000	40,000	13.2	3.6	16.8	16.1
Excluding Nigeria	19	7,967	34.3	90	270	-0.9	322.9	10.3	4.1	3.6	9.4	115.4	27.8	1.4	1.3	3.4	32.1	0.5	245,000	40,000	7.9	3.3	11.2	32.6
EAST ASIA & PACIFIC	7	13,184	600.4	1350	710	3.4	1539.6	18.1	11.7	1.1	2.6	450.9	61.4	3.4	0.3	0.8	276.9	9.5	300,000	40,000	83.1	7.0	90.0	15.0
Excluding China	6	3,623	281.4	221	785	2.5	571.2	16.9	15.8	2.6	2.0	196.6	52.8	5.4	0.9	0.7	103.8	5.6	300,000	40,000	31.1	3.7	34.9	12.4
SOUTH ASIA	6	5,120	257.5	1008	220	2.4	1680.7	31.1	32.8	1.7	6.5	217.1	80.3	4.2	0.2	0.8	174.3	7.4	180,000	40,000	31.4	1.7	33.1	12.9
Excluding India	5	1,922	62.7	259	180	1.8	180.7	26.7	9.4	0.7	2.9	89.6	56.0	4.7	0.3	1.4	50.2	2.3	180,000	40,000	9.0	1.6	10.6	16.9
EUROPE, MIDDLE EAST AND NORTH AFRICA	14	6,476	338.1	232	1795	3.1	1051.0	29.3	16.2	4.5	3.1	303.7	74.5	4.7	1.3	0.9	226.3	10.6	280,000	40,000	63.4	3.1	66.4	19.7
LATIN AMERICA AND CARIBBEAN	19	18,859	583.9	350	1190	0.0	2212.1	11.0	11.7	6.3	3.8	511.7	49.2	2.7	1.5	0.9	251.8	6.8	260,000	40,000	65.5	10.4	75.9	13.0
Excluding Brazil and Mexico	17	8,374	199.1	141	1160	-0.1	874.1	11.8	10.4	6.2	4.4	193.7	44.3	2.3	1.4	1.0	85.8	2.0	260,000	40,000	22.3	4.3	26.6	13.4
TOTAL	85	63,581	1935.9	3327			7502.6	19.4	11.8	2.3	3.9	1818.4	56.8	2.9	0.5	0.9	1030.0	29.5			268.4	31.5	299.9	15.5

TABLE A-2 ROAD NETWORKS BY GEOGRAPHIC REGION

REGION	COUNTRY	POP. 1984 (M)	AREA ('000KM2)	GNP/CAPITA 1984	GNP/CAPITA ANNUAL GROWTH 1975-85 (%)	TOTAL GNP 1984 ($M.)	TOTAL NETWORK LENGTH (KM)	TOTAL NETWORK DENSITY KM PER 100KM	TOTAL NETWORK DENSITY KM PER 1000	TOTAL NETWORK DENSITY KM PER $MnGNP	MAIN NETWORK LENGTH (KM)	MAIN NETWORK DENSITY KM PER 100KM2	MAIN NETWORK DENSITY KM PER 1000P	MAIN NETWORK DENSITY KM PER $MnGNP	MAIN PAVED NETWORK LENGTH (KM)	MAIN PAVED CONDITION G. (%)	MAIN PAVED CONDITION F. (%)	MAIN PAVED CONDITION P. (%)	MAIN PAVED CONST./IMPROVED IN --80/84-- (KM)	MAIN PAVED CONST./IMPROVED IN --80/84-- (%)	MAIN PAVED CONST./IMPROVED IN --75/79-- (KM)	MAIN PAVED CONST./IMPROVED IN --75/79-- (%)	MAIN UNPAVED NETWORK LENGTH (KM)	MAIN UNPAVED CONDITION G. (%)	MAIN UNPAVED CONDITION F. (%)	MAIN UNPAVED CONDITION P. (%)	MAIN UNPAVED CONST./IMP. --80/84-- (KM)	MAIN UNPAVED CONST./IMP. --80/84-- (%)
ESA	BOTSWANA	1.00	600	960	7.9	960	13,000	2.2	13.0	13.5	8,026	1.3	8.0	8.4	1,967	90	8	2	600	31	400	20	6,059	40	30	30	400	7
ESA	BURUNDI	4.60	28	220	0.9	1,012	5,400	19.3	1.2	5.3	2,900	10.4	0.6	2.9	744	58	37	5	390.00	52	40.00	5	2,156	60	25	15		
ESA	COMOROS	0.38	2	340	(1)	129	850	42.5	2.2	6.6	762	38.1	2.0	5.9	456	60	20	20	50	11	21	5	306	20	20	60		
ESA	DJIBOUTI	0.36	22	358	(1)	129	2,800	12.7	7.8	21.7	1,100	5.0	3.1		300	30	60	10	24	8	0	0	800	10	10	80		
ESA	ETHIOPIA	42.20	1,222	110	-0.9	4,642	43,200	3.5	1.0	9.3	13,600	1.1	0.3	2.9	3,800	33	34	33	485.00	13			9,800	33	34	33		
ESA	KENYA	19.60	583	310	0.1	6,076	55,000	9.4	2.8	9.1	25,300	4.3	1.3	4.2	6,000	32	52	16	1,400	23	1,600	27	19,300	66	17	17	358	2
ESA	LESOTHO	1.50	30	530	3.7	795	4,000	13.3	2.7	5.0	2,010	6.7	1.3	2.5	398	25	35	40					1,612	20	50	30		
ESA	MADAGASCAR	9.90	587	260	-3.4	2,574	50,000	8.5	5.1	19.4	10,150	1.7	1.0	3.9	4,890	20	30	50	300	6	450	9	5,260	20	20	60		
ESA	MALAWI	6.80	118	180	0.2	1,224	13,280	11.3	2.0	10.8	5,571	4.7	0.8	4.6	2,004	50	35	15	270	13	913	46	3,567	30	35	35	400	11
ESA	MAURITIUS	1.10	2	1,090	2.6	1,199	2,795	139.8	2.5	2.3	1,787	89.4	1.6	1.5	1,610								177					
ESA	RWANDA	5.80	26	280	1.0	1,624	10,000	38.5	1.7	6.2	4,000	15.4	0.7	2.5	800	80	20	0	300	38	60	8	3,200	20	80	0	3000	94
ESA	SOMALIA	5.20	638	260	-0.3	1,352	21,600	3.4	4.2	16.0	9,644	1.5	1.9	7.1	2,460	60	20	20					7,184	30	30	40		
ESA	SUDAN	21.30	2,506	360	-0.4	7,668	19,110	0.8	0.9	2.5	7,000	0.3	0.3	0.9	2,240	40	30	30	790.00	35			4,760	20	20	60		
ESA	SWAZILAND	0.71	17	800	-0.2 (*)	568	2,821	16.6	4.0	5.0	2,724	16.0	3.8	4.8	521	50	25	25	285	55	80	15	2,203	25	25	50		
ESA	TANZANIA	21.50	945	210	-1.7	4,515	53,600	5.7	2.5	11.9	17,700	1.9	0.8	3.9	3,240	38	34	28	581	18			14,460	5	47	48	1700	12
ESA	UGANDA	15.00	236	230	-3.3	3,450	27,037	11.5	1.8	7.8	5,691	2.4	0.4	1.6	1,726	10	59	31			110	6	3,965	52	26	22		
ESA	ZAIRE	29.70	2,345	140	-3.9	4,158	145,000	6.2	4.9	34.9	40,900	1.7	1.4	9.8	2,400	17	20	63	200	8	400	17	38,500	61	25	14		
ESA	ZAMBIA	6.40	753	470	-3.7	3,008	35,000	4.6	5.5	11.6	20,653	2.7	3.2	6.9	5,502	40	30	30	150	3	1,200	22	15,151	30	35	35	250	2
ESA	ZIMBABWE	8.10	391	760	-1.3	6,156	85,000	21.7	10.5	13.8	11,003	2.8	1.4	1.8	5,595	70	25	5					5,408	50	30	20	2090	39
COUNTRIES = 19																												
SUM		201.2	11,051			51,239	589,493	5.3	2.9	11.5	190,521				46,653								143,868					
AVERAGE				255	-0.1							1.7	0.9	3.7		42	32	26						42	30	28		
WA	BENIN	3.90	113	270	0.6	1,053	7,500	6.6	1.9	7.1	4,926	4.4	1.3	4.7	986	58	36	6	230	23	100	10	3,940	15	55	30	500	13
WA	BURKINA	6.60	274	160	0.9	1,056	11,200	4.1	1.7	10.6	6,300	2.3	1.0	6.0	1,400	40	40	20	400	29	281	20	4,900	10	30	60	355	7
WA	CAMEROON	9.90	475	760	3.9	7,524	64,905	13.7	6.6	8.6	13.500	2.8	1.4	1.8	2,900	60	30	10	783	27	797	27	10,600	20	50	30		
WA	CHAD	4.90	1,284	80	-7.7 (*)	392	31,300	2.4	6.4	79.8	3.800	0.3	0.8	9.7	163	4	0	96	7.00	4			3,637	8	19	73	1000	27
WA	CONGO	1.80	342	1,140	2.2	2,052	11,000	3.2	6.1	5.4	7,000	2.0	3.9	3.4	1,100	69	15	16	620	56	480	44	5,900	30	20	50	150	3
WA	C.A.R.	2.50	623	260	-1.4	650	22,600	3.6	9.0	34.8	5,250	0.8	2.1	8.1	442	36	35	29	269	61	65	15	4,808	68	16	16	955	20
WA	EQUAT. GUINEA	0.37	28	180	(1)	67	1,540	5.5	4.2	23.1	1.090	3.9	2.9		485	26	0	74			80.00	16	605	0	0	100		
WA	GHANA	12.30	239	350	-1.9	4,305	28,400	11.9	2.3	6.6	14,130	5.9	1.1	3.3	5,782	12	27	61	126	2			8,348	17	48	35		
WA	GUINEA	5.90	246	330	0.2 (*)	1,947	14,000	5.7	2.4	7.2	4,550	1.8	0.8	2.3	1,145	51	35	14	201	18	85	7	3,405	13	22	65	975	29
WA	GUINEA-BISSAU	0.88	36	180	-2.1 (*)	158	4,040	11.2	4.6	25.5	2,300	6.4	2.6	14.5	485	2	65	33	30.00	6	30.00	6	1,815					
WA	IVORY COAST	9.90	322	610	-2.2	6,039	47,880	14.9	4.8	7.9	13,680	4.2	1.4	2.3	3,620	78	15	7	955	26	1,330	37	10,060	30	60	10	170	2
WA	LIBERIA	2.10	111	470	-3.7	987	7,560	6.8	3.6	7.7	3,945	3.6	1.9	4.0	557	85	13	2	110	20	250	45	3,388	15	75	10	176	5
WA	MALI	7.30	1,240	140	0.0	1,022	13,500	1.1	1.8	13.2	5,222	0.4	0.7	5.1	1,890	43	33	24	540	29	378	20	3,332	11	4	85	1340	40
WA	MAURITANIA	1.70	1,031	450	-0.4	765	7,500	0.7	4.4	9.8	2,480	0.2	1.5	3.2	1,640	30	30	40	1,200	73	200	12	840	0	5	95		
WA	NIGER	6.20	1,267	190	-1.1	1,178	19,000	1.5	3.1	16.1	6,369	0.5	1.0	5.4	2,609	70	20	10	505	19	757	29	3,760	30	35	35	666	18
WA	NIGERIA	96.50	924	730	-3.3	70,445	108,000	11.7	1.1	1.5	29,100	3.1	0.3	0.4	21,100	62	15	23	4,980	24	7,588	36	8,000	0	10	90		
WA	SENEGAL	6.40	196	480	-1.3	3,072	11,700	6.0	1.8	3.8	9,700	4.9	1.5	3.2	3,762	51	36	13	470	12	740	20	5,938	4	26	70	400	7
WA	SIERRA LEONE	3.70	72	310	-0.3	1,147	9,924	13.8	2.7	8.7	7,040	9.8	1.9	6.1	1,280	20	45	35	240	19			5,760	30	40	30		
WA	THE GAMBIA	0.71	11	260	-1.7	185	2,388	21.7	3.4	12.9	1,209	11.0	1.7	6.5	447	27	50	23	210	47	30	7	762	30	42	28	310	41
WA	TOGO	2.90	57	250	-1.5	725	7,000	12.3	2.4	9.7	2,921	5.1	1.0	4.0	1,712	40	24	36	427	25	235	14	1,209	30	45	25	86	7
COUNTRIES = 20																												
SUM		186.5	8,891			104,769	430,937	4.8	2.3	4.1	144,512				53,505								91,007					
AVERAGE				562	-1.0							1.6	0.8	1.4		52	23	25						20	36	44		

(*) 1973-83
(1) Not Available

TABLE A-2 *continued*

REGION	COUNTRY	POP. 1984 (M)	AREA ('000KM2)	GNP/CAPITA 1984	GNP/CAPITA ANNUAL GROWTH 1975-85 (%)	TOTAL GNP 1984 ($M.)	TOTAL NETWORK LENGTH (KM)	TOTAL NETWORK DENSITY KM PER 100KM	TOTAL NETWORK DENSITY KM PER 1000	TOTAL NETWORK DENSITY KM PER $MnGNP	MAIN NETWORK LENGTH (KM)	MAIN NETWORK DENSITY KM PER 100KM2	MAIN NETWORK DENSITY KM PER 1000P	MAIN NETWORK DENSITY KM PER $MnGNP	MAIN PAVED NETWORK LENGTH (KM)	MAIN PAVED CONDITION G. (%)	MAIN PAVED CONDITION F. (%)	MAIN PAVED CONDITION P. (%)	MAIN PAVED CONST./IMPROVED IN --80/84-- (KM)	MAIN PAVED CONST./IMPROVED IN --80/84-- (%)	MAIN PAVED CONST./IMPROVED IN --75/79-- (KM)	MAIN PAVED CONST./IMPROVED IN --75/79-- (%)	MAIN UNPAVED NETWORK LENGTH (KM)	MAIN UNPAVED CONDITION G. (%)	MAIN UNPAVED CONDITION F. (%)	MAIN UNPAVED CONDITION P. (%)	MAIN UNPAVED CONST./IMP. --80/84-- (KM)	MAIN UNPAVED CONST./IMP. --80/84-- (%)
EAP	CHINA	1029.20	9,561	310	6.8	319,052	915,100	9.6	0.9	2.9	254,300	2.7	0.2	0.8	173,300	10	70	20	22,000	13	59,000	34	81,300	50	25	25		
EAP	INDONESIA	158.90	1,919	540	3.6	85,806	201,300	10.5	1.3	2.3	45,800	2.4	0.3	0.5	27,550	30	30	40	5,530	20	5,000	18	18,250	22	47	31	3500	19
EAP	KOREA	40.10	98	2,110	6.4	84,611	54,000	55.1	1.3	0.6	23,481	24.0	0.6	0.3	9,928	70	25	5	3,860	39	1,926	19	13,553	60	20	20		
EAP	MALAYSIA	15.30	330	1,980	4.1	30,294	45,000	13.6	2.9	1.5	25,324	7.7	1.7	0.8	23,479								1,845					
EAP	PAPUA N GUINEA	3.40	462	710	-0.8	2,414	18,545	4.0	5.5	7.7	3,652	0.8	1.1	1.5	726	34	45	21	110	15	109	15	2,926	23	71	6		
EAP	PHILIPPINES	53.40	300	660	0.1	35,244	155,669	51.9	2.9	4.4	53,864	18.0	1.0	1.5	14,192	31	54	15	900	6	500	4	39,672	25	50	25	1055	3
EAP	THAILAND	50.00	514	860	3.9	43,000	150,000	29.2	3.0	3.5	44,534	8.7	0.9	1.0	28,000	50	30	20	8,600	31	5,242	19	16,534	45	30	25		
COUNTRIES = 7																												
SUM		1,350	13,184			600,421	1,539,614	11.7	1.1	2.6	450,955				276,875								174,080					
AVERAGE				445	3.4							3.4	0.3	0.8		20	59	21						41	34	25		
SA	BANGLADESH	98.10	144	130	1.7	12,753	15,000	10.4	0.2	1.2	10,900	7.6	0.1	0.9	6,210	15	40	45	1,180	19	60	1	4,690	10	40	50		
SA	BURMA	36.10	677	180	3.9	6,498	27,983	4.1	0.8	4.3	25,400	3.8	0.7	3.9	8,400	0	50	50					17,000	0	50	50		
SA	INDIA/NATIONAL	749.20	3,288	260	1.9	194,792	1,500,000	45.6	2.0	7.7	32,000	1.0	0.0	0.2	31,600	20	45	35	2,500	8	3,000	9	400	20	40	40		
SA	INDIA/STATES										95,500				91,200	20	45	35					4,300	20	40	40		
SA	NEPAL	16.10	141	160	0.7	2,576	7,150	5.1	0.4	2.8	5,546	3.9	0.3	2.2	2,500	40	35	25	584	23	376	15	3,046	15	45	40	300	10
SA	PAKISTAN	92.40	804	380	3.3	35,112	107,673	13.4	1.2	3.1	38,830	4.8	0.4	1.1	24,142	18	50	32	1,940	8	2,500	10	14,688	5	25	70		
SA	SRILANKA	15.90	66	360	3.2	5,724	25,500	38.6	1.6	4.5	8,900	13.5	0.6	1.6	8,900	10	40	50	50	1	100	1	0	0	0	0		
COUNTRIES = 6																												
SUM		1,008	5,120			257,455	1,683,306	32.9	1.7	6.5	217,076				172,952								44,124					
AVERAGE				255	2.4							4.2	0.2	0.8		19	45	36						6	39	55		
EMENA	ALGERIA	21.20	2,382	2,410	3.2	51,092	78,190	3.3	3.7	1.5	39,347	1.7	1.9	0.8	32,480	40	32	28			1,070	3	6,867	25	50	25		
EMENA	CYPRUS	0.67	9	3,590	7.0	2,405	6,831	75.9	10.2	2.8	3,031	33.7	4.5	1.3	2,938	5	55	40	253	9	400	14	93	0	50	50		
EMENA	EGYPT	45.90	1,001	720	4.8	33,048	30,089	3.0	0.7	0.9	28,725	2.9	0.6	0.9	15,081	39	33	28					13,644					
EMENA	HUNGARY	10.70	93	2,100	5.1 (*)	22,470	138,185	148.6	12.9	6.1	24,000	25.8	2.2	1.1	24,000								0					
EMENA	MOROCCO	21.40	447	670	1.4	14,338	57,692	12.9	2.7	4.0	19,080	4.3	0.9	1.3	14,816	20	44	36	1,625	11	55	0	4,264					
EMENA	OMAN	1.10	300	6,490	4.4 (*)	7,139	18,123	6.0	16.5	2.5	8,474	2.8	7.7	1.2	3,292	66	20	14	1,950	59	900.00	27	5,182				690	13
EMENA	PORTUGAL	10.20	92	1,970	1.6	20,094	52,031	56.6	5.1	2.6	19,031	20.7	1.9	0.9	17,900	50	30	20	1,400	8	1,000	6	1,131	40	40	20	200	18
EMENA	ROMANIA	22.70	238	2,290	(1)	51,983	73,500	30.9	3.2	1.4	14,700	6.2	0.6	0.3	14,000	69	21	10	810	6	1,670	12	700	39	37	24		
EMENA	SYRIA	10.10	185	1,620	-0.2	16,362	26,200	14.2	2.6	1.6	15,700	8.5	1.6	1.0	11,700								4,000					
EMENA	TUNISIA	7.00	164	1,270	2.6	8,890	78,190	47.7	11.2	8.8	16,900	10.3	2.4	1.9	9,140	55	36	9	1,000	11	900	10	7,760	30	40	30	2300	30
EMENA	TURKEY	48.40	781	1,160	1.4	56,144	329,793	42.2	6.8	5.9	60,953	7.8	1.3	1.1	38,449								22,504					
EMENA	YEMEN AR	7.80	195	550	4.0	4,290	25,028	12.8	3.2	5.8	3,028	1.6	0.4	0.7	2.048	70	20	10	450	22	300	15	980	40	30	30	210	21
EMENA	YEMEN PDR	2.00	333	550	5.2	1,100	7,100	2.1	3.6	6.5	1,887	0.6	0.9	1.7	1,650	27	69	4	637	39	602	36	237	33	33	34		
EMENA	YUGOSLAVIA	23.00	256	2,120	2.6	48,760	130,000	50.8	5.7	2.7	48,880	19.1	2.1	1.0	36,630	30	41	29	1,358	4	441	1	12,250	30	50	20		
COUNTRIES = 14																												
SUM		232	6,476			333,115	1,050,952	16.2	4.5	3.1	303,736				224 124								79,612					
AVERAGE				1,456	3.1							4.7	1.3	0.9		40	35	25						30	46	24		
LAC	ARGENTINA	30.10	2,767	2,230	-1.9	67,123	212,305	7.7	7.1	3.2	36,505	1.3	1.2	0.5	27 056	35	21	44			2,280	8	9,449	20	40	40		
LAC	BARBADOS	0.26	0	4,340	1.6	1,128	1,670	388.4	6.4	1.5	1,367	317.9	5.3	1.2	1 367								0					
LAC	BELIZE	0.16	23	1,150	3.6 (*)	184	2,000	8.7	12.5	10.9	1,871	8.1	11.7	10.2	442	32	48	20					1,429	2	43	55		
LAC	BOLIVIA	6.20	1,099	540	-4.0	3,348	39,824	3.6	6.4	11.9	9,382	0.9	1.5	2.8	1.351	21	48	31	120	9			8,031	20	30	50		
LAC	BRAZIL/FEDERAL	132.60	8,512	1,720	1.2	228,072	1,316,343	15.5	9.9	5.8	64,642	0.8	0.5	0.3	45.291	30	42	28	6,570	15			19,351	30	42	28		
LAC	BRAZIL/STATES										162,596				55.887				8,000	14	8,000	14	106,709					
LAC	CHILE	11.80	757	1,700	0.9	20,060	79,000	10.4	6.7	3.9	22,831	3.0	1.9	1.1	8,964	33	56	11	630	7	750	8	13,867	7	75	18	500	4
LAC	COLOMBIA	28.40	1,139	1,390	1.7	39,476	77,200	6.8	2.7	2.0	24,397	2.1	0.9	0.6	9.620	42	37	21	1,730	18	1,953	20	14,777	42	37	22	1150	8

(*) 1973-83

(1) Not Available

TABLE A-2 *continued*

REGION	COUNTRY	POP. 1984 (M)	AREA ('000KM2)	GNP/CAPITA 1984	GNP/CAPITA ANNUAL GROWTH 1975-85 (%)	TOTAL GNP 1984 ($M.)	TOTAL NETWORK LENGTH (KM)	TOTAL NETWORK DENSITY KM PER 100KM	TOTAL NETWORK DENSITY KM PER 1000P.	TOTAL NETWORK DENSITY KM PER $MnGNP	MAIN NETWORK LENGTH (KM)	MAIN NETWORK DENSITY KM PER 100KM2	MAIN NETWORK DENSITY KM PER 1000P	MAIN NETWORK DENSITY KM PER $MnGNP	MAIN PAVED NETWORK LENGTH (KM)	MAIN PAVED CONDITION G. (%)	MAIN PAVED CONDITION F. (%)	MAIN PAVED CONDITION P. (%)	MAIN PAVED CONST./IMPROVED IN 80/84 (KM)	MAIN PAVED CONST./IMPROVED IN 80/84 (%)	MAIN PAVED CONST./IMPROVED IN 75/79 (KM)	MAIN PAVED CONST./IMPROVED IN 75/79 (%)	MAIN UNPAVED NETWORK LENGTH (KM)	MAIN UNPAVED CONDITION G. (%)	MAIN UNPAVED CONDITION F. (%)	MAIN UNPAVED CONDITION P. (%)	MAIN UNPAVED CONST./IMP. 80/84 (KM)	MAIN UNPAVED CONST./IMP. 80/84 (%)
LAC	COSTA RICA	2.50	51	1,190	-0.3	2,975	28,500	55.9	11.4	9.6	4,789	9.4	1.9	1.6	3,044	22	29	49	890	29	240	8	1,745	8	7	85		
LAC	DOMINICAN R.	6.10	49	970	0.2	5,917	17,200	35.1	2.8	2.9	3,475	7.1	0.6	0.6	2,485	52	10	38	800	32	200	8	990	0	22	78	200	20
LAC	ECUADOR	9.10	284	1,150	0.3	10,465	37,910	13.3	4.2	3.6	8,400	3.0	0.9	0.8	3,380	53	19	28	270	8	790	23	5,020	65	10	25		
LAC	GUATEMALA	7.70	109	1,160	-3.3	8,932	18,426	16.9	2.4	2.1	10,641	9.8	1.4	1.2	3,043	7	50	43	243	8	162	5	7,598	11	62	27		
LAC	HAITI	5.40	28	320	0.7	1,728	4,000	14.3	0.7	2.3	2,473	8.8	0.5	1.4	606	0	100	0	130	21	130	21	1,867	10	42	48		
LAC	HONDURAS	4.20	112	700	0.4	2,940	12,058	10.8	2.9	4.1	6,018	5.4	1.4	2.0	1,614	50	43	7			282	17	4,404	50	38	12		
LAC	JAMAICA	2.20	11	1,150	-4.0	2,530	17,700	160.9	8.0	7.0	4,750	43.2	2.2	1.9	4,365	10	73	17	222	5	64	1	385	1	56	43	254	66
LAC	MEXICO/FEDERAL	76.80	1,973	2,040	0.6	156,672	212,626	10.8	2.8	1.4	43,500	2.2	0.6	0.3	40,520	85	10	5	4,000	10	2,000	5	2,980	30	50	20		
LAC	MEXICO/STATES										47,300				24,200								23,100					
LAC	PANAMA	2.10	77	1,980	1.3	4,158	8,665	11.3	4.1	2.1	8,400	10.9	4.0	2.0	3,094	36	54	10	330	11	450	15	5,306	8	68	24		
LAC	PARAGUAY	3.30	407	1,240	3.7	4,092	24,329	6.0	7.4	5.9	11,241	2.8	3.4	2.7	1,695	73	22	5	340	20	470	28	9,546	44	38	18	780	
LAC	PERU	18.20	1,285	1,000	-2.5	18,200	58,516	4.6	3.2	3.2	27,300	2.1	1.5	1.5	7,178	24	24	52	920	13	70	1	20,122	10	30	60		
LAC	URUGUAY	3.00	176	1,980	-1.0	5,940	49,813	28.3	16.6	8.4	9,813	5.6	3.3	1.7	6,445	26	59	15					3,368	0	75	25		
COUNTRIES = 19																												
SUM		350	18,859			583,940	2,218,085	11.8	6.3	3.8	511,691				251,647								260,044					
AVERAGE				1,668	-0.03							2.7	1.5	0.9		44	32	24						24	43	33		
ALL REGIONS																												
COUNTRIES = 85																												
SUM		3,328	63,581			1,935,939	7,512,387				1,818,491				1,025,756								792,735					
AVERAGE				582								2.9	0.5	0.9		32	42	26						31	36	33		

(*) 1973-83

(1) Not Available

Technical Options for Road Maintenance in Developing Countries and the Economic Consequences

A. BHANDARI, C. HARRAL, E. HOLLAND, AND A. FAIZ

The basic issues concerning road maintenance are addressed: (a) selection of cost-effective maintenance policies, (b) effect of budget constraints on maintenance priorities, (c) relationship between initial pavement design strength and subsequent maintenance, and (d) economic traffic thresholds for paving gravel roads. The analysis is based on life-cycle cost simulation produced by the latest version of the World Bank's Highway Design and Maintenance Model (HDM-III), which evolved from an extensive program of empirical research conducted over more than 15 years.

Competing demands for resources require that developing countries search for the most economical design of highways and maintenance programs, taking into account not only the costs of government but also the larger costs of vehicle ownership and operation borne by road users. Under budget constraints, it becomes imperative to develop a system for assessing the priorities for the entire budget for the roads sector (capital and recurrent), which gives rise to a series of questions:

- How much should be spent on road maintenance and when should paved roads or unpaved roads be rehabilitated and maintained? Which maintenance measures have the highest payoff under varying circumstances?
- Can future maintenance requirements be reduced by building or restoring roads to higher standards today? Under what circumstances is this an economical strategy?
- How do budgetary and other constraints affect these choices? If restoring a deteriorated network implies acting on a core network and deferring or abandoning action on the rest of the network, what course should be chosen? What should receive higher priority: preventive maintenance on roads that are in fair condition or restoration of roads that are already in poor condition?
- What are the consequences of deferring maintenance on part or all of the network?
- Given the unsatisfactory state of road networks in most developing countries and the multitude of constraints to be overcome, what overall strategy should be adopted? Does it vary much from case to case?

Providing economic answers to these questions requires the ability to predict total transport costs—construction, reconstruction, maintenance, and road user costs—over the life cycle of the roads under various road design and maintenance strategies. The empirical knowledge concerning the underlying physical and economic relationships, particularly the road deterioration, user costs, and maintenance effects, has been too limited to lend much credibility to such modeling efforts.

Faced with this problem the World Bank in 1971 initiated what ultimately became an international collaborative program of primary data collection and research, first in Kenya and later, on a larger scale, in Brazil and India. The support for this effort came from the United Nations Development Program, the World Bank, and the governments of India, Kenya, Brazil, Sweden, Australia, and the United Kingdom. With participation by a number of research institutions, more than $20 million was spent for data collection and analysis to provide rigorous quantification of key relationships. Although gaps remain, basic relationships *(1, 2)* have now been statistically established for a substantial range of traffic and environmental conditions typical of developing countries. These new empirical relationships have in turn been incorporated into the World Bank's Highway Design and Maintenance Model (HDM-III), which, together with its companion Expenditure Budgeting Model (EBM), provides the capability to simulate and compare many alternative strategies according to standard economic criteria, with and without budget constraints *(3, 4)*.

Among the most important advances from this research program have been the twin abilities to (a) relate vehicle operating costs (VOC) to a measure of road surface condition (namely road roughness) and (b) measure roughness in a rigorous, systematic manner using the International Roughness Index (IRI) *(5, 6)*. As shown in Figure 1, vehicle operating costs constitute a large share (75 to 95 percent) of the total road transport cost, except when traffic volume is extremely low. Thus the effect on total transport cost of even a small percentage change in vehicle operating costs is large relative to the effect of changes in construction and maintenance costs. Before the HDM studies *(1, 7)*, no basic empirical data on the relationship between vehicle operating costs and pavement surface condition were available. Road investment decisions were guided by imprecise and fragmentary estimates of vehicle operation costs related primarily to the type of road (paved, gravel, earth). On the basis of improved estimation of vehicle speeds (in a free-flowing traffic regime) and operating costs as functions of road design characteristics, the HDM research suggests that vehicle operating costs are somewhat less sensitive to changes in road condition than previously estimated *(8)*.

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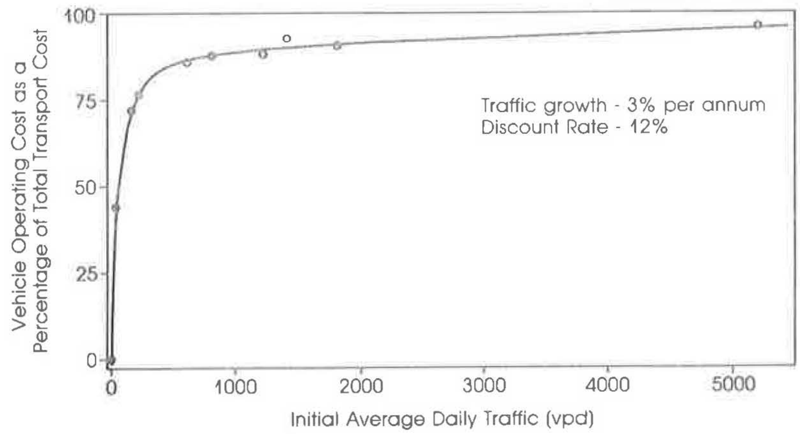


FIGURE 1 Vehicle operating costs as a percentage of total transport cost (construction, maintenance, and vehicle operating costs) for typical cases with optimal road maintenance.

CASE STUDIES

The HDM-III and EBM models were used in a series of case studies *(8)* to simulate the deterioration of roads under alternative maintenance options and to find the best investment and maintenance policies under various constraints. Road types and conditions, traffic, climate, and unit costs in the studies corresponded to those observed in three countries—Mali, Chile, and Costa Rica. Despite the limited inferences possible from the case studies, the consistency of the results permits generalizations for wider application.

Thirty-one maintenance policy alternatives were tested for paved roads and 10 for unpaved roads. The policies consisted of different maintenance packages (ranging from low-cost pothole patching, through bituminous resealing of the entire surface and more costly asphalt concrete overlaying, to major rehabilitation and reconstruction of the base and the surface) and specifications of the deterioration levels at which they would be applied. As a benchmark against which to measure differences in the costs of other alternatives, a null case was defined that included only the basic routine maintenance activities (drainage clearing, minimal vegetation control, and shoulder repair) that are also included in the other alternatives. Tables 1 and 2 contains a summary of the alternatives; each one is identified by a code (such as AL18), which will be used later in discussing the results. To illustrate, under alternative AL18, 100 percent of potholes would be patched each year, a surface treatment would be applied whenever 25 percent of the area was visibly damaged, and a 40-mm overlay would be applied whenever roughness reached a level of 5 on the IRI scale.

The roads in each country's network were grouped into broadly homogeneous classes according to surface type, condition in the initial year of the study, and traffic volume. For each class, road deterioration and maintenance activity over a 30-year period were simulated under various maintenance alternatives. Road maintenance costs and vehicle operating costs were computed, discounted to the initial year, and subtracted from costs for the null case, giving the net present value for each alternative relative to the null. From these results, the best strategy for different levels of available funds and discount rates was determined for each road class. The results for different road classes were combined with the aid of the EBM to find optimal network strategies, costs, and benefits under conditions of no budget constraint and also under varying levels and time periods of overall budget constraints. The detailed results from the case studies were used to explore cost-effective road investment and maintenance options. The main findings relate to the following factors:

- Selection of cost-effective maintenance policies.
- Optimization of maintenance expenditures under budget constraints.
- Decision criteria for pavement strength.
- Economic traffic thresholds for paving gravel roads.

SELECTION OF COST-EFFECTIVE MAINTENANCE POLICIES

The choice and staging of maintenance operations on paved and unpaved roads are strongly affected by the differences in their deterioration characteristics. On unpaved roads, the linear but rapid path of deterioration requires special attention to routine maintenance, particularly the frequency of blading. The nonlinear deterioration characteristics of paved roads offer more options for the choice and timing of maintenance.

To identify cost-effective road maintenance policies for paved roads, particularly under budget constraints, the trade-off between agency and user costs was examined. To illustrate, Figure 2 shows the results of such an analysis to evaluate maintenance alternatives (identified in this and other graphs by the codes in Tables 1 and 2) for low-volume paved roads in good to fair condition in Mali (average daily traffic of 400 vehicles). The bar chart (Figure 2a) shows the present value, discounted at 12 percent, of the net cost savings relative to the null case. To arrive at net cost savings, the increase in maintenance and construction costs incurred by the road agency is subtracted from the difference in vehicle operating costs. In most cases this yields a positive saving, but alternatives AL15, AL16, and AL17 (involving immediate application of a thick overlay) and alternatives AL20, AL21, and AL22 (involving immediate reconstruction) cost more than the benefits they yield when discounted at 12 percent.

Net present value, discounted at 12 percent, is maximized by strategy AL12 (patching all potholes annually and applying a

TABLE 1 MAINTENANCE POLICY ALTERNATIVES FOR PAVED ROADS

Alternative No.	Patching (percent area of potholes)	Resealing (percent applied to area damaged)	Overlay	Reconstruction
AL00 (Null)	0			
AL01	50			
AL02	100			
AL03	0			REC ST at 8.5 IRI
AL04	50			REC ST at 8.5 IRI
AL05	100			REC ST at 8.5 IRI
AL06	100	ST at 75[a]		
AL07	100	ST at 50		
AL08	100	ST at 25		
AL09	100	ST at 75		REC ST at 8.5 IRI
AL10	100	ST at 50		REC ST at 8.5 IRI
AL11	100	ST at 25		REC ST at 8.5 IRI
AL12	100		40 mm at 5 IRI	
AL13	100		40 mm at 4.2 IRI	
AL14	100		40 mm at 3.5 IRI	
AL15			IMM overlay (80 mm) + AL12	
AL16			IMM overlay (80 mm) + AL13	
AL17			IMM overlay (80 mm) + AL14	
AL18	100	ST at 25	40 mm at 5 IRI	
AL19	100	ST at 50	40 mm at 3.5 IRI	
AL20				IMM REC ST + AL12
AL21				IMM REC ST + AL13
AL22				IMM REC ST + AL14
AL23	0			REC AC at 8.5 IRI
AL24	50			REC AC at 8.5 IRI
AL25	100			REC AC at 8.5 IRI
AL26	100	ST at 75		REC AC at 8.5 IRI
AL27	100	ST at 50		REC AC at 8.5 IRI
AL28	100	ST at 25		REC AC at 8.5 IRI
AL29				IMM REC AC + AL12
AL30				IMM REC AC + AL13
AL31				IMM REC AC + AL14

NOTES: All alternatives include basic routine maintenance such as drainage clearing, minimal vegetation control, repair of shoulders and drains. ST = bituminous surface treatment; AC = asphalt concrete; REC = reconstruction with either ST or AC surface; IMM = immediate (i.e., first year of the analysis period); IRI = International Roughness Index.

[a]Damaged area constitutes the area of pavement surface with specific signs of distress and visible defects.

TABLE 2 MAINTENANCE POLICY ALTERNATIVES FOR UNPAVED ROADS

Alternative No.	Blading Frequency	Spot Regraveling	Gravel Resurfacing
AL00 (Null)	None	None	None
AL01	Once a year	30 percent of material loss	None
AL02	Every 8,000 vehicle passes	30 percent of material loss	None
AL03	Every 6,000 vehicle passes	30 percent of material loss	None
AL04	Every 4,000 vehicle passes	30 percent of material loss	None
AL05	Every 2,000 vehicle passes	30 percent of material loss	None
AL06–AL10	Same as AL01–AL06 in Table 1 but with gravel resurfacing		150 mm whenever thickness < 50 mm

NOTES: All alternatives include basic routine maintenance such as drainage clearing, minimal vegetation control, repair of shoulders and drains.

40-mm overlay whenever pavement roughness exceeds 5 IRI). But several other alternatives with different combinations of vehicle operating costs and road agency expenditures are almost as good by this measure. This finding is important because it widens the room to maneuver when agencies are subject to budget constraints. For example, the curve in Figure 2b relating agency expenditures to vehicle operating costs for selected alternatives shows that AL05 (pothole patching until roughness reaches an IRI of 8.5, then reconstruction) entails about one-half the road agency expenditure of alternative AL12, whereas vehicle operating costs are higher by about $1.10 for each agency dollar saved—a net loss of only $0.10 per $1.00 of reduction in agency expenditure. If funds are limited, this may be an attractive option.

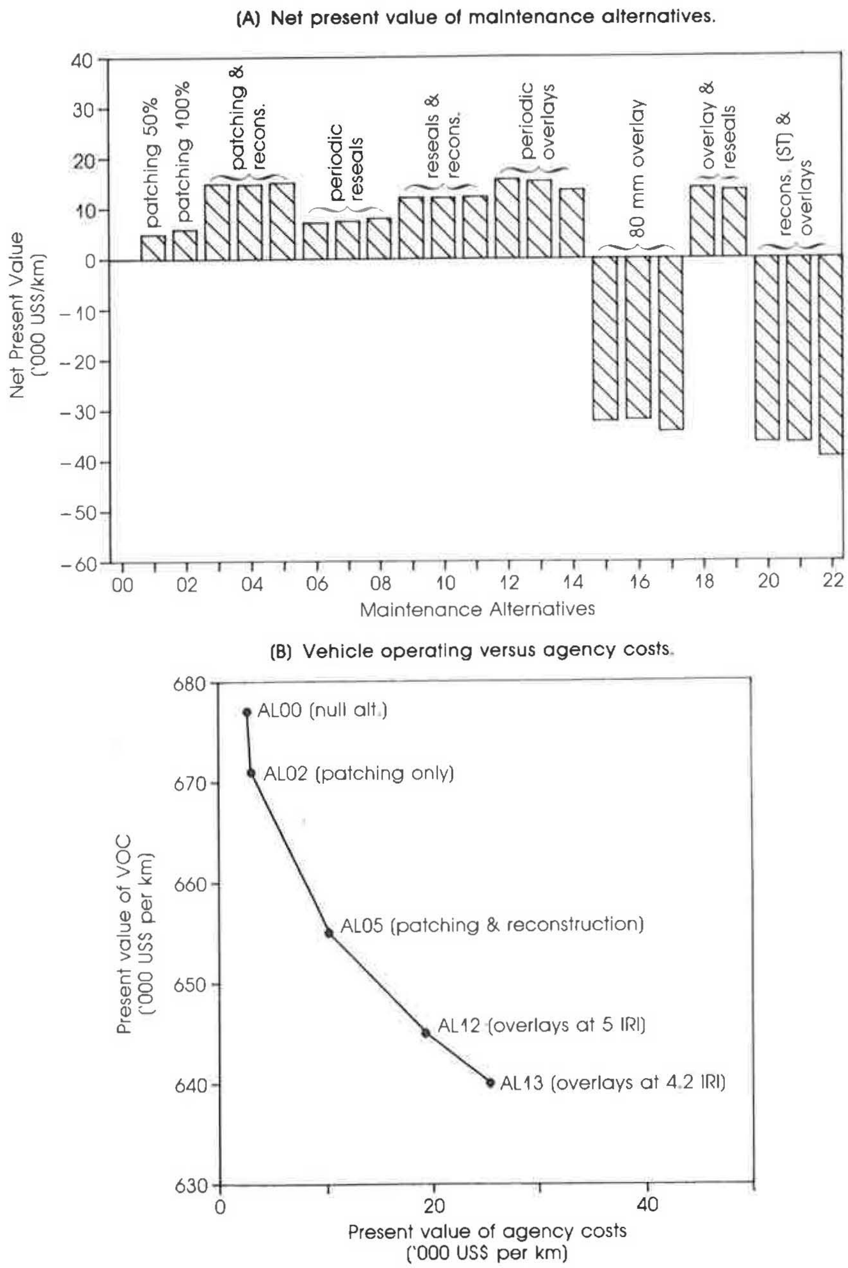


FIGURE 2 Low-volume paved road in good to fair condition (Mali). Analysis of maintenance alternatives.

The net present value of total transport costs for different levels of agency expenditures is shown in Figure 3 for four cases. The most efficient maintenance alternatives lie on the positively sloped segment of the outer boundary—the efficiency frontier. Alternatives represented by points inside the frontier are always inferior to a combination of maintenance options lying on the frontier. For example, in Figure 3a (Mali), alternative AL09 has a net present value of $12,000/km at a present value of agency cost of $15,800/km. A higher net present value should be obtained at the same agency cost by using AL05 on part of the road group and AL12 on the remainder, giving an average result that lies on the line connecting AL05 and AL12 on the graph. In the absence of budget constraints, the alternative that maximizes net present value should be selected.

Agency expenditures beyond this point (AL05) result in benefits that are less than the increased costs, as reflected by declining net present value. The curve also shows the optimal order of retracting when agency resources are cut. The lower-order options are selected by successively reducing agency expenditures in ascending order of their marginal contribution to net present value. Where traffic is heavier and especially where roads are initially in poor condition (Figures 3b and 3c), the economic loss per dollar saved by the agency is considerably higher and, of course, successive reductions in expenditure have increasingly costly consequences. The steepest slope of the efficiency frontier, indicating the severest penalty, is reached when the only expenditure available for cutting (always excepting minimal routine maintenance) is pavement patching. In none of these choices is agency cost today traded

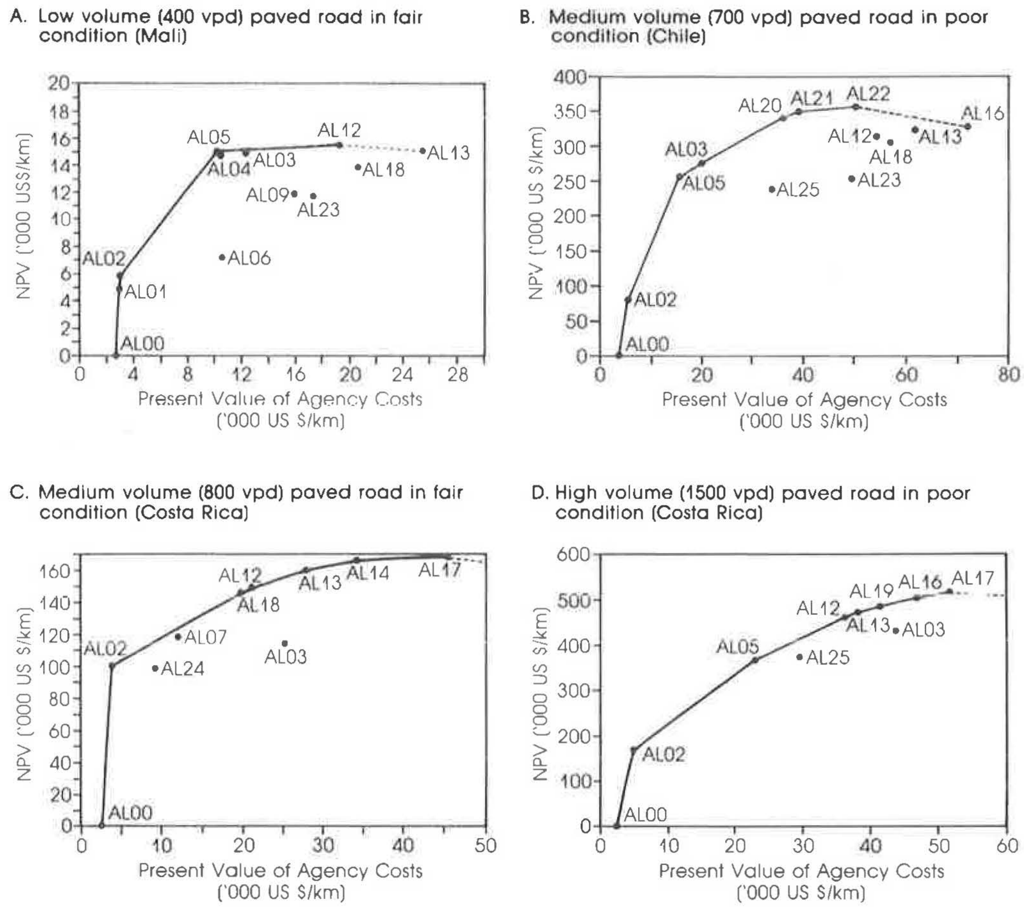


FIGURE 3 Net present value versus agency expenditures for different maintenance strategies.

off against significantly higher expenditures in the future; costs are simply transferred from the agency to the road users.

On unpaved roads, the primary maintenance-related determinant of roughness—and so of the cost of operating vehicles—is the frequency of surface blading. Simulation and costing of the effects of the various maintenance options (Table 1) show that blading costs and vehicle operating costs are closely balanced over a wide range of blading frequencies. Optimal blading frequency is in the range of one blading every 4,000 to 8,000 vehicle passes, which is consistent with generally accepted good practice (e.g., one blading a month at 150 to 200 vehicles a day). Incremental increases in blading frequency within this range result in marginal reductions in user costs that are almost completely offset by corresponding increases in agency cost. Figure 4 shows plots of net present value (NPV) versus blading frequency obtained from the Costa Rica case study.

Even at low traffic levels (25 vehicles a day), the economic returns on blading are substantial. Blading once a year appears to be an acceptable minimum threshold. Although blading once after every 4,000 to 8,000 vehicle passes would be an optimal policy, less frequent blading does not occasion serious economic loss if the road is regraveled at appropriate intervals.

Local conditions will strongly influence the maintenance options for unpaved roads. Extreme combinations of soils and climate (sands in arid climates, heavy clays in wet climates) may justify surfacing earth roads with gravel at an average daily traffic flow of fewer than 50 vehicles to ensure accessibility.

Where capital—especially foreign exchange—is scarce and unskilled labor is available at competitive rates (currently about $5 or less a day), the use of labor-based work methods for spot repairs on gravel roads and of simple drags attached to agricultural tractors or trucks to even out surface corrugations could prolong the time between bladings with mechanical graders. For unpaved roads with very low traffic volumes, increased use of labor for spot repairs could offer a viable alternative to mechanical means of maintenance, with the lower maintenance costs offsetting the somewhat higher vehicle operating costs *(9)*.

OPTIMIZATION OF MAINTENANCE EXPENDITURES UNDER BUDGET CONSTRAINTS

When the maintenance budget for a network is less than that required for the overall optimum, allocations to specific road classes (lengths of road sections grouped together on the basis of similar design, traffic, and condition characteristics and, where appropriate, further stratified by regional, climatic, or other relevant factors) must be reduced from their optimal levels. However, maintenance expenditures should not be reduced uniformly across all road classes. The loss in net present value will be minimized by first reducing allocations to road

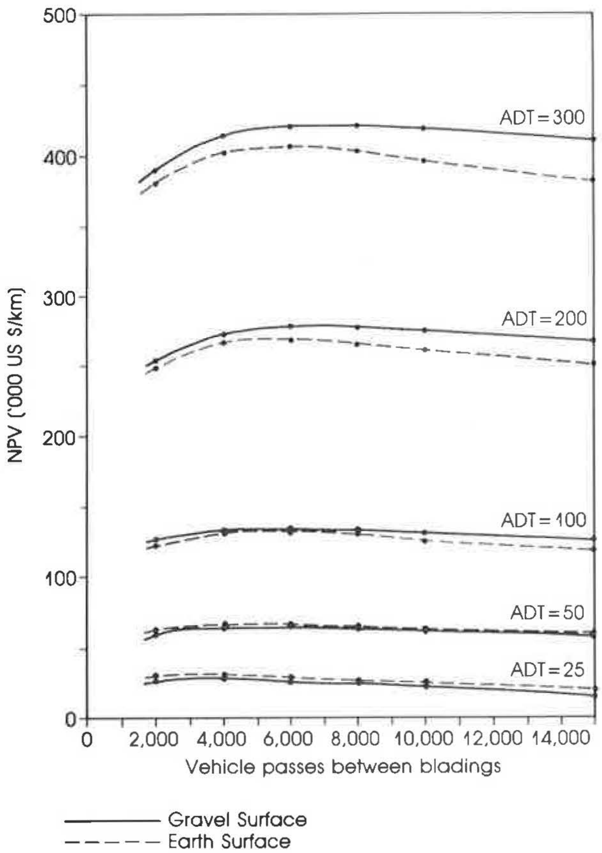


FIGURE 4 NPV versus blading frequency.

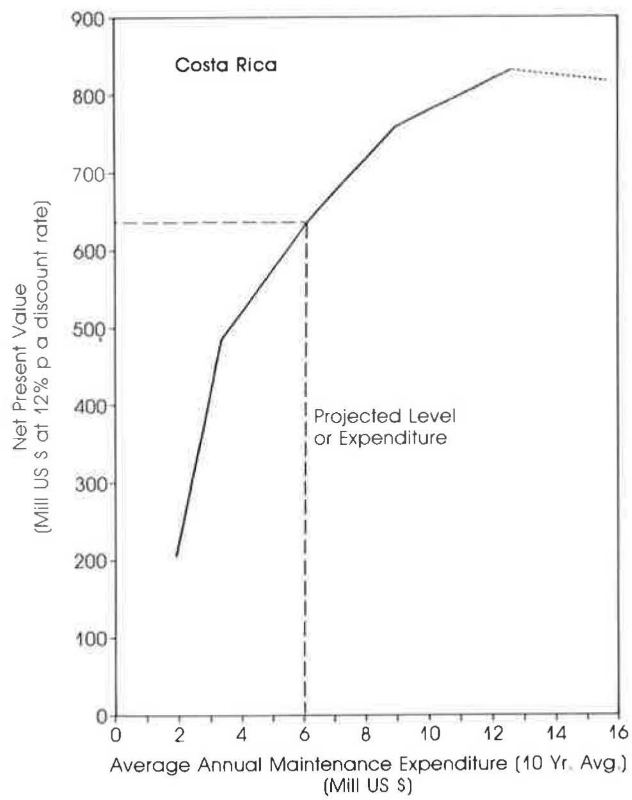


FIGURE 5 Variation of NPV for the entire road networks as a function of average maintenance expenditures.

classes for which the efficiency frontier is least steep. In general, candidates for cutting are high unit-cost maintenance operations on roads with low volumes and good existing surfaces. After the optimal activities have been completely replaced by next best options in a road class, the penalty for further cutbacks will be proportionately greater—the frontier will be steeper—and it may be economical to reduce allocations to some other road classes as well. Roads with high volumes and poor surface conditions suffer the greatest loss in benefit for each dollar of reduction in maintenance outlay, and their allocations should be reduced last.

The effects of reductions in the maintenance budget on the choice of alternatives and on the resulting benefits were examined for the road networks of Costa Rica, Chile, and Mali. In Costa Rica the maximization of total net benefits would require spending an average of $12.5 million/year on maintenance over the first 10 years with $38 million needed in the first year alone to rehabilitate the paved roads in poor condition. Figure 5 shows the maximum net present value of benefits (discounted at 12 percent a year) for the Costa Rican road network under different levels of average annual maintenance expenditures, optimally allocated among different classes of roads. If the budget is raised from the presently planned level of $6 million a year to the optimal level of $12.5 million a year over 25 years (or by $51 million in present value), the attainable net present value (with the best use of the funds in both cases) increases by $200 million, from $635 million to $835 million. The optimal program, even with unlimited funds, would not keep all roads in good condition. In Costa Rica, a high level of maintenance is required to keep two-thirds of the paved roads in good condition with the other one-third to be maintained to lower standards.

For Chile the best maintenance strategy for the road network is similar to that for Costa Rica: two-thirds of paved roads to be kept in good condition while maintaining the rest at lower standards. The optimal program involves immediate major expenditures on the rehabilitation of paved roads and assigns high priority to that activity even if the budget is cut.

In Mali, by contrast, where 84 percent of the paved roads carry fewer than 200 vehicles a day, only patching and basic routine maintenance are economically justified on most roads. The most economical option is indeed to keep only about 1 percent of the paved network in good condition with the rest of the network maintained at considerably reduced standards, mainly by patching and routine maintenance on paved roads and minimal blading on unpaved roads. Even so, about $9 million is required to clear Mali's backlog of economically warranted rehabilitation projects for higher-volume paved roads currently in poor condition. The average annual expenditure required to maintain the combined network of paved and unpaved roads is estimated to be about $6.2 million a year—about twice the current expenditure.

Maintenance activities are often deferred during periods of austerity. For unpaved roads, as long as basic routine maintenance is carried out regularly, the primary effect of deferring blading and, to a lesser extent, regraveling is to increase vehicle operating costs during the deferral period. The effect on subsequent road restoration costs is not large unless the road is allowed to become virtually impassable so that it has to be reconstructed, generally on a new alignment. For paved roads, both effects can be important: vehicle operating costs increase during the deferral period, and the cost of later pavement rehabilitation can increase substantially, depending on the stage in the deterioration process when deferral occurs. On newly constructed or rehabilitated pavements with light traffic loading, the effect of deferring maintenance (other than basic activities such as drainage) for 1 to 5 years is negligible. Once pavement condition becomes fair or poor, the impact is large.

DECISION CRITERIA FOR PAVEMENT STRENGTH

When a new pavement is constructed or an existing one replaced or overlaid, the choice of design strength should take into account the reliability of future maintenance. Low probabilities of adequate maintenance and timely strengthening in the future favor building a strong pavement initially because stronger pavements enjoy a longer grace period during which maintenance needs are minimal. A normal full-strength pavement is defined as one designed on the basis of accepted pavement engineering principles to carry a specific number of cumulative equivalent standard axle loads (ESALs) until an unacceptable level of functional serviceability is reached. To compensate for inadequate maintenance, a higher pavement strength than provided by normal designs may be warranted in certain situations. High probabilities of good maintenance will favor time-staging—that is, economizing on today's pavement and strengthening subsequently as needs emerge. Time-staging at the network level, however, is effective only when the condition of pavements is regularly monitored and evaluated with an appropriate pavement management system. Otherwise it is difficult to predict the critical points in the pavement life when a major maintenance intervention may be needed to prevent premature structural failure.

To justify the time-staging of road construction, a minimum probability of adequate future maintenance is required. To estimate this threshold probability, life-cycle costs for pavements with initial structural strengths ($\overline{SN}$) of 2.0, 3.5, and 5.0 were estimated for a range of traffic volumes and axle loadings in Costa Rica (light) and Mali (heavy). Three of the cases are shown in Figure 6. Each case shows life-cycle costs (at a 12 percent discount) for the first 14 of the 31 maintenance alternatives for paved roads specified in Table 1. In Case A, with average daily traffic (ADT) of only 500 vehicles per day (vpd) and light axle loadings, it would suffice to use a normal design ($\overline{SN}$ = 2.0) commensurate with the estimated ESALs because the life-cycle costs are consistently higher for a higher strength compensating design ($\overline{SN}$ = 3.5) under all maintenance assumptions. But with heavier traffic a different conclusion emerges, as shown by Case C (ADT = 2,500 and heavy axle loading). In this case, a normal full-strength pavement ($\overline{SN}$ = 5) will have a lower life-cycle cost, under almost any assumption about future maintenance, than one with a lower initial strength ($\overline{SN}$ = 3.5), which represents the time-staging option. At or above this combination of traffic and axle loadings it would not pay to consider the time-staging option.

Between these two limits, the decision for or against time-staging of construction is reached by balancing the potential loss if no maintenance will be done against the cost saving from time-staging that would be realized if future maintenance (including strengthening) were performed as desired. In this way a threshold probability of performing good maintenance in the future is obtained, above which the time-staging option could be justified. For Case B in Figure 6, for example, with an ADT of 1,000 vpd and light axle loads, this threshold probability may be derived as follows:

Let

x	=	probability of optimal maintenance (ALT 14),
$1\text{-}x$	=	probability of nil maintenance (ALT 00), and
Dopt	=	difference in life-cycle costs for initial pavement strength of $\overline{SN}$ 3.5 and $\overline{SN}$ 2.0, under ALT 14.
Dnil	=	difference in life-cycle costs for initial pavement design strength of $\overline{SN}$ 2.0 and $\overline{SN}$ 3.5, under ALT 00.

Then, from the inequality:

$$(Dopt)\,(x) > (Dnil)(1 - x)$$
$$\text{or } (1.27 - 1.23)x > (1.33 - 1.31)(1 - x)$$
$$\text{Therefore, } x > 0.33$$

In this case, time-staging of pavement construction should only be considered if there is a one-third or better chance of good maintenance being performed in the future (33 percent threshold probability).

Under funding arrangements that favor construction over maintenance or when external aid agencies are willing to finance construction but not maintenance expenditures, it is often expedient to forego maintenance until it becomes necessary to reconstruct the pavement. ALT 3 in Case B codifies such a maintenance strategy, an option that would also reduce life-cycle costs significantly, if there is fair expectation that funds for reconstruction would be forthcoming when needed. In this case, a less-than-full-strength design could be considered for initial construction, if the probability of obtaining future funds for reconstruction is 45 percent or better.

The data in Table 3 illustrate how the decision may vary in a wider array of cases. Combinations of discount rate, daily traffic, and axle loading are mapped out where the decision for or against time-staging is independent of the degree of uncertainty about future maintenance. In a middle area, however, the reliability of future maintenance matters. Time-staging is thus generally to be preferred if the probability of adequate maintenance in the future exceeds 30 or 75 percent, depending on traffic volumes and light axle loads. At higher discount rates (in this case 24 percent) time-staging tends to be a preferred choice even with high traffic volumes and axle loading and a relatively low probability of future maintenance. When capital is cheap or a greater weight is attached to long-term benefits (an intergenerational issue), stronger initial pavements based on normal design generally dominate (e.g., at a discount rate of 6 percent).

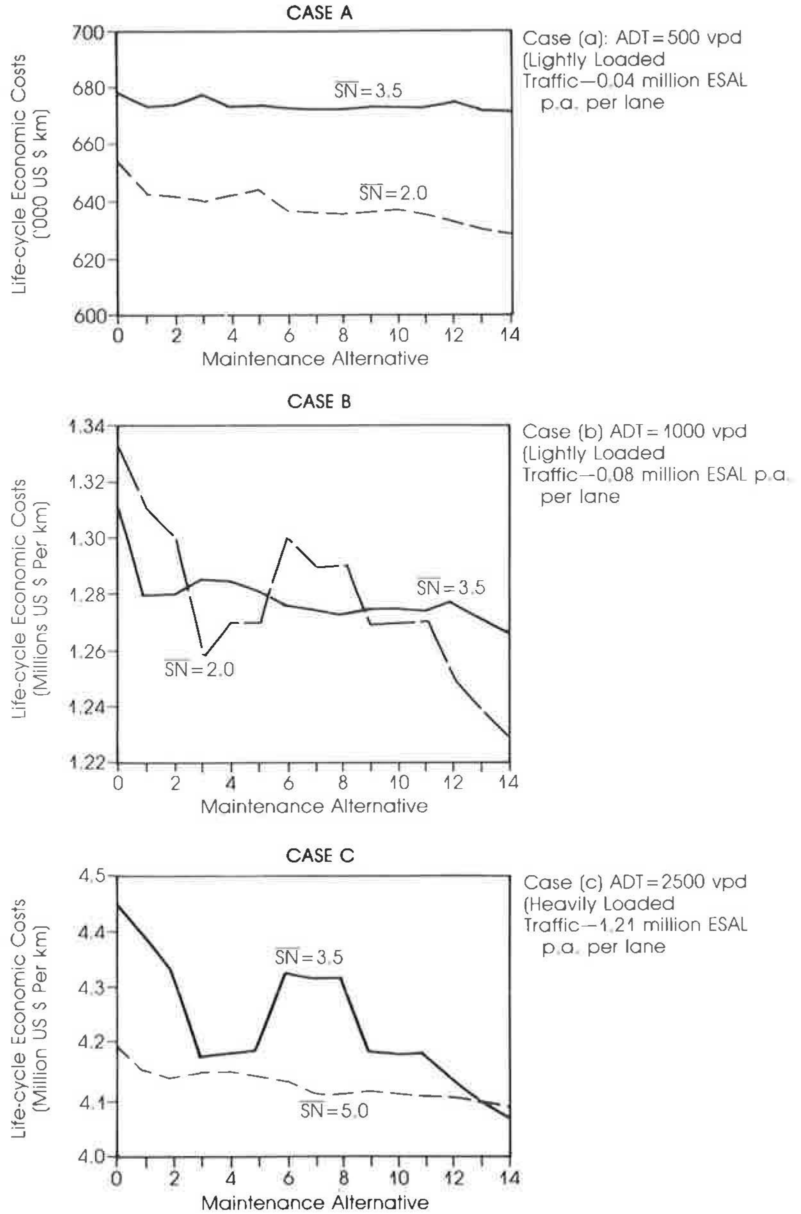


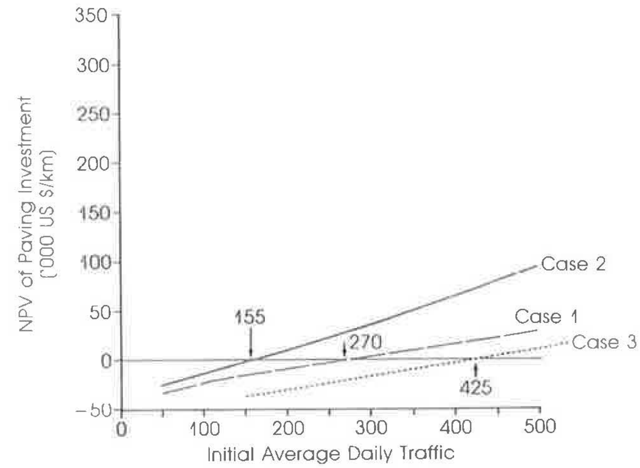
FIGURE 6 Influence of maintenance policies on selection of initial pavement strength (based on present value of life-cycle costs, discounted at 12 percent per annum).

ECONOMIC TRAFFIC THRESHOLDS FOR PAVING GRAVEL ROADS

Even with the best maintenance practice, vehicle operating costs on gravel roads are between 10 and 30 percent higher than on paved roads. In addition, the present value of the cost of routine maintenance and resurfacing is between five and eight times greater for a well-maintained, high-volume gravel road than for a newly built paved road. Paving is therefore indicated when the expected savings in vehicle operating and maintenance costs (relative to a well-maintained gravel road) exceed the present value of the paving cost.

These cost trade-offs now appear to cover a wide range of traffic volumes than had commonly been assumed. Applications of HDM-III in Costa Rica and Mali indicate that the breakeven traffic volume for paving may vary from under 100 vehicles a day to more than 400, depending on the costs of paving, the discount rate, the rate of growth of traffic, and the anticipated quality of future maintenance. Figure 7, based on unit costs and traffic composition typical of Mali, shows the effects of variations in traffic growth rates and paving costs (for a 12 percent discount rate).

Paving thresholds are also sensitive to variations in assumptions about the quality of maintenance. In cases in which experience shows that the probability of adequate future maintenance is low, the traffic threshold for paving is lowered. If there are no budget constraints, an economic case can be made for an all-weather paved road that may remain almost free of major maintenance interventions for 7 to 10 years. When examining total costs, however, more frequent regraveling and grading operations carried out efficiently are likely to prove



Case 1: Base Case, 0% p.a. Traffic Growth Rate, Optimal Maintenance Policies on Paved and Unpaved Roads.
Case 2: As Above, With 6% p.a. Traffic Growth Rate.
Case 3: 0% p.a. Traffic Growth and 50% Increase in Paving Cost.

FIGURE 7 Paving a gravel road at breakeven traffic volumes.

TABLE 3 CRITERIA FOR SELECTING TIME-STAGING OPTIONS FOR PAVEMENT DESIGN (minimum maintenance reliability for time-staging option)

ADT	Axle Loading[a]	Discount Rate (%) 6	12	24
300	Light	_[b]	_[b]	_[b]
	Heavy	30	_[b]	_[b]
500	Light	30	_[b]	_[b]
	Heavy	NA[c]	75	_[b]
1,000	Light	95	30	_[b]
	Heavy	NA[c]	80	_[b]
2,000	Light	95	80	15
	Heavy	_[d]	90	15
2,500	Light	_[d]	95	50
	Heavy	_[d]	_[d]	60

NOTES: The economic costs for paving ($1000s/km, 1984) assuming all earthworks and structures already in place were estimated as

$\overline{SN}$	*Costa Rica*	*Mali*
2.0	19.6	27.2
3.5	68.5	59.3
5.0	118.8	129.4

Minimum probability of adequate maintenance in the future; time staging conditional to this minimum level of maintenance reliability; otherwise use normal strength design.

[a]Light axle loading is representative of conditions in Costa Rica (0.05–0.10 million ESAL per year per lane); heavy axle loading is representative of conditions in Mali (1.2 million ESAL per year per lane).

[b]Compensatory design not applicable; low- to medium-strength pavements SN < 3.5) based on normal design, adequate for this level of traffic volume and loading.

[c]NA = time-staging option not applicable; use normal-strength design.

[d]Time-staging not applicable; high strength pavements ($\overline{SN}$ > 4.0) based on normal full-strength design appropriate.

more economical than paving, particularly if the future availability of maintenance funding is uncertain.

Paving gravel roads in arid zones is sometimes suggested as a means to alleviate the discomfort and inconvenience of travel on dusty roads, but it is difficult to quantify these benefits. Common observation suggests that vehicle speeds and passing opportunities on such roads are severely restricted by reduced visibility. The result is a traffic safety hazard similar to fog and congestion akin to that caused by heavily loaded slow-moving vehicles on narrow roads. Insufficient empirical information is available on traffic flow and vehicle operating characteristics in a dusty environment to evaluate the benefits of paving roads in arid or desert areas.

Lower paving thresholds may also be indicated for roads located in river deltas (lower Bangladesh), old lake beds, sandy deserts, and low coastal areas because of the scarcity of gravel deposits and other sources of aggregate. A possible technical alternative to using a gravel surface in these situations is to stabilize in situ soils by using small amounts of a suitable binder (bitumen, cement, lime, or fly ash) and then to protect the stabilized material from weathering and traffic, where necessary, by a light bituminous seal.

CONCLUSIONS

With the empirical knowledge gained in recent years on road deterioration and maintenance together with the methods that have been developed for simulating the processes and evaluating the results of large numbers of alternatives, it is now feasible to compare the economic consequences of different maintenance options in the context of actual conditions and thereby to find the best network-level maintenance policies, particularly under budget constraints.

A study in which these methods and relationships were applied to the road networks of three countries gave quantitative substance to some road investment and maintenance principles already known while showing that others apply only within narrow limits. The principal findings are discussed next.

- Vehicle operating costs (VOC) constitute a very large share (75 to 95 percent) of the total road transport cost, except when the traffic volume is extremely low. Hence, even a small percentage change in VOC is very large relative to changes in construction and maintenance costs. Until recently, basic empirical relationships linking vehicle operating costs to pavement surface condition (roughness) were not available. The past inadequacies in the empirical knowledge of basic road deterioration and VOC relationships may have contributed to premature paving of roads, particularly in low-traffic, high-cost environments and possible structural underdesign of heavily trafficked roads.

• The choice and staging of maintenance operations on paved and unpaved roads are strongly affected by the distinct difference in their deterioration characteristics. On unpaved roads, the rapid but essentially linear path of deterioration with respect to time and traffic requires special attention to routine maintenance actions, particularly the frequency of blading. The nonlinear deterioration characteristics of paved roads allow more room for the choice and timing of maintenance actions and permit trade-offs between agency and user costs, especially under budget constraints. A procedure for identifying cost-effective road maintenance policies based on a trade-off between agency and user costs is provided in this paper.

• When the maintenance budget for a network is less than optimal, maintenance allocations should not be uniformly reduced across the network. In general, the first candidates for cutting should be the high unit-cost maintenance operations on roads with low traffic volumes and good existing surfaces. Roads with very high volumes and poor surface conditions suffer the greatest loss in benefit for each dollar of reduction in maintenance outlay, and their allocations should be reduced last.

• Maintenance activities are often deferred during periods of austerity. For unpaved roads, as long as basic routine maintenance is carried out regularly, the effect of deferral on subsequent road restoration costs is not large unless the road is allowed to become virtually impassable so that it has to be reconstructed, generally on a new alignment. For paved roads, vehicle operating costs increase during the deferral period, and the cost of later pavement rehabilitation can be increased substantially, depending on the stage in the deterioration process when deferral occurs. For pavements in good condition with normal traffic loading, the effect of deferring maintenance (other than basic activities such as drainage) for 1 to 5 years is of no serious consequence. Once pavement condition is in the fair to poor range, the impact is large.

• When a new pavement is constructed or an existing one replaced or overlaid, the choice of design strength should take into account the reliability of future maintenance. Low probabilities of adequate maintenance in the future favor building a strong pavement initially because stronger pavements enjoy a longer grace period during which maintenance needs are minimal. High probabilities of good maintenance will favor time-staging, that is, economizing on today's pavement and strengthening subsequently as needs emerge.

• Even with the best maintenance practice, vehicle operating costs on gravel roads are between 10 and 30 percent higher than on paved roads. Also, the present value of the cost of routine and periodic maintenance is between five and eight times greater for well-maintained, high-volume gravel roads than for newly built paved roads. The breakeven traffic volume for paving, however, varies across a wide range of traffic volumes (4 under 100 to more than 400 vpd), depending on the cost of paving, the discount rate, the rate of traffic growth, and the anticipated quality of future maintenance. Lower traffic thresholds for paving may be indicated in conditions of climatic extremes (e.g., a dusty environment over prolonged periods) or in areas with a scarcity of gravel deposits or other cheap sources of aggregate.

REFERENCES

1. T. Watanatada et al. *Vehicle Speeds and Operating Costs: Models for Road Planning and Management.* HDM series. World Bank, Washington, D.C., 1987(a) (forthcoming).
2. D. O. Paterson. *Road Deterioration and Maintenance Effects: Models for Planning and Management.* HDM series. World Bank, Washington, D.C., 1987 (forthcoming).
3. *Highway Design and Maintenance Model—Description and Capabilities.* Transportation Department, World Bank, Washington, D.C., 1987.
4. T. Watanatada et al. *The Highway Design and Maintenance Model (HDM-III):* Vol. 1, Model Description. Vol. 2, User's Manual, HDM Series. World Bank, Washington, D.C., 1987(b).
5. W. Sayers et al. *The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements.* Technical Paper 45. World Bank, Washington, D.C., 1986.
6. M. W. Sayers et al. *Guidelines for Conducting and Calibrating Road Roughness Measurements.* Technical Paper 46. World Bank, Washington, D.C., 1986.
7. A. Chester and R. Harrison. *Vehicle Operating Costs: Evidence From Developing Countries.* Transportation Department, World Bank, Washington, D.C., 1987 (forthcoming).
8. A. Bhandari et al. *An Investigation of Cost Effective Road Maintenance and Improvement Options.* Discussion paper, Transportation Issues Series. Report TRP7. World Bank, Washington, D.C., 1987.
9. B. Coukis et al. *Labor-Based Construction Programs. A Practical Guide for Planning and Management.* World Bank, Washington, D.C., 1983.

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Road Deterioration in Developing Countries: Financial Requirements

GRAHAM SMITH AND CLELL HARRAL

This paper is part of a major policy study by the World Bank. It contains rough estimates of the aggregate cost of rehabilitating and maintaining the main road networks of 85 developing countries. The estimates use information on the condition of the network in each country, norms on economically justified maintenance standards, and uniform unit costs of rehabilitation and maintenance works by geographic region. Totals are given by region of the rehabilitation backlog—more than $40 billion, not counting bridges and all minor roads—and future annual maintenance needed to prevent the backlog (totaling $4 to $5 billion per year) from growing. The 85 countries are classified according to the burden of rehabilitation and maintenance needs relative to gross national product (GNP) and the adjustment required from present levels of expenditure on roads, including new construction. The results show a varied picture: good in much of East Asia, bad in much of South Asia and Africa. Indeed many African countries will need to make a major effort over at least a decade, with both large increases in total roads funding and a radical shift from new construction to rehabilitation and maintenance, to prevent their networks from deteriorating further, let alone restore them to an economically warranted condition. Options for finding the funds needed are reviewed.

Studies conducted by the World Bank on the road networks of Costa Rica, Chile, and Mali are reported in the paper by Bhandari et al. in this Record. They have shown that additional expenditures on rehabilitation and maintenance (R&M) can yield high returns. In both Costa Rica and Chile traffic volumes on most of the network are sufficient to justify high standards of maintenance, warranting approximately a doubling of the R&M budget in Costa Rica from what it was at the time of the study and an increase of about 40 percent (which was recently adopted) in Chile. Even in the case of Mali, where very low traffic volumes do not justify high levels of maintenance for most roads, the present low level of maintenance expenditures would nonetheless need to be doubled to provide the minimal level that is economically warranted.

In this paper these questions are addressed: What is the scale of financing required for road rehabilitation and maintenance throughout the developing world and how does it compare with present levels of road expenditures? What are the differences among countries? To answer these questions on a global scale a more simplified model is used, in reality amounting to some rules of thumb on economic levels of expenditure based on the case studies. No great degree of accuracy can be claimed, but the aggregate results are consistent with the findings of the more detailed studies, and they shed useful light on the relative severity of the maintenance problem in different regions and types of countries. The focus is limited to the main networks (see Faiz and Harral, "State of the Road Networks in Developing Countries and a Country Typology of Response Measures," in this Record).

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BASIS FOR THE PROJECTIONS

The Model

In the absence of detailed knowledge of traffic flows on the different road networks, the model requires as inputs only knowledge of the current breakdown of road condition into good, fair, and poor. It then uses standard assumptions derived from the results of the case studies on road life-cycle deterioration (varying by climatic zone) and economically justified amounts of rehabilitation (adjusted as a function of per capita income to reflect lower traffic volumes in the case of the poorer countries of sub-Saharan Africa) to predict the quantities of R&M needed. These quantities are then multiplied by average unit costs (varying by region) to arrive at financial requirements, broken down into rehabilitation, periodic maintenance (i.e., overlays for paved roads and regraveling for gravel roads), and routine maintenance.

Drawing on the case studies of Chile, Costa Rica, and Mali, it can be assumed that in countries that are neither exceptionally wet nor exceptionally dry, a newly constructed or rehabilitated paved road deteriorates slowly until after about 11 years when it makes the transition from good to fair condition. In the "fair" state an overlay will restore the pavement to as-new condition. If nothing is done, the road continues to deteriorate until about 7 years after the good-to-fair transition. Eighteen years after original construction (or the last overlay or rehabilitation), the road makes the transition from fair to poor. From this point on it will require rehabilitation to restore it to good condition.

The standard operation to restore a paved road in fair condition to its original condition is to apply a thin asphalt concrete overlay. In reality roads with heavy traffic will warrant thicker overlays and roads with light traffic will require perhaps no more than a surface dressing, but the thin overlay is an acceptable average in terms of cost and its contribution to the strength of the pavement.

Pavements deteriorate more quickly in wet climates and more slowly in dry climates. The values used in the model are as follows:

	Annual Rainfall (mm)	*Good-to-Fair Interval (yr)*	*Fair-to-Poor Interval (yr)*
Wet	Over 2,000	9	5
Moderate	600–2,000	11	7
Dry	Under 600	12	9

The cycle for unpaved roads is modeled somewhat similarly. All roads need regraveling on average about every 7 years. Every unpaved road is assumed to pass from good to fair condition 6 years after it is constructed. If funds are available, it is regraveled a year later; otherwise it remains fair for 4 years and passes to poor 10 years after construction (or last regraveling or rehabilitation).

The only parts of a network that should be in poor condition are those that carry insufficient traffic to warrant rehabilitation. The threshold for paved roads is generally about 200 vehicles per day and 150 vehicles per day for unpaved roads. As for routine maintenance, including patching, the case studies show that it is economically justified on the entire network in virtually all circumstances. The rehabilitation backlog can now be defined as all roads in poor condition with traffic exceeding the economic thresholds. Extrapolating from the few countries for which the relevant traffic data are available, in all except a few countries 100 percent of poor paved roads and 80 percent of poor unpaved roads carry sufficient traffic to warrant rehabilitation.

The exceptions are in sub-Saharan Africa where roads are known to have been paved at low traffic volumes and the main network includes many unpaved roads carrying only a few vehicles per day. Using findings from Mali and Niger, it is estimated that the share of poor roads with sufficient traffic to warrant rehabilitation is a linear function of GNP per head. For paved roads, interpolate between 0 percent at $0 per head to 100 percent at $500 per head; for unpaved roads the corresponding values are 0 percent at $150 per head and 80 percent at $500 per head.

Because few if any countries will be able to eliminate their backlog immediately, road sections now in fair condition will deteriorate to poor in the time that it takes to rehabilitate what is already poor, unless they are overlaid or regraveled. There is no information on the age distribution of roads now in fair condition (typically those built or last restored to good condition in the later 1960s or early 1970s), thus it is assumed to be uniform. Until about 1991, the annual periodic maintenance requirement will therefore be one-fifth, one-seventh, or one-ninth (depending on the climate) of the paved roads now in fair condition and one-sixth of the unpaved roads in fair condition. This level of effort will need to be sustained for the corresponding number of years until the entire length now in fair condition has been treated.

At the same time, road sections now in good condition will be deteriorating to fair. Most of these sections would have been built or last restored in the late 1970s. In the majority of countries the annual good-to-fair contingent will be less than the fair-to-poor contingent while the surge from the 1960s boom passes through. Where it is greater, that quantity should determine the annual periodic maintenance requirement because anything less will allow the fair contingent to build up. The estimate of the periodic maintenance requirement is therefore the greater of the annual good-to-fair and the fair-to-poor contingents. Where no information is available on the age distribution of the good roads (as is the case for all unpaved roads), it is assumed to be uniform, and the good-to-fair contingent is calculated as the 1984–1985 good length divided by the good-to-fair length given previously. For most countries the number of paved roads constructed between 1975 and 1979 and 1980 and 1984 is known. In the immediate future, no roads constructed in the 1980–1984 period will make the transition to fair, whereas those constructed between 1975 and 1979 are twice as likely to deteriorate to fair as the average of all combined, which the model takes into account.

The unit costs for each operation are given in Table 1. They were compiled by World Bank staff between 1983 and 1985 and updated to January 1985. The estimates for paved road rehabilitation do not include widening and minor alignment improvements that in practice are often carried out at the same time. Such capacity increases on existing paved roads normally are good investments and yield high economic returns. In most countries, therefore, it would be justified to spend at least 20 to 30 percent more than the strict rehabilitation amounts that emerge from this analysis.

It should be noted that according to this model (e.g., Mali) much of that portion of the road network in lower-income sub-Saharan Africa that has deteriorated to poor condition would not be rehabilitated because the low traffic volumes do not warrant the high expenditures necessary for such extensive restoration. In some cases there was not adequate economic justification for the original investments; in other cases low-cost roads were constructed for compelling social reasons, for example, to facilitate food movement in periods of famine. Improvements were undertaken that were not well-founded, such as paving unpaved roads in order to reduce maintenance requirements in the short run without adequate consideration of the large longer-term requirements.

More generally, few planners foresaw the economic decline of sub-Saharan Africa, and roads that were justified under forecasts of moderate traffic growth are no longer sustainable in the present prolonged period of traffic decline. Specifically, inferring present and future traffic as a function of per capita incomes, in the lowest income countries it is estimated that only 15 percent of the paved roads in poor condition would be rehabilitated, rising to 100 percent in countries with incomes of $500 or more. The remaining roads in poor condition would receive only higher levels of routine maintenance, which would not be adequate to restore normally accepted engineering standards but would result in some improvement over current conditions.

Because the requirements to restore the network to appropriate economic standards (the backlog) are very large in relation to available resources in most countries, it is necessary to postulate alternative targets. Three scenarios have been examined:

1. Clear the backlog of rehabilitation in 5 years or less,
2. Clear the backlog in 10 years, and
3. Keep the network in its present condition.

The costs to users of driving on roads in fair and poor condition during the 5- or 10-year catch-up period will certainly be

TABLE 1 UNIT COSTS OF MAINTENANCE AND REHABILITATION ($/km)

Routine Maintenance, All Regions				Periodic Maintenance		Rehabilitation	
Road Condition	Paved	Unpaved	Region	Paved	Unpaved	Paved	Unpaved
Good	450		ESA	40,000	10,000	180,000	45,000
Fair	500	1,000	WA	40,000	10,000	170,000	45,000
Poor	550		EAP	30,000	10,000	120,000	45,000
			SA	30,000	10,000	120,000	45,000
			EMENA	40,000	10,000	150,000	45,000
			LAC	40,000	10,000	130,000	45,000

NOTE: ESA = Eastern and Southern Africa; WA = Western Africa; EAP = East Asia and Pacific; SA = South Asia; EMENA = Europe, Middle East, and North Africa; and LAC = Latin America and Caribbean.

substantial. Here, however, the focus is solely on the financial requirements for the infrastructure—agency costs as described by Bhandari et al. elsewhere in this Record.

The Existing Backlog

On these assumptions the current backlog of rehabilitation for the main road networks is valued at approximately $41 billion (Table 2). Had these needs been met on a more timely basis, the cost would have been only about $10 to $12 billion. There would have been interest on the earlier outlays, but it would have been far more than offset by user cost savings.

These costs exclude bridges and the large tertiary and lower-order networks (for which data are unavailable). A speculative estimate for these components would be on the order of $15 to $25 billion additional, but under current circumstances only a part of this would be likely to meet the test of economic priorities. Similarly they exclude $3 billion for rehabilitation of main roads in the lowest income countries of Africa that would not, according to this analysis, be economically warranted.

Deterioration During 1986–1990

The current backlog is only a snapshot of present circumstances. Roads will continue to deteriorate. Many countries that added substantially to their networks in earlier years now find large portions of their network in fair condition. Unless overlaid or regraveled, such roads will deteriorate into poor condition over the next 5 to 9 years, after which they will require rehabilitation costing three to five times more. The cost of routine and periodic maintenance needed to prevent the parts of the network now in good and fair condition from deteriorating further during 1986–1990 is about $4.6 billion/year (Table 3). Provided these needs are met on a timely basis, requirements would then taper off after 1991, as the present surge of roads in fair condition passed. After allowing for this tapering, requirements to meet new deterioration expected over the 10-year period (1986–1995) would total about $43 billion.

TABLE 2 EXISTING MAINTENANCE BACKLOG ($ billion; 1984 dollars)

Region	Rehabilitation Paved	Rehabilitation Unpaved	Total
Eastern and Southern Africa	1.3	0.7	2.0
Western Africa	1.8	0.8	2.6
East Asia and Pacific	7.2	1.6	8.7
South Asia	7.4	0.8	8.3
Europe, Middle East, and North Africa	8.1	0.8	8.9
Latin America and Caribbean	7.6	2.8	10.4
Total	33.4	7.6	41.0
Percentage of total	82	18	100

NOTE: Row and column totals vary due to rounding.

TABLE 3 ANNUAL MAINTENANCE NEEDED TO FORESTALL DETERIORATION 1986–1990 ($ billion; 1984 dollars)

Region	Routine	Periodic Paved	Periodic Unpaved	Total
Eastern and Southern Africa	0.2	0.1	0.1	0.4
Western Africa	0.1	0.1	0.1	0.3
East Asia and Pacific	0.3	0.7	0.2	1.2
South Asia	0.1	0.3	0.04	0.5
Europe, Middle East, and North Africa	0.2	0.5	0.1	0.8
Latin America and Caribbean	0.4	0.6	0.3	1.3
Total	1.3	2.5	0.8	4.6
Percentage of total	28	54	17	100

NOTE: Row and column totals vary due to rounding.

This is clearly a lower limit, for it is unlikely that all needs will be met during the surge in the years immediately ahead. If, for example, 20 percent of the roads now in fair condition were allowed to deteriorate to the point where they require rehabilitation, the costs would increase by about $20 billion.

Annual Financing Needs

The annual R&M requirement is whatever fraction of the backlog each government decides to catch up on every year plus that required to meet future deterioration. Considering that all governments will aim to clear their backlogs in 5 or 10 years, the minimum needed over the next years is about $9 billion/year for the 10-year scenario ($4.6 billion for maintenance and $4.1 billion for rehabilitation), or $13 billion/year over 5 years ($4.6 billion plus $8.2 billion).

The breakdown of these totals by geographic region is given in Table 4, which also indicates the amount of foreign exchange required. The foreign exchange shares were estimated on the basis of recent World Bank appraisal reports. They are highest (70 percent) for overlays and rehabilitation of paved roads in

TABLE 4 ANNUAL R&M FINANCING REQUIREMENTS ($ billion)

	Total Cost, Target Year		Foreign Exchange, Target Year	
Region	10	5	10	5
Eastern and Southern Africa	0.6	0.8	0.3	0.4
Western Africa	0.6	0.9	0.3	0.5
East Asia and Pacific	2.1	3.0	0.8	1.2
South Asia	1.3	2.2	0.6	0.9
Europe, Middle East, and North Africa	1.7	2.6	0.8	1.3
Latin America and Caribbean	2.4	3.4	1.1	1.6
Total	8.7	12.8	3.9	5.8

NOTE: Row and column totals vary due to rounding.

low-income countries and lowest (30 percent) for routine maintenance in middle-income countries. For China and India, a uniform rate of 30 percent is used to reflect their policy of relying as much as possible on domestic resources. Thus the foreign exchange required for all 85 countries combined amounts to $4 to $6 billion/year for 5 to 10 years. Sub-Saharan Africa would require between $0.7 and $0.9 billion/year.

To give a sense of proportion, these sums are equivalent to four- to seven-tenths of one percent of the combined GNPs of the 85 countries studied. For the median country the value is somewhat higher—0.8 to 1.0 percent of GNP (because the needs happen to be proportionately greater in small countries). Another indicator of proportions is expenditure per kilometer. Averaged over paved and unpaved networks, the R&M requirement is $4,800 to $7,000/km.

The most important comparison is with present expenditures. This, however, is complicated by two limitations: data on present roads expenditure are available for only 66 of the 88 networks (85 countries plus 3 federal networks), and the breakdown among new construction, rehabilitation, and maintenance is known for only 18 of those 66. Among the 66, expenditures on roads in 1983–1985 averaged 0.7 percent of GNP; and among the 18, the split between new construction and R&M was on average approximately 50/50. In the African countries where it is known, the share of rehabilitation and maintenance ranged between 20 and 60 percent; in Europe, the Middle East, North Africa, and Latin America it was between 50 and 85 percent. Data are insufficient for generalizations about East Asia and South Asia. Applying these proportions to the 85 countries, total roads spending in 1984 is estimated at about $13 billion, of which about $6.5 billion was for R&M.

If this is correct, R&M allocations in aggregate would need to be increased by 33 to 100 percent from present levels to meet the target range of $9 to $13 billion. How much of an increase, if any, is required in total road budgets (rather than just R&M) will depend on how much new construction is retained. If it were eliminated entirely, no increase would be needed on a global basis, but if new construction continues at its present level (based on the preceding reasoning it is estimated to be about $6.5 billion per year), the overall increase will need to be 20 to 50 percent.

Country Differences

Nevertheless, these global abstractions are not what count for highway directors and budget decision makers around the world; circumstances are different in each country. The rough estimates presented here suggest that R&M requirements range from country to country from 0.1 percent of GNP to more than 5 percent and from 15 percent of present roads spending to more than 500 percent. The comparison with GNP indicates the relative burden of maintenance requirements, whereas the comparison with present total roads expenditures indicates the relative adjustment called for. If countries can then be classified according to whether they are about average, low, or high by each of these two measures, nine groupings emerge. Singling out only the four combinations of low and high values, those in the low-burden/low-adjustment category are in the best position, whereas those in the high-burden/high-adjustment category are in the worst position and are most in need. Furthermore, the countries in the low-burden/high-adjustment category are doing the least to meet their road needs in relation to their incomes and are well placed to solve their financial problems. In contrast, countries in the high-burden/low-adjustment category are, by these criteria, most deserving of external assistance because, in relation to their income, they are already making major efforts.

The data in Tables 6–8 show the countries classified using these criteria. The division relative to GNP is in three equal-sized groups, whereas the division relative to present roads expenditures is on a different basis, but one that yields groups of almost equal size. The "low-adjustment" countries are those that could clear their backlog while forestalling further deterioration in 5 years or less with no increase in their present budget and retaining at least 20 percent for new construction. Twenty-six countries are in this group (3 out of every 10 World Bank borrowers), which includes representatives of every region. It is striking that the low-burden/low-adjustment subgroup includes the entire East Asia region except Thailand (which is just outside the region). Also noteworthy are the three African countries that make up the deserving high-burden/low-adjustment subgroup: Lesotho, Malawi, and Niger.

The moderate-adjustment countries are defined as those that, while falling below the aforementioned threshold, can clear their backlog in 10 years if they increase their budget by as much as 50 percent; reallocate radically from new construction (bringing its share down to as little as one-fifth of the total, the same limit as set for the first group); and sustain that effort for an entire decade. Thirty-four countries are in this group (4 of 10 World Bank borrowers), which includes several major borrowers in Europe, North Africa, and Latin America, including Brazil and Mexico, as well as the Indian national highway network. With an 80/20 split between R&M and new construction, the median country in this group would need a 10 percent budget increase to clear its backlog in 10 years. If instead it chose to clear its backlog in 5 years with the same R&M and new construction split, it would need to raise its roads budget 70 to 80 percent.

The remaining 25 countries together with the India states networks require larger financial efforts. The 19 members of the high-burden/high-adjustment subgroup—14 in sub-Saharan Africa, 2 in South Asia, and 3 in Latin America and the

TABLE 5 ROAD USER TAXES: THEIR STRUCTURE AND CONTRIBUTION TO GOVERNMENT REVENUES IN SELECTED COUNTRIES

Country	Year	Taxes on Vehicle Acquisition: Import	Purchase	Registn	Annual Taxes on Ownership: Cars	Other Veh.	Drivers' Licenses	Taxes on Use: Fuel & Oil: Gas.	Diesel	Tires, spare parts	Tolls & road transp.	Total	Total RUC as % of: Expendi-tures on Roads	Total Govt. Rev's.	Taxes on Incomes, Profits & Cap. Gains as % of Total Rev's.
		(as percent of total road user charge revenues)													
ESA															
Kenya	81	22	15	..	—7—		1	—55—		..	..	100	138	12	29
Madagascar	81	—35—		..	—6—		..	—59—		..	..	100	..	16	16
Mauritius	81	20	..	1	—12—		..	45	12	9	..	100	1,700	13	18
Rwanda	84	18	..	1	—13—		..	—41—		12	12	100			
Somalia	79	NA	..	4	—NA—		..	49	51	..	..	100*	[305]	[11b/]	6
Sudan	81	27	..	..	—2—		..	—33—		21	4	100	269	8c/	16d/
Uganda	84	NA	..	..	—NA—		..	—81—		..	19	100*	[411]	[12]	7
Zimbabwe	83/4			—34—			..	58	9	..	..	100	345	14	42
WA															
Cameroon	78	57	..	..	—2—		..	—28—		12	..	100	273	14	14
Sierra Leone	79	35	..	..	—11—		..	—54—		..	..	100	200	7	24
AEP															
Indonesia	85/6	11	9	14	—12—		..	50	1	e/	3	100	110	5-6f/	74
Korea	83	NA	12	4	—16—		..	30	23	..	15	100*			
Phillipines	81	NA	NA	..	—13—		..	—87—		..	..	100*	[116]	[15]	22
Thailand	79	NA	26	..	—10—		..	—63—		1	..	100*	[174]	[14]	18
SA															
India	80/1	—13—			—18—		..	—45—		12	12	100	197	15	18
Pakistan	84/5	—25—		2	5	6	..	41	10	10	1	100	292	11	15
EMENA															
Oman	83	36	..	17	..		2	—45—		..	..	100	100	10	26
Turkey	83		—60—		—4—		..	—35—		e/	1	100			
Yemen AR	82	55	20	0	—7—		2	—16—		..	..	100	103	12	12
LAC															
Argentina	83		—11—		—14—		..	56	13	6	..	100	137	6	4
Brazil	83	NA	NA	..	—22—		..	—65—		..	12	100*		[4g/]	15
Chile	84	35	..	6	..		..	—55—		..	4	100	326	14	11
Dominica	80/1	—39—			—13—		..	—37—		12	..	100	..	15	17
Haiti	80	25	..	..	—9—		1	—56—		8	..	100			
Peru	80	27	..		—4—		..	—66—		..	4	100	156	5	27
Industrialized countries															
Australia	77/8	NA	NA	33	—4—		..	—58—		..	4	100*			
Canada	77	NA	NA		—29—			—71—		..	..	100*			
FR Germany	78	NA	NA		—24—		..	—76—		..	..	100*			
Gt. Britain	78	..	14		—23—		..	50	13	..	..	100*	[285]	[8]	40
New Zealand	78/9	12	29	7	..	8		—44—		..	..	100	204	9	65
USA	78		—28—				..	—72—		d/	1	100			

NA = not available (thought to be significant)
.. = no information (thought to be zero or insignificant)
* = total thought to be incomplete
[ ]= incomplete

a) 1980 data
b) 1979 RUC as % of 1978 total revenues
c) 1981 RUC as % of 1982 total revenues
d) 1982 data

e) included with taxes on vehicle acquisition
f) estimate
g) RUC exclude VAT

Sources:
Developing countries: World Bank appraisal reports and IMF Government Finance Statistics Yearbook.
Industrialized countries: Australian Bureau of Transport Economics, "Road Financing in Selected Countries," Occasional Paper 49, Canberra 1982.

TABLE 6 COUNTRIES ABLE TO ELIMINATE MAINTENANCE AND REHABILITATION BACKLOG IN 5 YEARS OR LESS WITHOUT RAISING PRESENT ROADS BUDGET

Low Percentage of GNP Required[a] (N = 13)	Moderate Percentage of GNP Required (N = 10)	High Percentage of GNP Required (N = 3)
Nigeria	Rwanda	Lesotho
Korea	Burundi	Malawi
Papua New Guinea	Cameroon	Niger
Indonesia	Ivory Coast	
China	Nepal	
Philippines	Yemen People's Democratic Republic	
Malaysia[b]	Turkey	
Yemen Arab Republic	Oman	
Hungary	Honduras	
Romania[b]	Paraguay	
Dominican Republic		
Ecuador		

NOTE: New construction not less than 20 percent of total.

[a]A low percentage of GNP for the 5-year target is ≤ 0.8 percent and high ≥ 1.6 percent. The corresponding thresholds for the 10-year target are 0.6 and 1.3 percent.

[b]Expenditure data not available. Classified by analogy on basis of condition data and institutional capabilities.

TABLE 7 COUNTRIES WITH MODERATE FINANCING PROBLEMS

Low Percentage of GNP Required (N = 4)	Moderate Percentage of GNP Required (N = 16)	High Percentage of GNP Required (N = 6)
Zimbabwe	Kenya[a]	Botswana
Sudan[a]	Mauritius[a]	Swaziland
Thailand	Mali	Somalia[a]
India National	Guinea	Togo
Bangladesh[a]	Benin	Central African Republic
Egypt	Burkina	Costa Rica
Syria[a]	Congo[a]	
Algeria[a]	Tunisia	
Mexico[a]	Morocco	
Argentina	Cyprus	
Chile	Guatemala	
Brazil	Uruguay	
	Peru[a]	
	Haiti[a]	
	Panama[a]	
	Barbados[a]	

NOTE: Able to clear backlog in 10 years by increasing roads budget by up to 50 percent and cutting new construction to 20 percent of new total.

[a]Expenditure data not available. Classified by analogy on basis of condition data and institutional capabilities.

Caribbean—face particularly daunting prospects. The African countries are already spending a relatively large share of GNP on roads, but until recently have been allocating the lion's share to expanding their still rudimentary networks. Even doubling their roads budget and cutting new construction back to 20 percent of the new total, almost all these countries would still not be able to clear their backlog of economically warranted rehabilitation in 10 years. Indeed, the median country in this group would need to triple its budget (with an 80/20 split) to do so. It would be a commendable achievement just to stabilize the most essential network and prevent further deterioration. For most African countries this will require a budget equivalent to 0.8 to 1.4 percent of GNP. The consequences of missing even this target is that in several countries the length of paved road in poor condition could easily double by 1990 from what it was at the end of 1984, and in a few years 100 percent of unpaved roads would be in poor condition.

It is perhaps surprising to find such higher-income countries as Yugoslavia and Portugal in the low-burden/high-adjustment subgroup. In the case of Yugoslavia, the explanation is that maintenance budget increases have fallen far short of rapid inflation several years in a row. A fourfold increase in the total roads budget appears needed just to clear the backlog in 5 years, but even then Yugoslavia's spending on roads would still be below the world average as a percentage of GNP. Portugal and Pakistan are in a similar, though not quite so extreme, situation.

TABLE 8 COUNTRIES WITH SEVERE FINANCING PROBLEMS

Low Percentage of GNP Required (N = 4)	Moderate Percentage of GNP Required (N = 3)	High Percentage of GNP Required (N = 19)
Ethiopia[a]	Tanzania	Madagascar
India States	Uganda[a]	Zaire
Portugal	Pakistan	Djibouti
Yugoslavia		Zambia
		Comoros
		Sierra Leone
		Mauritania
		Senegal
		The Gambia
		Liberia
		Equatorial Guinea[a]
		Chad[a]
		Guinea-Bissau[a]
		Ghana[a]
		Burma
		Sri Lanka
		Bolivia
		Belize
		Jamaica

NOTE: Unable to clear backlog in 10 years even with 50 percent increase in roads budget and restriction of new construction to 20 percent of new total.
[a]Expenditure data not available. Classified by analogy on basis of condition data and institutional capabilities.

India and China present a particular dilemma as to priorities between restoration and new construction. India's existing network is large but technically and economically obsolete. Replacement rather than restoration is probably the best solution. China is in reality worse off than India because of the sparseness and low standards of its network in relation to present and potential demands. Relief of capacity constraints will generate high-priority claims in these countries in the years ahead; the financing needs will be particularly large.

Options for Finding the Money

Several options are available for raising the additional financing needed. Several levels of government can take action. Any strategy to deal with the maintenance crisis should be a package of measures, including some or all of the following.

1. *Use the existing road maintenance budget more productively.* Most maintenance departments have substantial scope for raising the productive efficiency of the men, machines, and materials at their disposal. In "Organization and Management of Road Maintenance in Developing Countries" elsewhere in this Record, a number of recommendations are made on institutional and managerial options. They bear primarily on work carried out by government force account (direct labor); that is, most if not all of routine maintenance ($1.3 billion out of the annual requirement of $4.6 billion estimated) and that part of periodic maintenance not contracted out (some part of the remaining $3.3 billion per year). The relevant level for decision making is the maintenance department, although several institutional changes suggested will require higher-level approval.

2. *Devise a more cost-effective mix of maintenance and rehabilitation activities.* Bhandari et al., in a paper in this Record, summarize recent insights into efficient choices among alternative R&M operations for roads of various pavement types, surface conditions and traffic levels, and priorities among such road categories within a constrained budget. Particular attention should be directed to the ratio of extra road-user costs to each dollar in the agency's budget saved by successive cutbacks from the economic optimum. Decision making will be a joint effort by the maintenance department and the road authority's planning department.

3. *Reallocate from new construction.* The economic return on marginal increases in road maintenance budgets is often very high—more than 100 percent is not uncommon. And yet they are sometimes squeezed out by new construction projects with rates of return of 10 to 20 percent, or even lower. The massive reallocation from new construction that appears warranted in many countries calls for a substantial effort to improve the technical quality and hence credibility of such economic evaluations if they are to prevail against the strong political pressures normally favoring new works. The administrative separation of maintenance in the current budget from new construction in the capital budget may also have to be overcome. Furthermore, in countries heavily dependent on external concessionary financing, donors' bias toward new construction also has to be addressed.

4. *Reallocate from rail and elsewhere in transport.* Many developing countries could fund proportionally large increases in road maintenance by modest cuts in subsidies and capital grants for railways and other transport modes.

5. *Give transport a larger share of the total budget.* Transport's share of government spending in developing countries was cut substantially during the recession of the early 1980s. The average amount given by the International Monetary Fund *(1)* covering current and capital expenditures combined as a percentage of central government outlays, dropped steadily from nearly 9 percent in 1977 to below 6 percent in 1982; it rose slightly in 1983. As growth resumes, planning and finance ministries should reexamine the share they are now allocating

to transport, particularly in sub-Saharan Africa, where, as Faiz and Harral point out in a paper in this Record, the low density of population entails road requirements per $ million of GNP well above the average.

6. *Increase road-user charges and taxes.* If a bigger piece of the pie is infeasible, how about a larger pie? Road users in most developing countries already pay, in aggregate, taxes and duties on fuel, vehicles, and parts that substantially exceed government spending on roads (Table 5); nonetheless taxes on private automobiles are a cost-effective and rational substitute for a progressive income tax. Any additional charge on road users has the potential, if properly used for improving road conditions, to lower rather than raise vehicle operating costs—the obverse of the agency cost/user cost trade-off mentioned previously. Furthermore, almost everywhere heavy trucks are charged less than the variable cost of the road damage they cause. Governments could raise revenue while encouraging a shift to less-damaging axle configurations if they increased license fees, particularly for the worst offenders.

7. *Earmark road-user taxes for a road maintenance fund.* To protect a finance ministry's flexibility to manage a country's fiscal affairs, the World Bank generally discourages earmarking of taxes for specific expenditures (dedicated revenues). An exception may well be warranted, however, when the normal annual budget-setting mechanism consistently fails to vote adequate funds for road maintenance or funds voted fail to get through, and when a road fund could be relied on to deliver on both counts. One option would be a temporary surcharge on fuel taxes earmarked for road rehabilitation. A "sunset" provision is advisable under which the justification for the fund is reviewed every 5 years.

CONCLUSIONS

The intent of this paper has been to show that the financial requirements for road rehabilitation and maintenance are indeed large and urgent; $9 to $13 billion/year will be required over the next 5 to 10 years, equivalent in the median country to 0.8 to 1.0 percent of GNP. Among the 85 countries reviewed, some $30 billion could have been saved if roads had received periodic maintenance before they deteriorated to a state in which they required rehabilitation. The vehicle wear and tear suffered by road users, though not calculated, has probably been several times greater.

The needs are urgent; a "baby boom" of roads built in the 1960s and early 1970s are now approaching the transition from fair to poor condition. If only one-fifth of these roads are not serviced in time, road departments will sooner or later have to bear an extra $20 billion or more in rehabilitation costs. Aggregate spending on roads in 1984, estimated at about $13 billion, was barely adequate to cover these needs, even if it had been heavily concentrated on rehabilitation and maintenance; it was not—about one-half was spent on new construction.

The severity of the situation varies among countries; 3 out of 10 can eliminate their rehabilitation backlog in 5 years or less while forestalling further deterioration without an increase in their roads budget. However, some of these countries will need to reallocate substantially from new construction to R&M. East Asian countries are prominent in this group. Another 4 out of 10 countries can eliminate their backlog within 10 years by increasing their roads budget by as much as 50 percent and allocating no more than one-fifth of it to new construction. This group includes the majority of World Bank borrowers in Latin America, the Middle East, and North Africa, as well as several countries in sub-Saharan Africa.

The core of the problem is the 26 countries, which, even if they could make the latter adjustment and sustain it over a decade, could not restore their networks to an economically sound condition. Of this number 16 are in sub-Saharan Africa. There are many options appropriate to the various levels of government for finding the money needed; seven are identified in this paper.

REFERENCE

1. *Government Finance Statistics Yearbook.* International Monetary Fund, Washington, D.C., 1985, p. 54.

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Organization and Management of Road Maintenance in Developing Countries

CLELL HARRAL

The deteriorating state of roads in many developing countries is causing concern and has been the subject of a major policy study by the World Bank. This paper, a part of that study, contains a discussion of some of the intrinsic problems that undermine the efficacy and efficiency of public road authorities, particularly those in developing countries. A number of reforms are recommended in order to create stronger incentives for efficiency, including separation of the planning and control (client) functions from the works execution (contractor) functions; greater reliance on competitive tendering of routine as well as periodic maintenance; reorganization of equipment ownership and management; and changes in the role, sources, and contractual modes for foreign technical assistance.

Road authorities traditionally perform three primary functions:

1. Roads development and maintenance;
2. Control of contracted works, including not only new construction but also larger works for rehabilitation and periodic maintenance, and in some cases routine maintenance; and
3. Direct (force account) execution of routine maintenance, often periodic maintenance, and in some instances new roads construction.

Of these three functions, contracted works for new construction and capital renewal have normally accounted for the greater part of expenditures. Direct execution of maintenance works has accounted for the preponderant share of road authority employment, and, for a number of reasons, a disproportionate share of the difficulties that have been experienced.

Despite strenuous and protracted efforts—including management consultancies, technical assistance, and training totaling more than $1.2 billion from 1971 to 1985 by the World Bank alone—the bank, its cofinanciers, and the recipient countries have had few successes in establishing institutions capable of sustaining cost-effective road maintenance with domestic resources. Three factors appear responsible for this lack of success.

1. The chosen institutional model—essentially a public-sector monopoly responsible for planning, controlling, and executing maintenance—is not conducive to accountability. This is because (a) there is an inherent conflict in vesting the planning and control function and the execution function in the same authority, with the former usually being overwhelmed by executional concerns; (b) there are no compelling incentives for efficiency; and (c) as a public service agency the road authority is subject to constraints that affect its ability to retain sufficient numbers of competent technical and managerial staff, limit its managerial flexibility, and impose on it employment-generation objectives irrelevant to the job of road maintenance.

2. There is no spontaneous constituency or organized coalition of political interests exerting influence to ensure that adequate funds are provided for road maintenance or that effective use is made of the funds appropriated. The separation of road ownership and use and the insidious nature of the road deterioration process contribute to this absence of public attention and pressure. The principal consequences of the road authority's neglect are broadly diffused among the road-using public and are unlikely to be perceived until the problem has reached an acute stage. In addition, road transport in most developing countries is seldom threatened by competition from other modes so that public carriers are not driven by economic necessity to press for better roads.

3. Inadequate and imbalanced budgets, combined with the inflexibilities of the civil service, undermine any systematic organization of maintenance activities. With a large share of appropriations immutably absorbed in wages of large unskilled labor forces, even small fluctuations in budget appropriations have major impacts on the availability of critical complementary resources such as fuel or spare parts.

The absence of an active constituency to promote the broader public interest for an efficacious and efficient road maintenance service and the limited range of services for which rail, water, or other transport provides genuine competition typically spawns a lack of concern at the political and managerial levels of government. The road maintenance organization often comes to be viewed primarily as a source of political patronage and unemployment relief. Vested interests view the maintenance mission as secondary at best, and their interests often conflict with efficiency goals. Following Hirschman's paradigm *(1)*, although public control of roads and limited access to other modes do not allow much scope for exit, no voice is raised to express the public interest in an effective and efficient road maintenance service.

A common feature of this lack of success in institutional development is the absence of accountability in the maintenance organization. The analysis and recommendations presented here result, therefore, from a search for ways of strengthening accountability, bearing in mind that a mere reorganization of government or of formal procedures is not likely to achieve this. No one can be held responsible unless he is given the means to perform the function for which he is being held accountable. Therefore to establish accountability in organizations typically requires eliminating some of the constraints that limit performance and frustrate even the most

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determined efforts. Alternatively, some activities can be transferred from the organization to be performed under the discipline of competitive markets where results are tested anonymously. Promising reforms that create conditions for more effective accountability are being tested in several countries. Such reforms include splitting works execution (contractor) functions from planning and control (client) functions, the common element being a system of incentives that promises to induce efficiency in the different institutions. Some reforms focus exclusively on the public sector agency, but most involve greater reliance on the private sector to reduce the burden on the public authority. In their ultimate form, these reforms would rely on competition in the marketplace to establish the balance between the private sector and a quasi-autonomous public enterprise *(2)*. All imply a substantial change in the role, sources, and contractual modes for foreign technical assistance.

PUBLIC COMMITMENT AND ACCOUNTABILITY

It is significant that in all cases in which there has been substantial success in establishing effective road maintenance institutions, there have been individuals in positions of responsibility who grasp both the importance of the maintenance function and the necessity for the efficient use of resources (e.g., in Malawi and Paraguay the heads of state have taken a personal interest themselves). Without political commitment at some level, the maintenance function invariably suffers from neglect—it may be starved of finance, have its ostensible resources diverted to serve other purposes, and be shunned by the ablest civil servants.

In countless instances political and private interests have brought pressure to bear on road authorities to divert resources intended for road maintenance to other purposes. These are often though not always legitimate public interests, but regardless of motivation, the effect in disrupting the maintenance mission of the road authority is the same. Controlling such interference is often one of the most critical challenges faced by the management of road authorities. Sometimes it can be successfully resolved at the managerial level, but in other cases it is a political issue that can be resolved only at the political level. Therefore ways of creating counterweights in public opinion, necessary to strengthen the hand of rational government, should be considered. The consequences of road neglect are a matter of public interest, and, as such, they need to be made known to the general public and potential interest groups, associations of trucking and bus companies, and business more generally, including potential vendors of road maintenance supplies or services, in hopes of stimulating the coalition of interests necessary to influence public policy. An interesting precedent in the United States is the effort by the Urban Institute to instruct journalists and city dwellers more generally in ways to evaluate the efficacy and efficiency of their local governments in performing a wide array of municipal services, including road maintenance *(3)*. Similarly, in the United Kingdom county road authorities are now required to publish an annual report comparing the costs of operation with private contractors' rates *(4)*.

There are various examples of audit functions assigned to authorities within the governmental sphere independent of the agencies responsible for particular activities. The U.S. General Accounting Office is one such example; the independent inspectorate of education in the United Kingdom (Her Majesty's Inspectors of Education, independent of the Ministry of Science and Education) is another. These are control mechanisms in a system that provide for accountability—their ultimate effectiveness depends on accountability being seriously enforced. Whatever the auditing mechanism, the principle requires that an authority in government demand accounting for the state of the roads, maintenance activity in physical and financial terms, and the strategy employed and the reasons for it. Clearly, further experimentation is needed in developing countries (encouraged by aid agencies) in alternative ways of enhancing the public accountability of the road authorities.

MONITORING PERFORMANCE

Monitoring the performance of public road authorities is as essential for those who are to be held accountable for maintenance as it is for the audit of their performance. However, in many road authorities, it has proven to be extremely difficult. One of the most compelling conclusions to emerge from surveys of road maintenance conducted by the World Bank in Latin America and Africa is that critical management data are not available, are inconsistent, or are clearly incorrect in many cases (see box "Efficiency of Resource Utilization: West Africa and Latin America and Caribbean"). Such problematic areas include estimates of the condition of the network, maintenance requirements, equipment availability and utilization, maintenance outputs, and unit costs. Much can be done to improve the management of road maintenance operations without such information; for example, improved day-to-day field supervision without elaborate record keeping *(5)*. Clearly first priority must be placed on competent field supervision, for without it, any record-keeping function is meaningless.

But substantially strengthened program planning, as well as monitoring and control at the central level, is still essential for answering key questions concerning maintenance strategies. The key to effective maintenance is to anticipate needs, which is not feasible without a system of periodic inspection of pavement conditions. Any planning tool that is to be used has to be calibrated to specific country conditions, and that requires information not only on the condition of roads at a given time but also on their evolution. The second most important parameter to monitor on a continuous basis is traffic, not only in terms of total traffic volumes but also in terms of distribution by type of vehicles and axle loads.

ADMINISTRATIVE DECENTRALIZATION

Some have argued for regional decentralization of the integrated governmental road maintenance function primarily on the grounds that a road authority more accessible to local constituencies will be more responsive to the needs for better roads and will not have management difficulties as a result of scale and dispersal. World Bank experience is not conclusive on this point, but among the cases reviewed, there appears to be little correlation between success in road maintenance and the degree of regional centralization or decentralization. Among

Efficiency of Resource Utilization: West Africa and Latin America and Caribbean

Data from road maintenance surveys in Latin America and West Africa demonstrate that higher levels of output could have been achieved with the limited funds allocated to road maintenance but are inadequate to provide a meaningful quantification.

Nearly one-half of the countries in the Latin American survey carried out very low levels of periodic and routine maintenance considering their level of maintenance expenditure and the kilometers of roads actually maintained (i.e., excluding those roads that were not maintained at all in 1983 and 1984). Three countries resealed or strengthened less than 1 percent of the paved road network despite receiving the funds required to carry out at least one-half of required preventive maintenance. Even worse were two countries that resealed or strengthened 1 percent or less of their paved roads even though there were sufficient funds to carry out adequate preventive maintenance. Where these funds were absorbed is not clear. In two other countries, far more emphasis was placed on gravel roads with the result that hardly any work was done on the paved road network.

Given that a substantial portion of the road network in the region was in fair to poor condition because of the deferment of periodic maintenance, it might be expected that considerable expenditure had been put into routine maintenance, but this proved not to be the case. On average, light patching was only 25 percent of that required and heavy patching was 20 percent. Less than one-half of paved shoulders were maintained and less than 40 percent of culverts were cleaned annually. Gravel and earth roads were graded twice a year on average, although five countries were unable to grade roads even once a year. However, productivity was quite low—one grader accomplished only 3 km/day of mostly light grading compared with a more satisfactory norm of 5 to 6 km/day.

A similar situation prevailed in West Africa where only 1 percent of the paved roads and 3 percent of the gravel road network received any kind of periodic maintenance though funds were sufficient to carry out far more work. About one-half of the countries should have been achieving at least twice the level of periodic maintenance actually performed. Although there were few data on the level of routine maintenance, information from other sources indicated that the level was quite low in many countries. Productivity of graders was also quite low, particularly for four countries, which had an output of less than 0.25 km/day per grader.

the more successful cases, Paraguay is highly centralized, whereas Malawi is relatively decentralized. Both Korea and Algeria are very decentralized, but have achieved different levels of performance. Several countries (e.g., Kenya, Senegal, and Zaire) have alternated between centralized and decentralized organizations without clear evidence of significant differences in performance between the two approaches.

There also are obvious potential pitfalls in decentralizing authority and in increasing political sensitivities, as illustrated in the cases reviewed. Although there may be shortages of technical and managerial staff at the central levels, such shortages may be far more severe at the local level. Whether at the central or local level, greater political sensitivities may be accompanied by greater susceptibilities to divert maintenance funds to more popular construction activities to undertake cosmetic but ultimately ineffective maintenance measures, and, most critically, to employ large numbers of redundant staff—as demonstrated by experience in Kenya and Honduras, two of the more politically sensitive ministries.

FUNCTIONAL DECENTRALIZATION—HARNESSING COMPETITIVE FORCES

A stronger case can be made for administrative decentralization than for functional decentralization, which involves separating the planning and control functions from works execution, especially if competition can be relied on to operate in the latter. By limiting demands to planning and control functions, the road authority is less likely to be overwhelmed by executional priorities, and accountabilities can be strengthened. Second, contractors (private or parastatal) operating under strong incentives with greater managerial freedom to procure and manage resources and a better prospect for retaining the most productive staff, may stand a better chance of developing an efficient, lasting institutional capacity (in the form of a dynamic industry) for the execution of road maintenance services. Third, when contractors become involved in maintenance activities, their lobbying efforts can increase budgets for road maintenance.

The principal contrary argument, which varies depending on local circumstances, is that contracting maintenance may actually increase costs because of increased administration (e.g., measuring and certifying quantities for payment); increased redundancies (when the government establishment cannot be reduced or relocated to the private sector); or lack of genuine competition in the procurement process (in extreme form, tender collusion), which prevents cost savings from being passed on to the public. Other arguments are that contractors may not have the requisite capacity, or that those that have the capacity are disinterested in small routine maintenance contracts (especially in remote areas), and that contractors' resources might not be available to government to help meet emergencies, such as earthquakes, famines, and so forth.

The experience in the nine countries reviewed here *(6)* sheds light, both positive and negative, on these *a priori* arguments. Some mistakes have been made, but, in general, contracting of routine as well as periodic maintenance has proven to be remarkably efficacious. In seven of the nine countries reviewed, roads under contract are now generally well maintained; in the other two countries, Colombia and Nigeria, initial problems encountered in the first small experiments are now being overcome. The evidence also suggests that contractors can operate at lower costs. In the one case (Ponta Grossa, Brazil) where fully comparable costs under similar conditions were available, the force account operation, commonly viewed as very efficient, was found to be 59 percent more costly. Contractors have been attracted to maintenance opportunities even in remote areas, and often small local contractors can be found whose local base solves the problems of remoteness more cheaply than can the centralized road administration (or larger contractors). Contractors have also been willing to commit their resources to the government in the event of emergencies.

Thus, the possibility of contracting a major part of routine, as well as periodic maintenance should be considered by every road authority. Care must be exercised to ensure that the public monopoly is not replaced by a new cartel of private interests, as shown by experience in Nigeria and Brazil. Retention of at least a small governmental capacity, reorganized as a publicly owned contracting company or companies in competition with private contractors, will be desirable to ease transition problems and in the long run provide a source of comparative costs, help reduce the danger of monopolistic exploitation, and enhance government management flexibility. Putting the government in competition with contractors should stimulate pressures for efficiency on both sides. A major experiment along these lines has been under way in the United Kingdom since 1981 with very promising initial results *(4)*.

Although the overall burden of responsibilities on the road authority is normally reduced by the introduction of contractors, the nature of the government's responsibilities changes sharply, and there is increased need for contract management skills. Many governments may want to consider using a consultant or a management services contractor to develop management systems and contract instruments, as well as to provide training for nascent contractors and government staff. Where there is no well-established domestic contracting industry, routine maintenance—technically simple with minimal investment requirements—provides a suitable vehicle for development. Careful planning and introduction of contracts on a small trial basis initially can reduce risks, permitting the government and contractors to develop capabilities before putting too heavy a burden on a new system. All of the successful contracting schemes have involved close coordination between the government and the contractor in defining the work to be done and in planning the work program.

MEASURES TO IMPROVE THE EFFICIENCY OF GOVERNMENT OPERATIONS

In cases in which direct government operations remain a significant portion of the total maintenance efforts, it is essential to improve their efficacy and efficiency. Needed improvements in management of equipment must be considered before human resources.

Equipment Management

Equipment is one of the most costly resources in road maintenance, yet all available evidence suggests that equipment use is extremely low, often no more than one-half reasonable norms (see box "Equipment Utilization: West Africa and Latin America"). Although availability (i.e., the amount of time a machine is in operating condition) may be good during the first 1 or 2 years of the life of new equipment, thereafter it typically declines sharply, as machines begin to wear and maintenance is inadequate due to lack of spare parts and properly trained mechanics. Equipment utilization may be poor even during the first years (sometimes because of the lack of fuel) and, because it is dependent on availability, is necessarily poor during subsequent years.

Many of the most serious inefficiencies stem from the imbalance in different resources. Available resources first go to paying permanent staff salaries and little may be left for spare parts, fuel, or other complementary resources (see box "Overstaffing and Resource Imbalances: Kenya"). In many cases the problem is compounded by the restricted availability of foreign exchange. Higher productivity can be achieved by allocating funds among the different activities in a more balanced manner—and the more restricted the budget, the more critical is this balance. In practice, this often implies reallocating a significantly higher fraction of available budgets for the recurrent foreign exchange costs of spare parts, fuel, bitumen, and so forth, in order to ensure effective use of equipment and associated work forces.

Equipment Utilization: West Africa and Latin America

According to data from West African and Latin American surveys, vehicle and equipment utilization was well below what is generally regarded as efficient—1,250 hr/year. In West Africa, vehicles and equipment were operated an average of 630 hr/year, ranging from 420 hr for steelwheel and tire rollers to 840 for dump trucks. In Latin America, utilization of vehicles averaged 800 hr and equipment 750 hr; in one-half of the cases, equipment was used less than 700 hr/year. Plants such as asphalt finishers and asphalt and aggregate crushing had even lower rates of utilization; asphalt finishers had the lowest rate of 420 hr/year.

Low utilization rates are partly explained by lack of spare parts and fuel for equipment fleets. In the case of West Africa, low expenditures on spare parts and fuel appears to have been a major reason for low utilization. According to the limited data available, about 40 percent of authorities received only one-half of the necessary funds for spare parts to keep the fleet fully operational. In 1982 expenditure on fuel in nine countries was only about one-third of that required to keep the equipment fleet operational 1,000 hr/year. Altogether, the data available for 1982 indicate that at least one-half of the countries had equipment fleets that could not be maintained because of a lack of spare parts or could not be operated because of a lack of fuel.

In the case of Latin America, the explanation for low utilization of equipment is not so readily apparent. In general, authorities had sufficient funds for spare parts to operate the fleet 1,000 hr/year although there were three cases in which the funds allocated were much lower. On average, agencies received 82 percent of the funds required for fuel but about 40 percent of the agencies received less than two-thirds of the funds required to keep the fleet operational 1,000 hr/year. Part of the explanation for low utilization may lie in poor management of equipment fleets and possibly insufficient numbers and quality of mechanics.

Several questionnaires returned from both regions did not include data on equipment utilization or on required expenditure for spare parts and fuel; in other surveys such data were inconsistent. Also, estimates of equipment depreciation were given in few returns. The weakness of such data indicates in some cases the complete absence of cost-accounting systems for equipment and in other cases the lack of monitoring and analysis of data collected. The failure to cost the use of equipment and the lack of proper financing mechanisms for equipment replacement has been one important reason for the increasing age of fleets in many Latin American and West African countries where, according to the survey, about one-half of the maintenance equipment was more than 7 years old.

Overstaffing and Resource Imbalances: Kenya

In Kenya operating funds (for fuel, spare parts, bitumen, etc.) for maintenance activities have become more scarce during the past few years. The effects of the general budgetary squeeze were exacerbated by two parallel developments affecting the roads department: the growth in permanent establishment personnel and the government's district focus policy. Until fiscal year 1982 the roads department had employed on average some 9,500 personnel under the casual labor (works paid) regime while some 1,000 staff were in the permanent establishment. The corresponding emoluments constituted some 39 percent of the total recurrent budget (KL 6.7 million out of KL 17.3 million). From all sources an amount of KL 9.7 million was available for operations, which at the time was already inadequate.

Three years later, however, the situation had dramatically deteriorated. The number of establishment positions in the roads department had increased from 1,000 to 14,600. The integration of works paid personnel in the establishment explains only part of the growth. As part of the district focus policy, other ministry personnel at the local level were brought under the umbrella of the roads department. As a result in 1986, of the total personnel, more than 94 percent came under the district, and of the funds that are handed over to the district (KL 10.5 million, representing more than 55 percent of the total budget of the roads department), more than 90 percent were spent on personnel-related expenditures, leaving little for operations. Meanwhile, funds for operations controlled by headquarters were down to KL 6.3 million.

Accountability for equipment management and incentives for efficient utilization need to be strengthened in most road authorities. In some authorities, efficient management has been achieved through operation of departmental plant-hire schemes on a basis similar to a commercial plant-hire organization. By compelling explicit accounting of costs, such schemes inculcate greater cost consciousness and, hence, generate pressures within the government for efficient utilization of plant and vehicles, helping to control diversion and curtail excess investment. By making finances of the plant-hire organization dependent on revenues generated from plant hirings, strong incentives may be generated to keep the plant in operation because a broken-down plant generates no revenues. Spare parts can also be regularly replenished and equipment replaced out of revenues generated from plant hire. Unfortunately, such schemes have not worked well in many developing countries during recent years partly because of the public administration's failure to resist pressures from equipment users to understate equipment costs, or even to see to it that the bills are paid, and partly because of the reluctance of treasury officials to cede financial autonomy. Consequently, funds generated are neither adequate nor available on a timely basis, and the true costs of equipment remain hidden.

Plant-hire schemes, however, are not inherently complex or difficult to undertake. Successful schemes exist in Cameroon and Malawi as well as several industrial countries. Some mechanism to ensure proper pricing, budgeting, and financing will be an important ingredient of any program to ensure more effective use of government-owned equipment.

Human Resources

There is room for improved utilization of human resources in several different facets of road maintenance. At one end of the spectrum is the substitution of unskilled labor for machinery. If properly managed, labor-based methods can be more cost-effective than equipment for many maintenance activities in which wage rates are less than about $5 to $6 per day. They are less dependent on foreign resources and for that reason are normally less susceptible to disruption. They create needed employment opportunities and increase self-reliance. To be cost effective, however, labor-based methods must be properly organized with strong incentives for efficiency structured into the conditions of service. The simple lengthman system whereby individuals living alongside the road are retained to maintain 2 to 5 km (thus minimizing demands for costly transportation), with payment and continued employment dependent on satisfactory performance, has served many countries well.

It is critically important to preserve the employer's flexibility in hiring and firing and to avoid the buildup of large unskilled labor forces on permanent civil service status. In many countries the road authority has been viewed as a source of employment. The Kenya example illustrates typical consequences. In many countries, this is a critical problem that must be addressed, either through long-term attrition (as in Brazil since 1972) or through transfer of maintenance responsibilities and employment opportunities (under more flexible, incentive-based terms) to alternative organizations such as contractors (Argentina during 1979–1984). It is significant that in Malawi and Paraguay the permanent labor force has been kept small, complemented by casual labor as required and as funding permits.

At the opposite end of the spectrum is the government's difficulties in retaining competent managers, engineers, technicians, foremen, mechanics, and so forth. It is unlikely that constraints on civil service salary scales will be removed, but often some measures can be taken to raise incentives for the most productive staff to remain in service with the road authority. In Ethiopia, as in the United Kingdom *(4)*, the road authority has, after some trial and error, managed to incorporate bonus incentives based on work unit productivity. In several countries, field allowances not only encourage more active field supervision by middle level managers but also serve to raise levels of compensation.

High levels of staff turnover are likely to continue in most government agencies, however, and the road authority will need to train and develop substantially larger quantities of staff than its own needs would otherwise dictate. In effect the ministry of works serves as a training and proving ground for personnel for the private sector as well, and this is a useful role for it to play. However, it does give rise to the demand for more effective manpower planning, training, and development programs to anticipate and meet needs. These plans should deal not only with the quantitative requirements of the training program but also with the qualitative aspects as well and should be based on in-depth analysis of the type of skills that need to be developed. They should incorporate the role of technical assistance, particularly when expatriates are retained in line-management positions, an alternative that in the short run may yield substantial results in dealing with emergency situations. In the case of Malawi, after more than two decades, well-experienced local staff have been groomed for executive positions and the number of expatriates is declining sharply. (See box "Successful Manpower Management and Development in Malawi".)

Ultimately, the most critical factor is personnel management. Staff must be motivated and inculcated with a sense of duty and accountability. High performance must be recognized and rewarded. Recruitments and appointments to managerial positions must be based on competence and not patronage. Weak performances are all too often blamed on inadequate training when they have their roots in inadequate, nonexistent, or unenforced personnel management policies. Under these circumstances even the most expensive training schemes are powerless to correct the problem.

Successful Manpower Management and Development in Malawi

The ministry of works and supplies has about 100 professional staff, 450 subprofessional and supervisory staff, and about 1,350 other permanent staff for a total permanent staff of only 0.3 employees per km of main road. In addition, an average of about 2,300 workers are employed on a casual basis (predominantly for maintenance of lower-class rural roads), but this number fluctuates between 1,500 and 3,300, depending on the season and the workload.

In the past the ministry was administered by senior expatriate staff in line management, but expatriates have been gradually replaced—declining from 135 in 1977 to only 35 today—as qualified Malawians gained the necessary training and experience. The majority of graduate civil engineers comes from the Blantyre Polytechnic, but some have received their first or second degree overseas. The ministry has a total of 44 posts at the graduate entry level, and operates an in-house training program of 2 to 3 years' duration, leading to registration examination by the Malawi Board of Engineers. Only after registration are the engineers eligible for promotion to the lowest professional grades. Subsequent promotion is dependent on ability and experience. The expatriate professional staff compete on an equal basis with Malawians for promotion to higher level positions. The result of this system has been the building up over time of a well-qualified and experienced professional staff.

TECHNICAL ASSISTANCE

Technical assistance for road maintenance has traditionally focused on advisory services, management systems, and training for the public sector roads authority. Rarely in World Bank practice has technical assistance provided management services in an executive as distinct from an advisory capacity; the Malawi case discussed earlier is among a few exceptions, which would also include Zaire or the Côte d'Ivoire. Typically the scheme is such that the purveyor of technical services has only an advisory role with at most indirect responsibilities for any measurable output, very limited risks, and at best limited incentives for improving performance.

Attempts have been made to come to grips with this problem through performance incentives for the providers of technical assistance. To do so involves changing roles, a different apportionment of risks between the provider of technical assistance and the government client, and possibly different sources of technical assistance. Traditional suppliers of technical assistance are generally not well structured financially to accept significant risks. For this and other reasons, it may also be desirable to look to new sources for technical assistance.

One obvious source in the road maintenance field is international civil engineering contracting companies. Construction companies are, of course, fully accustomed to risk-taking and performance-related incentives. They also have staff with requisite qualifications who are accustomed to working together as management teams in developing countries. With the prolonged worldwide downturn in major construction, companies that previously would not have been interested in merely management services type of contracting appear now to welcome such opportunities.

REFERENCES

1. A. Hirschman, *Exit, Voice, and Loyalty*. Harvard University Press, Boston, Mass. 1970.
2. C. Harral. *World Bank Experience With Highway Maintenance: Time for New Directions?* Paper presented at the PTRC Annual Meeting, London, England, July 1985.
3. H. Hatry et al. *How Effective Are Your Community Services? Procedures for Monitoring the Effectiveness of Municipal Services.* The Urban Institute, Washington, D.C., 1977.
4. B. Cox. *Evaluation of Incentives for Efficiency in Road Maintenance Organization: The UK Experience.* Discussion Paper. Transportation Issues Series. Report TRP4. World Bank, Washington, D.C., 1987.
5. R. Robinson. *Road Maintenance—Planning and Management for Developing Countries.* U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, Great Britain, 1985.
6. C. Harral, E. Henriod, and P. Graziano. *An Appraisal of Highway Maintenance by Contract in Developing Countries.* Discussion Paper. Transportation Issues Series. Report TRP1, World Bank, Washington, D.C., 1986.

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Development of Spring Load Restrictions for Local Roads

T. RWEBANGIRA, M. S. RUTHERFORD, J. P. MAHONEY, AND R. G. HICKS

Load restrictions to reduce or preclude pavement damage during spring thaw periods are widely used in the United States and Europe. Load restrictions are primarily applied to low-volume road networks. In recent years extensive examinations of load restriction-related issues have been conducted in states such as Alaska, Minnesota, and Washington. The development of guidelines for use in determining where to apply the load restrictions and their magnitude is reported in this paper. A survey of current practice in the United States and Canada revealed that load restrictions are applied mostly to pavements that have subgrades composed of moisture-susceptible silts and clays. It also revealed that the restrictions are mostly applied to aggregate and asphalt-surfaced pavements. The maximum legal loads are generally reduced about 40 to 50 percent for single axles and 30 to 50 percent for tandem axles during the spring thaw period. The current study recommends that load restrictions be applied whenever a pavement's spring surface deflections are greater than 45 to 50 percent of summer deflections. The extent of load restrictions suggested is a minimum of 20 percent and a maximum of 60 percent. A load reduction range of 40 to 50 percent should accommodate a wide range of pavement conditions.

In areas of the United States that are subjected to moderate or severe seasonal freezing, pavement structures can be susceptible to weakening during the thawing period (normally during the spring but this can occur several times during the winter months). To preclude accelerated pavement deterioration two possibilities exist:

1. Apply load restrictions during the thawing (or critical) period.
2. Design, construct, or otherwise modify the pavement structure to prevent or reduce the thaw-weakening phenomenon.

Due to budget constraints in many agencies faced with this problem, the only choice is Item 1. A review of the literature quickly reveals that few rational procedures have been used to determine the magnitude of the load restrictions. Therefore, a need exists to develop guidelines oriented toward local agencies to assist them in handling this serious problem.

The damage to a pavement structure is directly related to the magnitude and frequency of the load applied. This was clearly demonstrated by the AASHO Road Test *(1)*. Subsequent studies of material behavior have demonstrated that the fatigue and permanent deformation characteristics of many materials depend on the magnitude and frequency of stress and strain levels induced *(2)*. A majority of the state departments of transportation use the *AASHTO Interim Guide for Design of Pavement Structures (3)* when designing their pavement thicknesses (or at least a portion of the AASHTO guide). In designing a specific pavement using this method, the traffic is converted to equivalent 18,000 lb loads for a given design period and for known or assumed material properties. Any lowering of material strength or increase in the number of equivalent 18,000 lb loads reduces the life of the pavement. Thus, the method of load reduction in response to reduction in pavement materials strength is a reasonable way to maintain the design life and general serviceability of the pavement, hence, the need for load restrictions during critical pavement periods.

Local and state highway agencies have a wide variety of practices for imposing weight restrictions in advance of the "spring thaw." Truck weight enforcement programs adopted by the various agencies vary widely in terms of the weight limits applied, the forms the restrictions take, and their implementation. The decision to close or open a facility is largely determined by experience and sometimes political pressures. Little definitive data exist to assist in decision making, especially for secondary and lower category highways even though these types of highways comprise the bulk of county and city highway systems. Because local governments generally have low to modest maintenance budgets, they normally cannot afford to overlay the pavements after damage during the spring thaw. Therefore, a need exists to develop criteria for the restriction of truck weights during the spring thaw.

OBJECTIVES

The objective of this paper is to report on part of the study carried out to develop guidelines for local governments to use in establishing weight restrictions on county and city pavements in advance of spring break-up *(4)*. The following is reported:

1. A summary of current practices,
2. Development of load limits, and
3. Development of guidelines that can be used by local agencies to assess the need and magnitude of load restrictions.

SUMMARY OF CURRENT PRACTICES

Summarized in this section is part of the survey of current practices dealing with load limits and typical structures on

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TABLE 1 SUMMARY FROM AGENCIES INTERVIEWED

Location	Types of Pavement Failure Associated with Spring Thaw	Extent of Problem	How Are Locations for Load Restrictions Determined?
Alaska DOT	Alligator cracking, rutting, frost boils	Statewide	FWD, visual observations, measurements of thaw depth, experience
Idaho DOT	Foundation, deep base, surface	15 percent of system	Experience
Iowa DOT	Spring breakup	Low-volume roads	Selected by district engineers
Bremer County, Iowa	Pavement breakup, rutting	Up to 50 percent on aggregate-surfaced, up to 10 percent on paved	Visual observation of heaving or pumping, or both
Maine DOT	Alligator cracking	Low-volume roads statewide	Selected by district engineers
Minnesota DOT	Rutting, alligator cracking	Limited	Experience of maintenance engineer and deflection measurements with road rater and FWD
Anoka County, Minnesota	Alligator cracking, potholes	Not too extensive due to restrictions	Construction history and design, and Benkelman beam deflections
Maple Grove, Minnesota	Frost boils, alligator cracking	Citywide	Uniform load restriction policy for all streets
Wright County, Minnesota	Rutting, alligator cracking	Variable from year to year	Road rater deflections
Montana DOT	Frost boils	Statewide to minimum structure roads	Judgment of maintenance personnel
New Hampshire DOT, Division 2	Alligator cracking, rutting, frost heave	Modest	Judgment of maintenance personnel based on whether heavy hauling is occurring
North Dakota DOT	Surface break, potholes	Varies yearly depending on frost penetration	Experience
Nova Scotia DOT	Varies depending on structure and loads	Not extensive	Benkelman beam testing
Oregon DOT	Heave, cracking, pavement breakup	Central, eastern part of state	Experience and visual observation
Benton County, Oregon	Alligator cracking and breakup	All road construction types	Experience
South Dakota DOT	Potholes, edge failure, alligator cracking	Highways with thin mats typically restricted statewide	Experience
Washington State DOT	Alligator cracking, pavement breakup	Central and eastern Washington on a few low-volume roads	Judgment of maintenance personnel
Benton County, Washington	Pavement breakup, frost heave, base failure	Moderate	Observation of road conditions

which they are applied. The survey results are from contacts and visits with selected agencies throughout the United States and Canada. The relevant questions on load limits were

1. Types of facilities requiring weight restriction during the spring thaw period,
2. Types of pavement failures associated with spring thaw,
3. The magnitude of weight restriction and how such policies were developed.

To collect the needed information, three survey techniques were used: the initial information request, interviews, and follow-up requests. The response by the agencies contacted is given in Table 1.

Highways Receiving Load Restrictions

This question was concerned with defining the types of highways receiving load restrictions. The responses indicate the following:

1. Load restrictions by state agencies were applied to both primary and secondary roads, but mostly secondary. Few states have applied them to Interstate highways. Local agencies generally applied load restrictions to all types of facilities.
2. Of those states responding, load restrictions were generally applied to roads with average daily traffic (ADT) less than 2,500 and 10 percent trucks or less. Local, city, and county agencies applied restrictions to roads with ADT levels up to 30,000 and up to 10 percent trucks.
3. Primarily, load restrictions were applied to pavements that had moisture-susceptible silt or clay subgrades. If the agencies had granular subgrades, load restrictions were not usually required.
4. Load restrictions (if used) were normally applied to aggregate- or asphalt-surfaced roads. Most portland cement concrete pavements reportedly had adequate structure to withstand the critical thaw period.
5. The pavement cross sections to which load restrictions were applied generally ranged as follows:

	Range	*Normal*
Asphalt surface, in.	$1^1/_2$ to 5	2 to 4
Aggregate base, in.	4 to 18	6 to 12

Thicker pavements apparently have sufficient strength to withstand the effects of the thaw-weakening period.

Design Information for Roads Receiving Load Restrictions

This question addresses design information such as whether frost penetration is considered in thickness design, the age of the pavement, and typical drainage conditions. The results indicate

1. Some of the state agencies surveyed design pavements for partial frost protection whereas others did not consider frost protection in design at all. Most local agencies did not consider frost protection in their design procedure.
2. Several of the agencies used load restrictions in lieu of designing for full frost protection.
3. A variety of design procedures were used to determine layer thickness. The most common was the AASHTO method. Others included the Hveem method, experience, or precedent.
4. Pavements receiving load restrictions tended to be 10 to 20 years old or older. In some cases they tended to be farm-to-market types of roads constructed after World War II.
5. Drainage conditions for pavements receiving load restrictions varied from poor to good. There appeared to be little relation between surface drainage and the need for load restrictions.

Magnitude of Load Restriction

This question addressed the current load limits and how they were determined. The significant findings include the following:

1. For most agencies normal load limits were 18,000 to 20,000 lb on a single axle and 34,000 lb on tandem axles.
2. Spring load restrictions generally ranged from 10,000 to 14,000 lb for single axles and 18,000 to 28,000 lb for tandem axles.
3. Percentage reductions were 30 to 50 percent for single axles and 18 to 47 percent for tandem axles.
4. Most load limits had been established from experience. Only a few states, such as Alaska *(5)*, Minnesota *(6)*, and Washington *(7)*, had conducted extensive studies.
5. Only three of the agencies used deflection measurements to establish load limits.

The summary of current practices clearly shows the types of pavement structures that are subjected to spring load restrictions. It also shows the types of failure associated with spring thaw, as well as the magnitude of normal and spring load limits. Using the information from current practice, an attempt is made in the following sections to develop a rational procedure for spring load limits.

DEVELOPMENT OF LOAD LIMITS

The development of the procedure used to establish guidelines on the magnitude of spring load restrictions is presented in this section. The procedure is based on pavement structural analysis using a layered elastic program and typical pavement structures.

Analytical Procedure

Layered elastic theory has been widely applied to analyze pavement response to load. Several analysis programs exist for mainframe and microcomputers; the program selected for this study was ELSYM5 *(8)*. This program was developed at the University of California, Berkeley, and can be used to analyze up to 10 identical loads in a 5-layer system. It computes stresses, strains, and displacements at specified points and assumes the material behavior is linear elastic.

It has been widely recognized that base course and subgrade materials (both coarse and fine) exhibit nonlinear elastic behavior. Because test cases used in the study are hypothetical, representing a range of structural conditions that might be found anywhere in the frost areas of the United States, it was not possible to identify any meaningful nonlinear relationships. In addition, in reviewing data from previous frost studies performed for the Washington State Department of Transportation *(7)*, it was found that the behavior of the materials was not highly nonlinear in the ranges of stresses studied. Therefore, it is believed that a linear elastic analysis was capable of providing adequate results.

Structure Cross Section

The structure cross sections used in the study were selected to represent as near as possible the types of road construction and subgrade materials present in the geographic region and jurisdictions of interest. Therefore, the data obtained in the interviews were weighted heavily in the selection of the structure cross-section cases.

Surface courses were assumed to be either asphalt concrete (AC) or bituminous surface treatment (BST) with thicknesses ranging from 2 to 4 in. The base course was assumed to be unstabilized aggregate varying from 6 to 12 in. thick. No subbases were considered. Subgrades of both coarse and fine materials were investigated. The specific cases analyzed are given in Table 2.

Material Properties

Several different cases of environmental conditions occur in a pavement structure annually that have an effect on the pavement structure's stiffness properties and therefore, its response. If it is desirable to restrict loads during spring when overall structural stiffness is reduced so that the strains and deflections experienced are comparable to those during the full-strength summer case, then the stiffness properties of the summer case and various stages of spring thawing need to be modeled.

For the reference condition, a range of resilient properties was selected to represent the surface course, base course, and subgrade. The analysis performed assumed that for the condition of a base course underlain by a weaker material, the base course resilient modulus was a function of the underlying material. The following relationship was used:

$$Mr_{\text{base}} = 1.5\ Mr_{\text{subgrade}}$$

This type of relationship originally used by Heukelom and Klomp *(9)* has been subsequently used by the Shell Oil Company *(10)* and by the Asphalt Institute *(11)* in their respective pavement design methods. The commonly used range for the modular ratio is about 1.0 to 4.0 (for this study a value of 1.5 was selected, which is in the lower end of the range).

TABLE 2 SUMMER PAVEMENT STRUCTURE

Type	Material	Thickness (in.)	Resilient Modulus (psi)
Surface	BST or ACP	2	300,000
	ACP	4	300,000
Base	Gravel	6	Base M_R = 1.5 Subgrade M_R
		12	
Subgrade	Fine-grained	212	7,500
	Coarse-grained	212	40,000

A range of subgrade resilient moduli was selected from results of field and laboratory data and is given in Tables 3 through 5. The values represent typical moduli for soils ranging from silty-clay to gravel *(7, 11, 12)* for the different cases of thawing condition analyzed. Because the asphalt concrete and bituminous surface treatment resilient moduli are highly dependent on temperature, the modulus value selected for the summer case was 300,000 psi and was based on a reference temperature of 75°F *(10)*. Using the same reference data *(10)*, the surface course resilient modulus during the spring thaw (temperature of 40°F) was found to be 1,200,000 psi.

During the early thawing period, the base course resilient modulus can be reduced substantially due to moisture conditions and undrained loading. The base course assumed during this period was either 25 or 50 percent of the reference (summer) condition. This decision was based in part on work reported by Lary et al. *(7)* and Shook et al. *(11)*. The cases that were analyzed during thawing included the following:

1. Thaw to the bottom of the base course,
2. Thaw 4 in. into the subgrade, and
3. Thawing complete.

When thawing occurred in the subgrade, the Mr_{subgrade} was assumed to be 5 to 50 percent of the reference (summer) condition (Tables 3 and 5). Where the subgrade material was frozen, the resilient modulus was assumed to be 50,000 psi.

Loading Cases

Currently, most jurisdictions, whether national, state, or local, restrict loads on classes of roads according to axle loads. Based on information obtained in the interviews and a review of current practice throughout the United States, a maximum single axle load of 20,000 lb and a tandem axle load of 34,000 lb were selected as reference load levels.

Because the ELSYM5 program models the wheel loads with a circular configuration, it was decided that the loading was most accurately represented by selecting the maximum load and corresponding tire pressure recommended by the Tire and Rim Association for a particular tire size *(13)*. Load reductions were modeled by maintaining the contact pressure (tire pressure) and reducing the load, thereby reducing the contact area.

The loading cases evaluated included the following tires: single axle-single tire (16.5-22.5), single axle-dual tires (10-22.5), and tandem axle-dual tires (10-22.5). The loads and pressures for each of these cases are given in Table 6. All loading cases were analyzed for 20 and 100 percent of the maximum load to obtain load-deflection and load-strain plots.

Parameters Calculated

When a pavement fatigue analysis is performed, two strain parameters are used. These parameters are the tensile strain at the bottom of the surface course (ε_t) and the vertical strain at the top of the subgrade (ε_{vs}). Another parameter typically considered as well is the maximum pavement surface deflection (δ). In addition to these widely used damage indicators, some researchers *(7, 14)* have found that the vertical strain at the top of the base course (ε_{vb}) was also an indicator of distress due to a weakened condition. As a result, for this study, all of these parameters were considered potential indicators of excessive load. Therefore, an increase in any one of these parameters above the reference level (summer condition) constituted a required reduction in the load level sufficient to maintain them at levels comparable to the reference (or summer) conditions. The locations of these parameters are shown in Figure 1.

Once the deflections and strains were calculated, the determination of the spring load that caused the same damage as the maximum legal allowable load during the summer could be computed. This can be illustrated using a plot such as the one shown in Figure 2. The plot was constructed as follows:

1. Plot δ, ε_t, ε_{vb}, and ε_{vs} for two loads used in the spring analysis (hence spring thaw material properties), and load-deflection and load-strain lines were drawn through these points. The load levels used in the analysis were 20 and 100 percent of the legal maximum. This was done for different structural profiles and material combinations.
2. Enter the plot on the vertical axis with the summer deflection or any summer strain value.
3. Draw a horizontal line to intersect the appropriate load-deflection or load-strain value.
4. At the intersection, a vertical line is drawn to intersect the horizontal or tire-load axis.
5. The values at the intersection with the tire-load axis are the tire loads that would result in the same deflection or strains

TABLE 3 SPRING THAW PAVEMENT (COMPLETE THAW)

Type	Material	Thickness (in.)	Resilient Modulus (psi)
Surface	BST or ACP	2	1,200,000
	ACP	4	
Base	Gravel	6	Base M_R = 1.5 Subgrade M_R
		12	
Subgrade	Fine-grained	-	15, 20, 25% of Summer Subgrade M_R
	Coarse-grained	-	25, 30, 50% of Summer Subgrade M_R

TABLE 4 SPRING THAW PAVEMENT STRUCTURE (THAW TO BOTTOM OF BASE)

Type	Material		Thickness (in.)	Resilient Modulus (psi)
Surface	BST or ACP		2	1,200,000
	ACP		4	1,200,000
Base	Gravel		6	25, 50% of Summer Base M_R
			12	
Subgrade	Frozen		Depth of freeze minus surface, base, and thawed subgrade	50,000
	Unfrozen	Fine-grained	212	7,500
		Coarse-grained	212	40,000

TABLE 5 SPRING THAW PAVEMENT STRUCTURE (THAW TO 4 IN. BELOW BASE)

Type	Material	Thickness (in.)	Resilient Modulus (psi)
Subgrade	BST or ACP	2	1,200,000
	ACP	4	1,200,000
Base	Gravel	6	Base M_R = 1.5 Subgrade M_R
		12	
Subgrade	Thawed fine-grained	4	5, 15% of Summer Subgrade M_R
	Thawed coarse-grained	4	25, 50% of Summer Subgrade M_R
	Frozen fine-grained and coarse-grained	Depth of freeze minus surface, base, and thawed subgrade	50,000

TABLE 6 LOADING CASES

Case	Size (Nominal)	Tire Pressure (psi)	Tire Load (lbs)
Single Axle (Max. Load = 20,000 lb)			
a) Single Tires	16.5-22.5	90	9900
b) Dual Tires	10-22.5	100	5000
Tandem Axle (Max. Load = 34,000 lb Axle Spacing = 48 in.)			
a) Dual Tires	10-22.5	100	4250

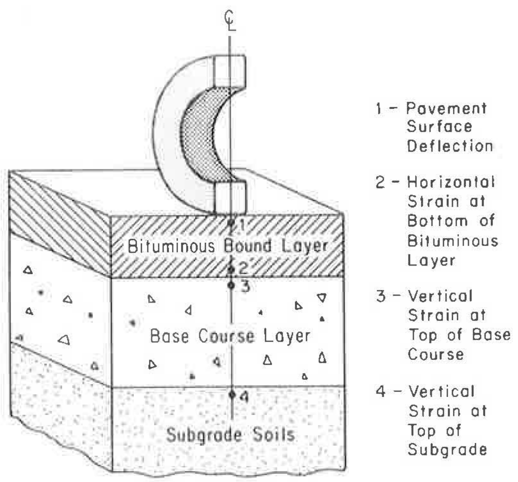

FIGURE 1 Pavement response locations used in evaluating load restrictions.

as obtained during the summer under the maximum allowable loading.

From these values, the percentage reduction in summer load required to maintain the same strains and deflections was computed.

Sensitivity Analysis

A sensitivity analysis was carried out to test how the magnitude of load reduction varied with some variation in the input parameters. To do this, the pavement surface modular ratio ($M_r$spring/$M_r$summer) was first varied from 1.25 to 3.75. The second item varied was the magnitude of the subgrade strength reduction during the spring thaw. Finally, the percentage reduction in resilient modulus was varied from 70, 80, and 85 percent for fine-grained soils, and 50, 70, and 75 percent for coarse-grained soils. The results of the sensitivity analysis *(4)* indicated that

1. Load reduction during spring thaw is more sensitive to changes in subgrade than pavement surface modulus.
2. The subgrade strength reduction of 75 percent for fine-grained soils resulted in a reasonable value for spring load reductions when compared to current practice. The corresponding value for coarse-grained soils was found to be 50 percent.

Structural Analysis Results

Typical results of the structural analysis are given in Table 7. The thawing cases include complete thaw, partial thaw to the bottom of the base course, and partial thaw 4 in. into the subgrade (i.e., 4 in. below the bottom of the base). Typical results of load reduction for various pavement structural sections for the complete thaw case are given in Table 7. The load reduction is also shown for various axle and tire configurations, and the results in Table 7 are for a single axle and both single- and dual-tire configurations. Load reduction results are given for both fine- and coarse-grained subgrade soils. The results in Table 7 are for a coarse-grained subgrade. Only one case is shown here; for complete results please refer to *Guidelines for Spring Highway Use Restrictions (4).*

DISCUSSION OF RESULTS

Magnitude of Load Reduction

The magnitudes of load restriction vary with both pavement structure and load response parameter (deflection and strain) (Table 7). The calculated load reductions (for those cases that require a reduction) ranged from a low of 1 percent to a high of 69 percent *(4)*. For all cases, the surface deflection and vertical subgrade strain provided the most consistent load-reduction values (for the assumed conditions). The tensile strain (bottom of surface course) and vertical strain at the top of the subgrade criteria resulted in the largest reductions in load. An average load reduction of 34 percent results for the complete thaw and partial subgrade thaw cases for fine and coarse-grained soils for the subgrade vertical strain criterion (includes both 2- and 4-in.-thick surface courses) *(4)*. For the same conditions, but for 2-in.-thick surface courses only, the average load reduction increases to 45 percent. The corresponding value for 4-in.-thick surface courses is 21 percent. An average load reduction of 39

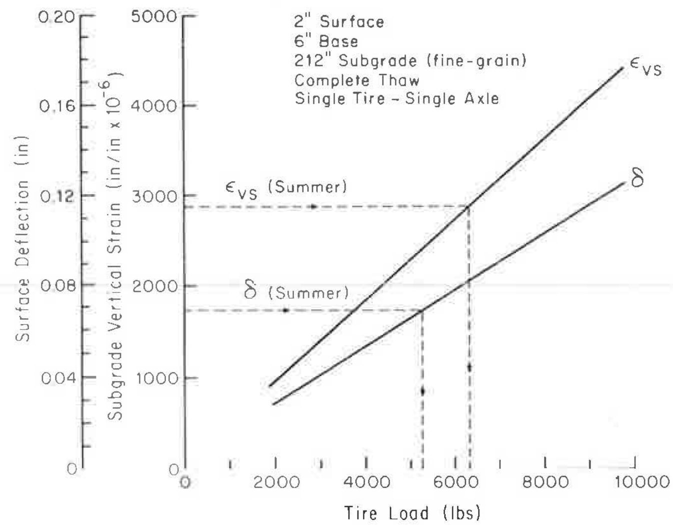

FIGURE 2 Graphical illustration of the determination of allowable load during spring thaw period.

percent results for the complete thaw and partial subgrade thaw cases for fine-grained soil and both thickness levels of surface course (based on the subgrade vertical strain criterion as before). For the same conditions but for 2- and 4-in.-thick surface courses, the average load reductions are 52 and 25 percent, respectively.

Thus, for fine-grained soils (which are the types of soils that generally necessitate the need for load restrictions), a load reduction of about 50 percent is needed for thin-surfaced bituminous pavements. The benefit of thicker surface courses (or stabilized pavement layers in general) is illustrated for the 4-in.-thick surface course. For the fine-grained subgrade case, a load reduction of about 25 percent is needed (or one-half the load reduction amount needed for the 2-in.-thick surface course).

It should also be noted that there are no significant differences in reductions for single and dual tires *(4)*. For both fine- and coarse-grained soils in the complete thaw case, the dual-tire configuration results in slightly higher reductions than the single tire. The dual-tandem configuration results in about the same range of load reductions; although the deflections and strain levels are lower than the single and dual-tire single-axle cases. The maximum strain values for the dual-tandem configuration generally occurred between the dual tires.

Consequence of Maintaining Loads

An evaluation of the consequences of maintaining the maximum summer loads during the spring was performed. This was done by examining criteria generally accepted as indicators of pavement distress. These are the maximum tensile strain at the bottom of the bituminous-bound layer (fatigue cracking) and the vertical strain at the top of the subgrade (rutting). The Asphalt Institute criteria *(11)*, have been used to determine the number of load applications to failure for any given strain. The results are given in Table 8 for prediction of loads to failure for complete thaw. Other conditions evaluated included thaw to bottom of base and thaw 4-in. below the bottom of the base. The data in Table 8 show the summer and spring strain values and the corresponding loads to failure, they also show the percentage change in pavement life (number of loads to failure) between summer and spring cases. This is shown for several pavement structural sections and for both fine- and coarse-grained subgrade soil. The remaining cases can be found in *Guidelines for Spring Highway Use Restrictions (4).*

The predicted loads to failure for the load cases evaluated are relatively low for the fine-grained subgrade cases (both summer and spring conditions). This is due in part to the cross sections selected for evaluation but primarily the material properties (the principal material property being resilient modulus). The negative percent change in the loads to failure (summer to spring) is consistently high for the 2-in.-thick surface course cases. For the 4-in.-thick surface course, occasionally the spring condition (with the higher stiffness surface course) results in a positive change in the estimated loads to failure (e.g., longer pavement life).

DEVELOPMENT OF IMPROVED GUIDELINES

Guidelines for Where to Apply Load Restrictions

The procedure to establish load restrictions was based on the assumption that pavement response (deflection and strain) during the spring thaw should be limited to those estimated for summer conditions. The way to achieve equal pavement response is to reduce allowable axle loads (or individual tire loads). Further, many agencies have the capability to measure pavement surface deflections with equipment such as the Benkelman beam, Dynaflect, or the Falling Weight Deflectometer (FWD). Thus for both the fine- and coarse-grained subgrade cases, the percent increase in surface deflection was calculated for summer to complete spring thaw for both single-tire–single-axle and dual-tire–single-axle conditions. These deflection increases were matched with the associated load reduction percentages; a summary is given in Table 9 and plotted in Figure 3. The data in Table 9 show the increase in surface

TABLE 7 PERCENT LOAD REDUCTION FOR COMPLETE THAW—COARSE-GRAINED SOILS—SINGLE AXLE, 50 PERCENT REDUCTION IN SUBGRADE RESILIENT MODULUS

Pavement Structural Section		Load Reduction (Percent)							
		Single Tire (a) – Pavement Response Criteria				Dual Tire (b) – Pavement Response Criteria			
Surface Thickness (in.)	Base Thickness (in.)	Pavement Surface Maximum Deflection	Bituminous Tensile Strain	Base Vertical Strain	Subgrade Vertical Strain	Pavement Surface Maximum Deflection	Bituminous Tensile Strain	Base Vertical Strain	Subgrade Vertical Strain
2	6	32	60	37	30	43	8	1	26
	12	33	61	38	39	34	5	1	40
4	6	10	NR	NR	NR	11	NR	NR	23
	12	11	NR	NR	19	12	NR	NR	26

Notes: (a) Single tire: Tire size: 16.5 - 22.5 Maximum legal tire load: 9,900 lb. Tire pressure: 90 psi
(b) Dual tires: Tire size: 10 - 22.5 Maximum legal load per tire: 5,000 lb Tire pressure: 100 psi
(c) NR = No Reduction

TABLE 8 CHANGE IN PAVEMENT LIFE, SINGLE TIRE, SINGLE AXLE, TENSILE STRAIN BOTTOM OF BITUMINOUS BOUND LAYER, COMPLETE THAW

Pavement Structural Section		Fine-Grained Soil					Coarse-Grained Soil				
		Summer		Spring[a]		Percent	Summer		Spring[a]		Percent
Surface Thickness (in.)	Base Thickness (in.)	Strain (in./in. × 10^{-6})	Loads to Failure	Strain (in./in. × 10^{-6})	Loads to Failure	Change Loads to Failure	Strain (in./in. × 10^{-6})	Loads to Failure	Strain (in./in. × 10^{-6})	Loads to Failure	Change Loads to Failure
2	6	950	10,800	902	3,900	–64	190	2.1×10^6	312	128,600	–94
	12	899	12,900	870	4,400	–66	182	2.5×10^6	296	152,900	–94
4	6	655	36,670	372	72,100	+97	243	956,100	193	624,600	–34
	12	629	41,800	365	76,700	+84	232	1.1×10^6	186	705,900	–37

NOTES: Equation for estimating number of loads to cause up to 10 percent cracking in the wheelpath: $\log N_f = 15.947 - 3.291 \log (\varepsilon_t/10^{-6}) - 0.854 \log (M_R/10^3)$. Single tire, single axle: Load = 9,900 lb; tire pressure = 90 psi.

[a]Spring case for complete thaw: (a) Fine-grained: 75 percent reduction in subgrade resilient modulus; (b) Coarse-grained: 50 percent reduction in subgrade resilient modulus.

TABLE 9 SURFACE DEFLECTION INCREASES (FROM SUMMER TO COMPLETE THAW CASE) AND ASSOCIATED LOAD REDUCTIONS

Pavement Structural Section		Single Tire – Single Axle		Dual Tires – Single Axle	
Surface Thickness (in.)	Base Thickness (in.)	Surface Deflection Increase (a) (Percent)	Load Reduction (b) (Percent)	Surface Deflection Increase (a) (Percent)	Load Reduction (b) (Percent)
Fine-grained Subgrade					
2	6	76	43	98	49
2	12	80	44	100	50
4	6	22	18	43	23
4	12	25	20	47	26
Coarse-grained Subgrade					
2	6	44	30	67	26
2	12	45	39	68	40
4	6	10	—	29	23
4	12	11	19	31	26

Notes: (a) Increase in pavement surface deflection from summer to complete spring thaw
(b) Load reductions from Tables 4.6 and 4.7 for the subgrade vertical strain response criterion

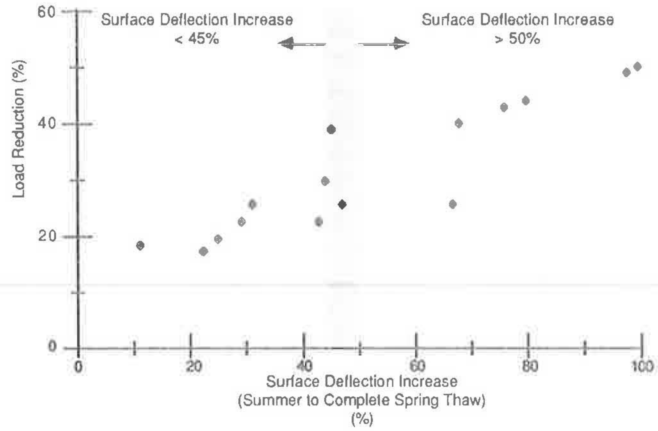

FIGURE 3 Development of surface deflection for locating pavements requiring load restrictions.

deflection corresponding to the complete thaw case. The data also show the load reduction necessary to maintain the deflections at their summer values. The results are given for the various pavement structures, subgrade types, and single- and dual-tire configurations.

An examination of Figure 3 reveals that pavement sections that have surface deflections 45 to 50 percent higher during the spring thaw than in summer are candidates for load restrictions. Clearly, this is not an absolute criterion for selecting pavement sections to receive load restrictions. Site-specific conditions could significantly alter the deflection increase threshold. For example, a relatively thin or weak pavement section may have relatively high summer deflections. Thus, spring thaw deflections may need to increase much less than the threshold level of 45 to 50 percent to necessitate load reductions. Surface deflection increases of less than 45 percent result in load reductions of about 25 to 30 percent or less, which is in agreement with the work by Connor *(15)*.

Other criteria that should be considered in selecting pavements for load restrictions include

1. Surface thickness,
2. Pavements on fine-grained subgrades, and
3. Local experience relating to observed moisture and pavement distress.

Pavements on fine-grained subgrades, such as silts and clays (Unified Soil classifications ML, MH, CL, and CH), are candidates for load restrictions. Again, the depth of ground freezing is important.

The observed site-specific drainage is significant in assessing the need for load restrictions. Poor drainage from side ditches, available groundwater, high winter precipitation, and snow removal policies should be considered. For example, pavement in cold but dry locations probably will not need any type of restrictions.

Another criterion to use for selecting locations for load restrictions involves observation of pavement distress such as fatigue (alligator) cracking and rutting. If these distress types primarily occur during the spring thaw, load restrictions are needed if options such as strengthening the overall pavement structure are not possible (or appropriate).

Overall, local experience relating to the conditions associated with the performance of an individual agency's road network is important. Clearly, various nondestructive pavement response measures such as surface deflection can help define the potential pavement weakening during the thaw period; however, the experience of agency personnel should be used to the fullest extent possible.

Guidelines for Load-Restriction Magnitude

The load reductions used by the agencies contacted range from about 20 to 60 percent. An average load reduction for seven locations (individual state areas) is approximately 44 percent (standard deviation of about 8 percent) *(4)*. This suggests that reducing the load on individual axles (or tires) by about 40 to 50 percent reduces the associated pavement response to levels that preclude or reduce the resulting pavement distress to acceptable levels.

To further examine the amount of load reduction needed, Figure 4 was developed. This is a plot of load reduction (percent) versus the increase in pavement life due to the application of load restrictions (percent). The load reduction percentages were obtained from tables similar to Table 7 (for the vertical strain at the top of the subgrade cases only). The increase in pavement life was obtained from tables similar to Table 8. To determine the increase in pavement life from these tables, the negative change in pavement life (based on the rutting failure criterion) is eliminated as a result of load reductions, thus increasing the potential pavement life. All three tire-axle configurations were used. This curve contains data points for both the 2- and 4-in.-thick surface courses and both fine- and coarse-grained subgrades for the rutting failure criterion (a wide range of conditions). Undoubtedly, different failure criteria would tend to shift the curve.

The results given in Figure 4 show that as the load reduction percentage is increased the associated pavement life is increased (as expected). An increasing slope is noted for load reductions greater than about 20 percent. The following potential pavement life increases result as a function of load reduction (starting with a load reduction of 20 percent):

Load Reduction (%)	*Pavement Life Increases (%)*
20	62
30	78
40	88
50	95

Thus, if the 44 percent load reduction level is used (average of the seven states previously noted), this results in a potential improvement in pavement life of about 90 percent. The basic (and very conservative) assumption is that all the pavement damage (hence load reduction benefit) can occur during the thaw-weakened period. For some pavements, this may actually occur but generally would not be the case for most. What this curve allows is for an agency to select the amount of benefit desired and restrict loads accordingly.

Clearly, the needed level of load reduction is not as simple as an examination of Figure 4 suggests. For example, many thin or generally weak pavement structures need high levels of load reduction during the spring thaw period to prevent significant pavement damage (i.e., small or even modest levels of load reduction will not preclude significant pavement damage).

To further assist agencies, Figure 5 was developed. This figure is a plot of the load reduction required to maintain equivalent summer rutting levels (similar to Figure 4) versus reduction in remaining life due to spring thawing. Figure 5 was developed for the same tire-axle cases and the rutting failure criterion as used in Figure 4. The differences in remaining life between the actually applied and required load reductions were based on the relative values of the equivalent summer vertical subgrade strain (which results in the required load reduction) and that strain resulting from the actually applied load reduction. The family of curves shown are for various levels of actually applied load reduction (0 to 50 percent).

For example, if a pavement section actually needed (or required) a 40 percent load reduction to prevent pavement damage from exceeding that accumulated during the summer but only a 30 percent load reduction was actually applied, then the reduction in remaining life would be about 40 percent. Again, if the required load reduction is 40 percent but only a 20 percent load reduction was applied, then the reduction in remaining life would be slightly more than 60 percent.

If load restrictions are to be used, it appears that a minimum load reduction of 20 percent is needed. Load reductions greater than 60 percent would appear to be excessive (given the assumptions used in the preceding analysis). Further, general national practice is to use load reductions ranging from 40 to 50 percent. The analysis performed in this study tends to confirm this range of load reduction.

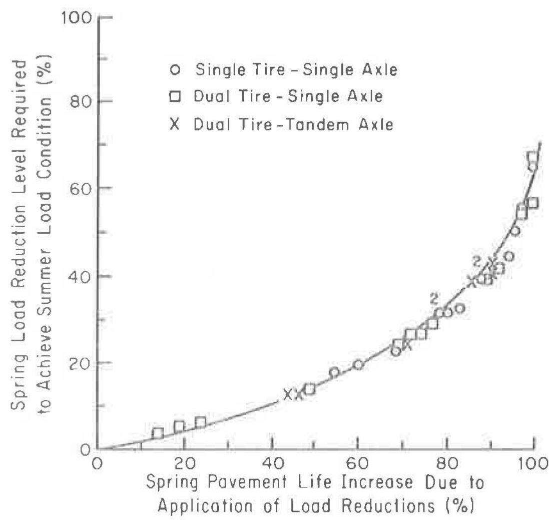

FIGURE 4 Load limit percentages from measured maximum spring deflections and known or assumed acceptable summer deflection levels.

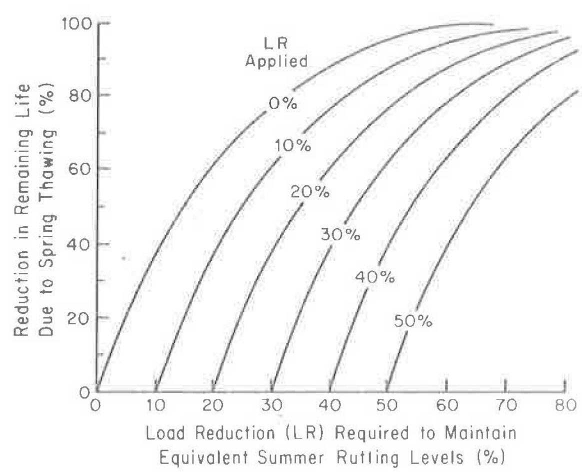

FIGURE 5 Increase in pavement life due to application of load reductions.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results of this study indicate the following conclusions are warranted:

1. Surveys conducted in this study reveal the following:

- Load restrictions are applied mostly to pavements that have subgrades composed of moisture-susceptible silts and clays.
- Load restrictions are applied mostly to aggregate or asphalt-surfaced pavements, or both types. These pavements are usually older (about 20 years).
- The maximum legal loads are generally reduced from about 40 to 50 percent for single axles and 30 to 50 percent for tandem axles.
- Judgment by field personnel is primarily used to assess where, when, how much, and how long to apply load restrictions.

2. In the determination of where to apply load restrictions, the following is often considered:

- Comparison of summer and spring pavement surface deflection data,
- Surface thickness,
- Moisture conditions,
- Subgrade type, and
- Local experience.

3. The average load restriction applied by the agencies interviewed (based on seven individual state areas) is about 44 percent. Further, an analysis based on characterizing a pavement structure as a layered elastic system suggests that a minimum load restriction level (if any load reduction is needed) is 20 percent. Load reductions greater than 60 percent are not justifiable for the wide range of cases studied. Current national practice and the analysis performed in this study suggest that for those pavements that need restrictions, load

reductions ranging from 40 to 50 percent should accommodate a wide range of pavement conditions.

Recommendations

The following recommendations have been developed on the basis of the study findings:

1. Where to apply load restrictions: If pavement surface deflections are available to an agency, spring thaw deflections that are 45 to 50 percent greater than corresponding summer deflections suggest a need for load restriction. Further, considerations such as pavement surface thickness, moisture condition, type of subgrade, and local experience should be considered. Subgrades with Unified Soil Classifications of ML, MH, CL, and CH will result in the largest pavement weakening.
2. Load restriction magnitudes can be based on guidance provided in Figures 4 and 5. A minimum load reduction level should be 20 percent. Load reductions greater than 60 percent generally are not warranted based on potential pavement damage. A load reduction range of 40 to 50 percent should accommodate a wide range of pavement conditions.

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REFERENCES

1. *Special Report 61E: The AASHO Road Test.* Report 5, Pavement Research. HRB, National Research Council, Washington, D.C., 1962.
2. C. L. Monismith and D. B. McLean. Technology of Thick Lift Construction—Structural Design Considerations. *Proc., Association of Asphalt Paving Technologists,* Cleveland, Ohio, 1972.
3. *AASHTO Interim Guide for Design of Pavement Structures—1972.* American Association of State Highway and Transportation Officials, Washington, D.C., 1981.
4. M. S. Rutherford, J. P. Mahoney, R. G. Hicks, and T. Rwebangira. *Guidelines for Spring Highway Use Restrictions.* Report FHWA-RD-86-501, U.S. Department of Transportation, Aug. 1985.
5. B. Connor. *Rational Seasonal Load Restrictions and Overload Permits.* Alaska Department of Transportation, Juneau, 1980.
6. M. S. Kersten and E. L. Skok, *Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota.* Interim Report, Investigation 183. Minnesota Department of Highways, St. Paul, 1968.
7. J. A. Lary, J. P. Mahoney, and J. Sharma. *Evaluation of Frost Related Effects on Pavements.* Report WA-RD 67.1. Washington State Department of Transportation, Olympia, May 1984.
8. R. G. Hicks. *Use of Layered Theory in the Design and Evaluation of Pavement Systems.* Report FHWA-AK-RD-83-8. Alaska Department of Transportation and Public Facilities, Juneau, July 1982.
9. W. Heukelom, and A. J. G. Klomp. Dynamic Testing as a Means of Controlling Pavements During and After Construction. *Proc., First International Conference on the Structural Design of Asphalt Pavements,* Ann Arbor, Mich., 1962.
10. A. I. M. Claussen, J. M. Edwards, P. Sommer, and P. Uge. Asphalt Pavement Design—The Shell Method. *Proc., Fourth International Conference on the Structural Design of Asphalt Pavements,* Ann Arbor, Mich., 1977.
11. J. F. Shook, et al. Thickness Design of Asphalt Pavements—The Asphalt Institute Method. *Proc., Fifth International Conference on the Structural Design of Asphalt Pavements.* Delft University of Technology, The Netherlands, Aug. 1982.
12. T. C. Johnson, D. M. Cole, and E. J. Chamberlain. *Influence of Freezing and Thawing on the Resilient Properties of a Silt Soil Beneath an Asphalt Concrete Pavement.* Report 78-23. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Sept. 1978.
13. *1979 Year Book.* The Tire and Rim Association, Inc., Akron, Ohio.
14. R. N. Stubstad and B. Connor. *Prediction of Damage Potential on Alaskan Highways During Spring Thaw Using the Falling Weight Deflectometer.* Alaska Department of Transportation, Fairbanks, 1982.
15. B. Connor, *Rational Seasonal Load Restrictions and Overload Permits,* Alaska Department of Transportation, Juneau, 1980.

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Evaluation of Subjective Rating of Unpaved County Roads in Indiana

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Counties and other local highway agencies continually use visual or subjective rating systems for routine and periodic road inspections. In a study of unpaved roads in Indiana, a subjective rating of unpaved roads was evaluated. Using a rating scale ranging from 0 to 5 for worsening road condition, regression relationships were determined among a panel condition rating and measured road roughness number, average rater speed and visually rated corrugation, potholes, rutting and gravel looseness. As expected, the panel condition rating worsened with increasing roughness, and average rater speed decreased with increasing panel condition rating. However, because most of the roads studied were in reasonable condition, considerable reduction in average speed was not experienced. An examination of road distresses also showed that corrugations and potholes were more related to panel condition rating than the other distresses. The results were used to suggest a basis for selecting maintenance activity based on the panel condition rating, present serviceability rating, roughness, and average speed. A comparison of ratings by the study panel from Purdue and panels from two countries indicated that the county panels generally rated their roads to be in better condition than the Purdue panel. However, in any subjective rating, consistency within any group is the most important consideration.

Over the years visual or subjective assessment of road condition has been the traditional method of inspection by highway engineers. Application of a visual assessment procedure requires experience and a knowledge of maintenance and improvement practices that apply to identified distresses. Several attempts have been made to quantify these visual ratings by using numeric ratings to represent pavement and surface conditions. Such subjective numeric ratings have also been related to measure roughness and other measurable road surface distresses, such as cracking and patching, as well as rut depth *(1–7)*.

Carey and Irick defined the concepts of present serviceability index (PSI) as a result of work at the AASHO Road Test *(1)*. These concepts involved the road user who determined whether or not the road condition was satisfactory. The PSI was obtained by correlating user opinions with objective measurements of road roughness (using AASHO slope profilometer) and the extent of cracking and patching as well as rutting in asphalt pavements. A rating scale from 0 to 5 representing the range from "impassable pavement" condition to a "perfectly smooth" pavement was used by a panel of road users who drove and rated selected road sections. The individual panel member's average ratings for any section, designated the present serviceability rating (PSR), was correlated to the objective measurements applying regression techniques. The rating calculated using the resulting regression equation is the PSI *(4)*. Separate equations relating PSI and roughness have been derived in Indiana for rigid and flexible pavements *(7)*; however, different equations are required if these concepts are to be applied in evaluating unpaved roads.

Hutchinson *(8)* cautioned the use of subjective rating systems, and Weaver *(3)* reported application of psychophysical principles to the quantification of the attribute of pavement serviceability. As a result of Weaver's work, a rating procedure using these principles is currently being used by the New York State Department of Transportation for the evaluation of the state highway system. The extent of some of these developments was outside the scope of the needs of typical county highway departments and was not considered in this study.

In this paper a subjective rating using ride comfort (PCR) on county gravel and stone roads in Indiana is evaluated. The purpose of the analysis was to determine the relationship between average PCR and measured roughness, average rater speed, as well as visually assessed road distresses and cross-sectional characteristics.

SELECTION OF COUNTIES AND ROADS

The five Indiana counties selected were Bartholomew, Huntington, Jasper, Tippecanoe, and Warrick (Figure 1). Their locations were chosen to cover the major engineering soil groups in the state and also to represent the major climatic zones within the state. Both the subgrade soils and the weather were expected to highlight basic differences in unpaved road performance in Indiana.

DETERMINATION OF SIZE OF RATING PANEL

The number of raters is important for reducing errors in the rating. Nakamura *(9)* proposed that if an error of 1.0 can be permitted, just two or three raters would be required. It was shown, however, that as a rule, a panel of 5 to 10 members would be necessary for a representative rating of roads. The use of rating schemes involving panels of 10 or more on a routine

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FIGURE 1 Location of study counties in the state of Indiana.

basis at the local level may present resource and management problems. Such larger-size panels could be used periodically to determine road needs for preparation of road plans. Nevertheless, some form of rating system would still be required for the local highway staff to determine on routine inspection the condition of paved and unpaved roads in their network. Five panel members were in this study.

COMPOSITION OF STUDY RATING PANELS

Raters differ in their perception of road condition, and differences can occur among raters of different professions and backgrounds. Lay raters were found to rate pavements higher than highway engineers *(9)*. This finding was later supported by Yoder and Milhous *(4)*.

In this study, unpaved road sections were rated by two panels. The first panel consisted of five graduate and research engineers from Purdue University who assessed the condition of all roads in each of the five counties. The second panel was expected to be a team of at least three officials, including the engineer, supervisor, or foreman or other county highway official as appropriate; however, only Huntington and Bartholomew counties were able to form rating panels for this study.

Each panel member undertook an independent road condition assessment based on criteria presented after an initial training session.

ASSESSMENT OF RIDEABILITY, DISTRESSES, AND AVERAGE SPEED

Each panel member rated the rideability (ride comfort) of the road surface and assessed the rating and percentage of road surface covered by corrugations, potholes, rutting, gravel loss and looseness, cross section, camber or cross slope, and side drainage. Each member's average travel speed over the section was also calculated. The rating form completed by the panel is shown in Figure 2, and the rating criteria for assessing rideability and gravel road surface distresses are given in Table 1.

Rideability

Rideability was assessed while the rater maintained a speed of 40 mph (64 kph) on each section unless prevailing road conditions required a reduction in speed. This speed was chosen because it was considered the lowest speed limit that an average automobile travels on a good gravel or stone road in Indiana. Most automobiles can usually travel faster than 40 mph. In rating the rideability of the road, care was taken to consider ride comfort alone to avoid any influence of road surface conditions. It was also important that unpaved roads be rated in their own right without comparing the ride with expectations on paved roads. This was emphasized because of the possibility that people not accustomed to driving on gravel and stone roads might rate such roads poorer than individuals with experience of rating or driving on unpaved roads. This aspect was investigated further when the ratings by local officials and the panel from Purdue University were compared.

Ride quality in Table 1 was defined as high, medium, or low as follows:

1. *High.* Vehicle vibrations are noticeable, but no reduction in speed is necessary for comfort and safety; or individual bumps or settlements cause the vehicle to bump slightly with little discomfort.
2. *Medium.* Vehicle vibrations are significant and some reduction in speed is necessary (by up to 10 mph or 15 kph) for safety and comfort; or individual bumps or settlements cause the vehicle to bounce significantly, creating some discomfort.
3. *Low.* Vehicle vibrations are so excessive that speed must be reduced considerably [by 15 mph (25 kph) or more up to 20 mph (32 kph) or less] for safety and comfort; or individual bumps or settlements cause the vehicle to bounce excessively, creating substantial discomfort or a safety hazard or high potential for vehicle damage.

Average Rater Speed

Average rater speed was tested as a possible rating criterion and it was assumed that vehicles will reduce speeds below 40 mph

HIGHWAY EXTENSION RESEARCH PROJECT FOR INDIANA COUNTIES AND CITIES
SCHOOL OF CIVIL ENGINEERING, PURDUE UNIVERSITY

GRAVEL ROAD CONDITION RATING FORM

COUNTY ____________ ROAD NAME/NO. ____________ NAME OF RATER ____________ DRIVER 1 ____________

DATE ____________ WEATHER ____________ DRIVER 2 ____________

ODOMETER READING/ DISTANCE	SECTION NUMBER	TRAVEL TIME (SECS)	RIDE COMFORT (PCR)	CORRUGATIONS		RUTTING		POTHOLES		GRAVEL LOOSENESS		SIDE DRAINAGE		CAMBER/ CROSSFALL	
				RATING	PERCENT SECTION	RATING	PERCENT SECTION	RATING	PERCENT SECTION	RATING	PERCENT SECTION	RATING	PERCENT SECTION	RATING	PERCENT SECTION

FIGURE 2 County unpaved road condition rating form.

TABLE 1 DESCRIPTION OF RATING SPECIFICATIONS

Distress Type	No. Rating	Description	Distress Specification
Rideability	5	Very poor	Ride was very uncomfortable, with several speed changes. Vehicle operation was at low speeds of about 20 mph.
	4	Poor	Ride was uncomfortable. Speed changes of more than 10 mph occurred.
	3	Fair	Speed changes up to 10 mph occurred but ride quality was medium.
	2	Good	Very little speed change on the ride (less than 5 mph) at few locations only.
	1	Very good	It is possible to operate at 40 mph with no change. Ride quality is high.
Corrugation	5	Very severe	Corrugations are more than 2 in. deep. Ride quality is low.
	4	Severe	Corrugations are 1.5 to 2 in. deep. Ride quality is low to medium.
	3	Moderate (fair)	Corrugations are about 1 in. deep. Ride quality is medium.
	2	Slight (good)	Corrugations have just begun. (About ½ in. deep.) Ride quality is medium to high.
	1	Very good	Corrugations are not noticeable. Ride quality is high.
Rutting	5	Very severe	Ruts with mean depth greater than 2 in. Ruts are so bad that vehicles are forced to use ruts or choose other paths.
	4	Severe	Ruts are between 1.5 and 2 in. Vehicle paths are forced.
	3	Moderate	Ruts about 1 in deep. Vehicle paths may be forced.
	2	Slight	Ruts are about 0.5 in. deep. Vehicle paths are barely affected.
	1	Very good	Ruts are barely noticeable or absent.
Potholes	5	Very severe	More than 40 holes within 100 yd or meters. Ride quality low.
	4	Severe	Between 30 and 40 holes in 100 yd or meters. Ride quality is low to medium.
	3	Moderate (fair)	About 20 to 30 holes in 100 yd or meters. Ride quality is medium.
	2	Slight	About 10 holes in 100 yd or meters. Ride quality is medium to high.
	1	Very good	Fewer than 10 holes in a 100 yd or meter section. Ride quality is high.
Gravel looseness	5	Very loose	Gravel or stone is in place but not compacted. Ride quality is low.
	4	Loose	Gravel or stone is in place but is only slightly compacted. Ride quality is low to medium.
	3	Moderate	Gravel is fairly compacted in wheel paths with few loose stones. Ride quality is medium.
	2	Slight (good)	Gravel or stone surface has good compaction with few loose gravel or stone. Ride quality is medium to high.
	1	Very good	Gravel or stone is well compacted. Very little loose gravel exists. Ride quality is high.

(64 kph) if the road condition is poor. Average rater journey speed over the section was determined by measuring the time taken to travel a particular section length. The vehicle odometer was used to determine distances between intersections marking the beginning and end of study road sections. Each gravel road section in the five study counties was rated during field surveys in the summer of 1983. Sections in Tippecanoe county were rated again in 1984.

Roughness Measurements

A portland cement association (PCA) roadmeter supplied by the Division of Research and Training (DRT) of the Indiana Department of Highways (IDOH) was used by DRT staff for measuring roughness on the study road sections. Roughness unit was "counts per mile" measured at a speed of 20 mph (32 kph), which was found to create fewer instrumental problems compared with a speed of 50 mph (80 kph) normally used for PCA roadmeter measurements. Measurements were made over an entire 1-mi (1.6 km) section following the normal practice by the DRT of measuring roughness on 1-mi sections on the state highway network. Calibration was provided from measurements by the DRT on an existing paved road section as well as other measurements relating roughness at various measuring speeds *(10)*.

RESEARCH DESIGN AND STATISTICAL ANALYSIS

The statistical design of the experiment was a Nested Factorial Design with unequal cells. Based on the selection of roads and the panel condition rating procedure adopted, an experimental layout is shown in Figure 3 for Huntington County. A similar design applies to Bartholomew County, which also formed a rating panel. Experimental layout for the other three counties is similar, but excludes county raters.

The dependent variable PCR was tested first for normality then analysis of covariance (ANCOVA) was conducted to determine the effect of counties, roads within counties, sections within roads, and individual raters using the general linear model procedure of the Statistical Analysis System (SAS) computer package *(11)*. The Statistical Package for Social Sciences (SPSS) was used in all other statistical analyses *(12)*.

The analysis of variance showed the interaction between individual panel members and counties to be significant at an α-level of 0.05, thus violating the assumption of additivity required for analysis of variance *(10, 14)*. This interaction was further investigated by plotting the average PCR for each rater in each county. The resulting graph is shown in Figure 4 for the three counties—Bartholomew, Jasper, and Tippecanoe—for which concurrent roughness measurements were taken with panel condition ratings. The crossing of the lines between Raters 1 and 2 depicts some rating inconsistencies introduced by differences in ratings by both Raters 1 and 2 compared with ratings by other panel members. Apart from individual variation in rating by Rater 1, a difference may have been introduced by Rater 2 as a result of a panel member substitution in 1984 for rating assessments in Tippecanoe County. Because the results were inconsistent across counties, the data were analyzed separately.

ROADS / SECTIONS		PANELS: PURDUE 1	2	3	4	5	COUNTY 1	2	3
R1	S1	1*	1	1	1	1	1	1	1
	S2								
R2	S1								
	S2								
R3	S1								
	S2								
R4	S1								
	S2								
	S3								
R5	S1								
	S2								
	S3								
R6	S1								
	S2								
	S3								
	S4								
R7	S1								
	S2								
R8	S1								
	S2								

* NOTE: One rating per panel member on each section

FIGURE 3 Experimental layout—Huntington County example.

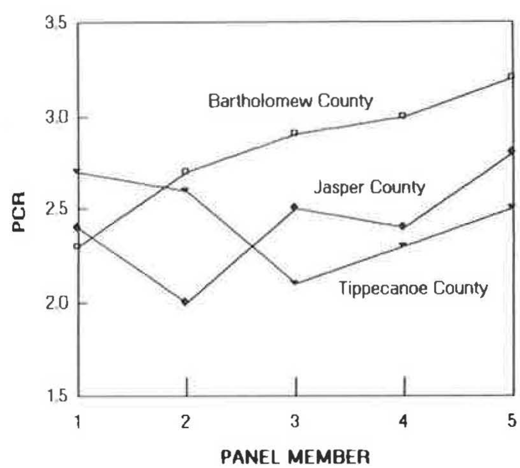

FIGURE 4 Average individual panel member ratings in three study counties.

DISCUSSION OF REGRESSION ANALYSIS RESULTS

PCR, a dependent variable, was analyzed in regression, and roughness number (RN), distress rating variables, and average rater speed were analyzed as independent variables. The results of the analyses are discussed next.

PCR and Roughness

The equations relating PCR and roughness are shown in Figures 5 to 7 for Bartholomew, Jasper, and Tippecanoe Counties, respectively. It should be noted, however, that the PCR rating

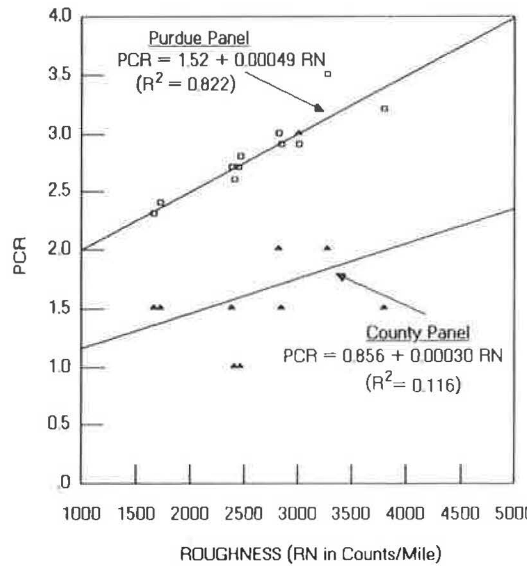

FIGURE 5 PCR versus roughness—Bartholomew County.

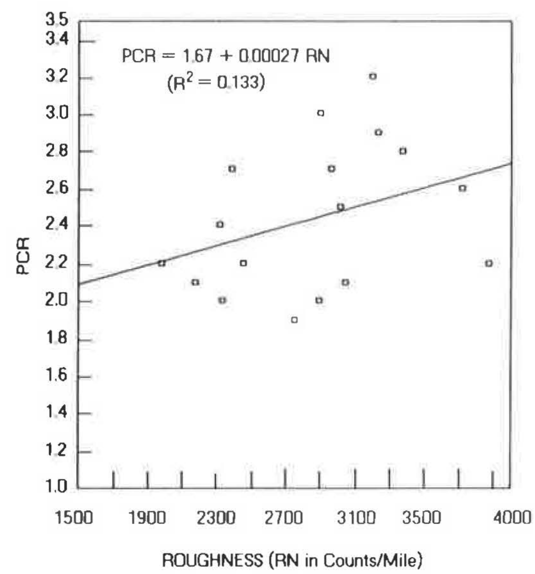

FIGURE 6 PCR versus roughness—Jasper County.

used in this study provides a higher value with worsening rideability (0 to 5). Hence, a perfect road has an effective rating of 0, representing a condition for which the rater feels zero or no discomfort. A very rough pavement approaches a rating of 5. The preceding rating scheme was adopted and considered acceptable after discussions with rating panel members and county highway officials.

A relationship between PCR and the present serviceability rating of AASHO *(1)* is shown in Equation 1.

$$PSR = 5 - PCR \quad (1)$$

In all three counties, there appeared to be a logical relationship between PCR and roughness. PCR increased with roughness as expected. However, the R^2 for Jasper County data was a low of 0.133 compared with ratings for Bartholomew and

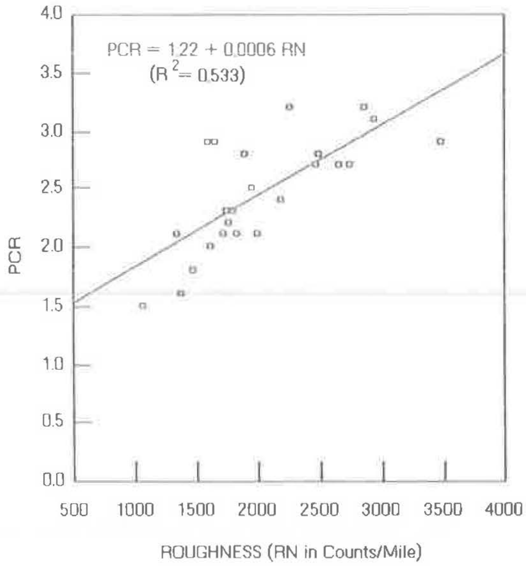

FIGURE 7 PCR versus roughness—Tippecanoe County.

Tippecanoe Counties with R^2 values of 0.822 and 0.533, respectively. The higher variability in Jasper County could be the result of saturated subgrades prevalent in most parts of the county that tended to create an uneven ride and distort the perception of ride comfort.

PCR and Average Rater Speed

The regression relationships between PCR and average rater speed are shown in Figures 8 to 10 for three counties. In general, R^2 values for the PCR and average rater speed rela-

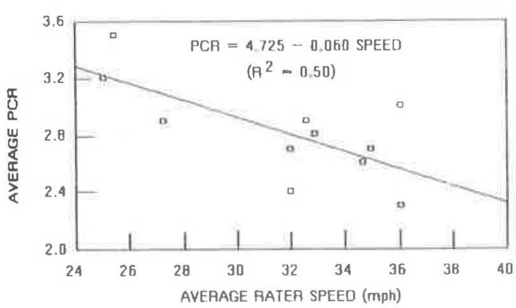

FIGURE 8 Average PCR versus average rater speed—Bartholomew County.

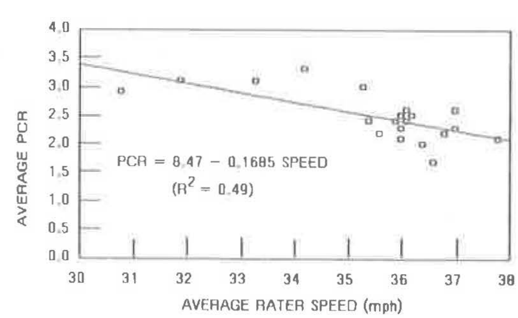

FIGURE 9 Average PCR versus average rater speed—Huntington County.

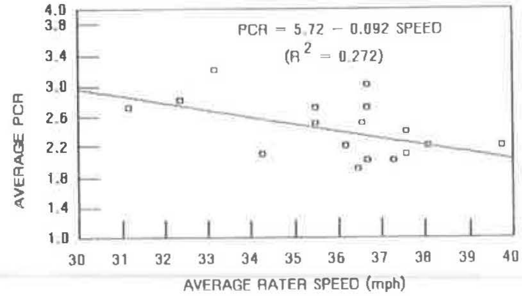

FIGURE 10 Average PCR versus average rater speed—Jasper County.

tionships ranged from 0.05 to about 0.50 for the five counties. Although vehicle speed is affected by worsening road conditions, it was not clearly demonstrated in two of the counties with R^2 values of 0.05 and 0.1. The R^2 values of 0.49 and 0.50 in two counties have demonstrated that a relationship exists between average PCR and average rater speed. However, a wider range of gravel road condition would be required to show the true effect of road condition on speed. The range of unpaved road condition encountered during the studies did not affect speeds enough to highlight any differences.

PCR and Visual Rated Distresses

Visually rated distresses included in the analysis were corrugations, extent of rut development, potholes, and gravel looseness. Each distress condition was given a rating together with an assessment of the percentage of the road section covered by the distress. It was assumed that the remainder of the section had a distress rating of 1 (very good). Equation 2 was used to calculate new ratings.

$$\text{New rating} = \frac{\text{Rating} \times \%\ \text{area}}{100} + (1 - \%\ \text{area}/100) \qquad (2)$$

New rating values ranging between 1 and 5 were estimated for their relationship to PCR.

Effect of Unpaved Road Surface Distresses

The results of regression analysis showing regression constant (β_0), coefficient (β_1), and R^2 values for each distress type are given in Table 2. Visual rating for corrugations exhibited the best relationship to average PCR. PCR increased with worsening or increasing corrugation rating. Similar relationships were obtained for average pothole ratings and gravel looseness. However, the relationships to PCR were not as clearly defined for ruts and gravel looseness as for corrugations. A decrease in PCR values occurred with increasing gravel looseness rating in some counties. The latter may be because gravel or stone is usually applied loose on unpaved county roads. A decrease in gravel looseness as defined in Table 1 depicts improved compaction or dispersal of loose gravel to expose a hardened unpaved road surface crust that would improve the PCR rating. The higher constant and coefficient values for the relationship of PCR to ruts in Bartholomew County could be the result of other factors that were not analyzed.

TABLE 2 REGRESSION OF PCR VERSUS DISTRESS RATINGS FOR FIVE STUDY COUNTIES IN INDIANA

County	β_0	β_1	R^2
	Corrugation		
B[1]	1.043	1.206	.705
H	.865	.957	.475
J	.736	1.112	.265
T	.663	1.267	.325
W	1.716	.831	.427
	Potholes		
B	1.146	1.330	.254
H	1.424	.872	.100
J	.661	1.433	.564
T	.088	2.105	.302
W	1.874	.876	.456
	Ruts		
B	7.479	-4.509	.160
H	2.146	.315	.007
J	-.841	3.168	.163
T	1.330	.881	.070
W	1.893	1.207	.135
	Gravel Looseness		
B	5.149	1.071	.217
J	1.597	.454	.238
H	1.989	.183	.038
T	1.566	.427	.066
W	3.557	-.167	.038

1. B = Bartholomew; H = Huntington; J = Jasper; T = Tippecanoe; W = Warrick

Visual conditions ratings were made from a moving vehicle and as a result, ruts shallower than 2 in. (5 cm) and gravel looseness could not be easily identified. However, ruts deeper than 2 in. (5 cm), which are usually signs of a failing unpaved road surface condition, can be identified more easily from a moving vehicle. Similarly, potholes and corrugations are two easily identifiable distresses that can be visually rated from a moving vehicle even in their early stages of development. Although camber and drainage ratings were recorded to complete the inspection survey, no regression relationships were determined between PCR and the two variables. Rating of gravel looseness, drainage, and camber should be included in the inspection survey, however, to decide side ditching, grading, or major improvement needs based on PCR.

Comparison of Panel Ratings

To compare the ratings of the Purdue University panel and county officials in Bartholomew and Huntington Counties, one-way analysis of variance tests were conducted on the data. Using the SPSS computer packages, homogeneity of variance tests were conducted by applying the Cochran C and Bartlett-Box tests, as well as a range test using the least-squares difference (LSD) procedure *(12, 14)*. The LSD procedure is equivalent to a standard *t*-test because only two means were tested. The results of the analysis for the two counties are given in Tables 3 and 4.

In both cases, the mean of the ratings by the county panel was lower than the mean of the ratings by the Purdue panel. The analysis of variance test showed that the difference between groups was significant in both cases at an α-level of 0.05. The homogeneity of variance tests and the range test also confirmed that apart from average rater speeds for Huntington County, where the differences in variance were statistically significant, all the other variances depicted in the tables can be assumed to differ little, and, hence, the means could be compared. The results of the analysis of the means show that officials in both counties rated unpaved roads with lower PCR (in better condition) than did the Purdue panel. The difference between groups may also be confounded by the differences in the vehicles used for the ratings. County officials used pickup trucks normally used for county highway duties, whereas the Purdue panel used Chevrolet Citation automobiles. The test conditions were considered realistic, however, because the county officials would rate roads under normal working conditions while driving pickup trucks. Relationships obtained using the Purdue University panel may be made applicable to county raters by applying a reduction factor of about 1.

APPLYING THE RATING SCHEME IN ROAD SURFACE MANAGEMENT

Using the relationships determined in this paper, Table 5 was prepared to serve as a preliminary guide in road surface management decisions for selected Indiana counties *(10, 15)*. The simplified decision basis can be easily applied by a typical county, and a PCR or PSR rating scheme can be used.

CONCLUSIONS

Regression relationships were determined between PCR and roughness with R^2 values of 0.822 and 0.533. This confirms that on gravel roads, PCR and roughness are acceptable criteria for representing road condition, and relations exist between PCR and roughness number. Because roughness is an accepted criterion for determining unpaved road condition, PCR (or PSR) may be substituted in the absence of suitable equipment. PCR will enable the ranking of roads by condition, but additional assessment of surface distresses and drainage will be required to enable the improvement required to be accurately determined. Although a logical relationship was found between PCR and average rater speed, additional research using a wider range of road condition is required to confirm the potential use of speed as a rating criterion.

Corrugation and potholes are related to PCR and can be assessed visually. A distress rating and the percentage of the road surface it covers are two measures determined for the preceding distresses to estimate a new rating.

The PCR values used ranged from 0 to 5 with higher values for rougher roads. PCR predictions using equations presented in this paper were determined by the five-member study panel from Purdue. In general, the Purdue panel was found to rate the roads to be in poorer condition than did county officials. Because most of the relationships derived in this paper used the

TABLE 3 COMPARISON OF MEANS OF RATINGS AND AVERAGE SPEEDS OF PURDUE PANEL AND OFFICIALS OF BARTHOLOMEW COUNTY

Statistic	Purdue Panel		County Officials	
	Rating	Average Speed (mph)	Rating	Average Speed (mph)
Number of Sections	50	39	20	20
Mean	2.83	30.64	1.65	34.58
Standard Dev.	0.55	4.26	0.75	4.32
Standard Error	0.08	0.68	0.17	0.97
Range of Values	2-4	21.2-38.3	1-3	22.8-40.
95% Confidence Interval (Means)	2.26 - 2.59	29.3 - 32.0	1.3 - 2.	22.8 - 40.

Homogeneity of Variance and Means Comparison Tests

Test	Rating		Average Speed	
	Test Value	Probability	Test Value	Probability
Cochran C	0.648	.80	.508	.934
Bartlett-Box	2.688	.101	.006	.938
Difference between Means	1.18	-	3.94	-
LSD Range Statistic	.085	-	.648	-

TABLE 4 COMPARISON OF MEANS OF RATINGS AND AVERAGE SPEEDS OF PURDUE PANEL AND OFFICIALS OF HUNTINGTON COUNTY

Statistic	Purdue Panel		County Officials	
	Rating	Average Speed (mph)	Rating	Average Speed (mph)
Number of Sections	95	74	57	55
Mean	2.5	33.49	1.4	41.
Standard Dev.	0.68	2.35	0.53	5.74
Standard Error	0.07	0.273	0.07	0.774
Range of Values	1-4	29.2-43.2	1-3	31.-61.
95% Confidence Interval (Means)	2.36 - 2.64	32.9 - 34.0	1.26 - 1.54	39.5 - 42.6

Homogeneity of Variance and Means Comparison Tests

Test	Panel Rating		Average Speed	
	Test Value	Probability	Test Value	Probability
Cochran C	0.622	.032	.857	.000
Bartlett-Box	4.138	.042	47.55	.000
Difference between Means	1.10	-	7.55	-
LSD Range Statistic	.05	-	1.49	-

TABLE 5 SUGGESTED MAINTENANCE STRATEGIES FOR VARIOUS ROAD CONDITIONS

PCR	Equivalent PSR	Average Speed (mph)	Roughness (counts/mi)	Maintenance Options
1.5	3.5	>40	< 1000	No Maintenance
2.0	3.0	>40	1000 - 1500	Light Grading & Local Repairs
2.5	2.5	36-40	2000 - 3100	Grading & Local Repairs
3.0	2.0	28-35	2900 - 3000	Heavy Grading
3.5	1.5	24-27	3700 - 4000	Rehabilitation * Check Condition for
4.0	1.0	<24	4600 - 5000	Deep Ruts, Gravel Loss & Other Failure Types.

* NOTE: A detailed condition survey will be required to determine the extent of rehabilition required

Purdue panel ratings, a reduction in PCR by a factor of about 1 is required to conform to typical county panel ratings. On the other hand, the low R^2 values obtained by using the county panel data showed the influence of the smaller panel size and the potential variability in the ratings. With experience in applying the rating scheme in five counties, the Purdue panel was likely to conform more closely to the specified rating criteria.

For most local highway agencies, subjective rating schemes are still practical for road condition assessment and screening. Relationships can be determined between the PCR and measured roughness number for each local area. However, it is important to provide a longer training period and to ensure consistency within the same group of raters even though slight differences may occur in some individual ratings. For Indiana counties, preliminary decision guidelines were suggested for road surface management.

REFERENCES

1. W. N. Carey and P. E. Irick. The Pavement Serviceability Performance Concept. *Bulletin 250,* HRB, National Research Council, Washington, D.C., 1960.
2. M. A. Karan, D. H. Kobi, C. B. Bauman, and R. C. G. Haas. Subjective and Mechanical Estimations of Pavement Serviceability for Rural Urban Road Networks. In *Transportation Research Record 715,* TRB, National Research Council, Washington, D.C., 1979, pp. 31–36.
3. R. J. Weaver. Quantifying Pavement Serviceability as it is Judged by Highway Users. In *Transportation Research Record 715,* TRB, National Research Council, Washington, D.C., 1979, pp. 37–44.
4. E. J. Yoder and R. T. Milhous. *NCHRP Report 7: Comparison of Different Methods of Measuring Pavement Condition.* Interim Report. HRB, National Research Council, Washington, D.C., 1964.
5. J. W. Lund and L. G. Hendrickson. Performance Rating for Aggregate-Surfaced Roads. In *Highway Research Record 311,* HRB, National Research Council, Washington, D.C., 1970.
6. J. B. Nick and M. S. Janoff. Evaluation of Panel Rating Methods for Assessing Pavement Ride Quality. In *Transportation Research Record 946,* TRB, National Research Council, Washington, D.C., 1983, pp. 5–13.
7. *A Comprehensive Study of Roadmeter Roughness Number with Riding Comfort for Indiana Pavements.* Final Report. Report FHWA/IN/RTD–85/1. Division of Research and Training, Indiana Department of Highways, West Lafayette, July 1985.
8. B. G. Hutchinson, Principles of Subjective Rating Scale for Construction. In *Highway Research Record 46,* HRB, National Research Council, Washington, D.C., 1963.
9. V. F. Nakamura. *Serviceability Rating of Highway Pavements.* M.S. thesis. Purdue University, West Lafayette, 1961.
10. J. D. N. Riverson. *Unpaved Road Maintenance Management in Local Highway Systems.* Ph.D. dissertation. Purdue University, West Lafayette, Ind., Dec. 1985, pp. 165–289.
11. *SAS User's Guide 1982.* SAS Institute, Inc., Raleigh, N.C., 1982.
12. N. H. Nie, C. H. Hull, J. G. Jenkins, K. Steinbrenner, and D. H. Bent. *Statistical Package for Social Sciences.* McGraw-Hill, New York, 1975.
13. J. Neter, W. Wasserman, and M. H. Kunter. *Applied Linear Statistical Models.* Regression, Analysis of Variance, and Experimental Design. Richard Irwin, Inc., Homewood, Ill., 1985.
14. V. L. Anderson and R. A. Maclean. *Design of Experiment: A Realistic Approach.* Marcel Dekker, Inc., New York, 1974.
15. J. D. N. Riverson, Local Unpaved Road Surface Management in Indiana. *Proc., 72nd Annual Purdue Road School,* West Lafayette, 1986.

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A Microcomputer Program to Assist in Low-Volume Road Rehabilitation Decision Making

RONALD W. ECK

An approach to optimizing expenditures of road rehabilitation funds is outlined using U.S. Forest Service roads in the Appalachian region as an example. Main components of the approach are a technique for identifying deficient road links, a line deterioration model, and a network investment strategy optimization model. The focus of this paper are the details of a guided decision-making tool for determining whether a road link is a candidate for upgrading. From a list of physical and operational roadway characteristics warranting upgrading, a flowchart was developed to encourage engineers or planners to think in a logical step-by-step fashion about the rehabilitation needs of a particular roadway link. An interactive microcomputer program has been written for both the Apple and IBM PC computers to facilitate use of the model. By considering one link at a time and answering yes or no to questions about roadway characteristics, the user branches through the program until reaching one of two possible outcomes: (a) upgrading is not warranted, or (b) upgrading is warranted and the link should be included in the network optimization model. Program output is a list of those road links in a jurisdiction that are candidates for rehabilitation. The paper contains a detailed flowchart of the model. Although originally developed for the Appalachian region, the model is flexible enough that it can be easily modified or enhanced based on local conditions and the experience of the user.

Low-volume rural roads, those carrying 400 vehicles/day or fewer, are vital to the U.S. economy. State farm-to-market roads, county roads, and township roads provide the accessibility required by agricultural commerce. Forest and park roads are necessary for the operation, maintenance, and accessibility of forests and parks.

Although low-volume roads in the United States carry only about 8 percent of total highway travel, they are economically important because they constitute more than two-thirds of public highway mileage *(1)*. Because the limited financial resources available have to be spent over so many miles, low-volume roads have historically been designed and operated at minimal cost. Most of the existing low-volume road system has been built using design, operational, and maintenance practices that have evolved from subjective experience and judgment rather than from an objective evaluation of quantifiable performance. Because they are the largest single class of highways, objective guidelines for design, operation, and maintenance of low-volume roads are imperative to optimize the use of available funds.

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Properly designed low-standard earth and gravel roads are usually adequate to handle the initially imposed traffic. Over time, however, such roads may become deficient. For example, under conditions of increasing traffic volume (perhaps due to change in functional use), maintenance and vehicle operating costs increase, making it necessary to consider upgrading the road. Other factors that may cause roads to be considered as deficient include inadequate geometrics, poor drainage, inadequate bridges, and weak subgrade soils. In view of these factors, agencies responsible for low-volume roads must continually analyze their road networks to identify and upgrade deficient road links. However, it should be noted that by law most local agencies deal with either maintenance or construction in most cases. There is a definite need for a third category of activity, that of rehabilitation.

Within the low-volume road network of a particular jurisdiction are many road links. For purposes of discussion, a road link is defined as a length of road with uniform characteristics. Because the road network, for the most part, is composed of low-cost, low-volume links, its management is quite different from that of higher type road networks. The planner or engineer must always be aware of the adverse effects that are sometimes caused by the special constraints and characteristics of low-volume roads.

At one or more times during the life of some of these road links, major construction or reconstruction activities may be needed to provide the level of service desired. However, within a planning period, if the needed upgrading efforts are not scheduled with sound engineering judgment, the road links may deteriorate substantially. This deterioration not only increases recurring maintenance and vehicle operating costs, but makes the cost of upgrading greater in the end as well.

The economic evaluation of maintenance and upgrading activities is based on the premise that the role of maintenance is not merely to preserve the road. Rather, it is to keep the road in a condition that permits vehicles to operate at the cost level at which the total transport cost is lowest. Total transport cost is the sum of the construction, maintenance, and vehicle operating costs *(2)*. This combination implies a systems maintenance effort, that is, drainage structures must function, brush must be controlled, and slides and slumps must be repaired.

Routine maintenance is used here to refer to those items regularly performed by maintenance crews throughout the year. Examples of routine maintenance include blading and smoothing the surface, patching isolated areas where surface material has been lost, cleaning and repairing culverts, cleaning ditches, cutting vegetation, and repairing bridge decks and railings. Scheduling and performing this work normally are responsibilities of the front line supervisors of the crews, within the overall plan and budget.

As used here, upgrading and rehabilitation refer to the more extensive maintenance and construction activities that are required only every several years. Examples include resurfacing with gravel, paving a gravel road, resurfacing a paved link, modifying geometrics, and replacing a bridge structure. Because these activities are usually expensive, authority for planning and scheduling rests with someone higher than first-line supervisors.

Typically, funds are not sufficient to meet all of the upgrading needs. The engineer or planner must therefore decide not only what schedule of upgrading is appropriate for each deficient road link, but also which links require an investment in upgrading at all. In addition, political realities of public pressure and political influence may require that certain upgrading activities be planned regardless of other indications.

This study was undertaken to try to develop an objective, technically sound methodology, applicable to forest roads in the Appalachian region, for identifying deficient road links and for determining optimum timing for their upgrading. The methodology, which is an aid in the decision-making process, addresses the following questions.

1. Which of the road links within a jurisdiction may warrant upgrading at some time during the planning period?
2. Within this period, what would be the optimal schedule for implementing the needed upgrade for each link so as to minimize the total costs for upgrading, maintenance, and vehicular operation of the entire plan?

Although there is a brief discussion of the systems approach used to meet the second objective, the focus of this paper is primarily on the first objective, that is, identifying links that are candidates for upgrading.

LITERATURE REVIEW

This section contains the results of that portion of the project literature review concerned with identifying factors that affect road-upgrading decision making in general and in the Forest Service road network of the Appalachian region in particular. A number of researchers have investigated the inclusion of a variety of factors related to decisions about upgrading or rehabilitating low-volume roads. Because space does not permit a complete review of the literature, only the major references pertinent to the study in question are presented.

Among the most prominent research that has been conducted relative to improvement investments on low-volume roads have been that of Robinson et al. *(3)* and Parsley and Robinson *(4)*. Their efforts have been helpful in defining factors pertinent to optimum timing of road-upgrading activities. The factors identified in their research were used to predict surface deterioration, rehabilitation costs, maintenance costs, and road user costs. Some of the general categories of factors considered were the following: route location, road design standards, terrain information, properties of construction materials, construction unit costs, environmental factors, vehicle operating costs, traffic and vehicle loading data, maintenance policy, and maintenance unit costs. These factors were considered relative to earth, gravel, and paved roads.

Three references in the literature were valuable in assisting the researchers in determining factors relevant to the optimal timing problem in the Appalachian region. Howlett and Hudson et al. enumerated many factors characteristic of low-volume roads that are not characteristics of higher type roads *(5, 6)*. In addition, they mentioned some special factors that are unique to the management of Forest Service roads.

Koger's report included a thorough review of Forest Service literature related to the construction, rehabilitation, and cost of Forest Service logging roads in the Appalachian region *(7)*. His review resulted in a lengthy list of important factors affecting road construction and location. Major categories of factors included topography, soils and geology, road standards, and maintenance policies. In addition, Koger presented the following list of conditions, characteristic of many Forest Service roads in the Appalachian region, that may present construction or maintenance problems *(7)*.

- Low or swampy areas,
- Long level sections with poor drainage,
- Rocky areas,
- Steep side slopes requiring large cuts and fills,
- Sharp curves or switchbacks,
- Steep grades,
- Streambeds and frequent stream crossings,
- High water tables with many springs and seeps,
- High natural soil erosion and slope instability, and
- Northern exposure.

From the literature review, the researchers identified many factors relevant to road-upgrading decision-making in the Appalachian region. The following list of factors was believed to be pertinent by the researchers.

Age of roadway surface
Annual maintenance costs
Construction costs
Degrees of roadway deterioration:
  Roughness
  Rut depth
  Cracking
  Gravel loss
  Patching
Delay costs
Design standards
Gradient
Horizontal curvature
Maintenance policy
Material costs
Performance rates (equipment and staff)
Planning horizon
Resource (equipment and staff) availability
Roadway surface type
Roadway width
Soil characteristics
Traffic control
Traffic loads

Traffic volume (ADT) and composition
Vehicle running costs:
  Fuel
  Oil
  Depreciation
  Maintenance
Vehicle speeds
Vehicle types
Weather:
  Temperature
  Rainfall

In developing the list, all variables that were enumerated in the literature review were evaluated to determine their suitability to the problem of modeling road-upgrading decision making. Evaluation of factors was based on appropriateness of the variable to the Appalachian region and on data availability. The list contains only those physical factors and operational characteristics of road links that can be quantified. For example, although social or political pressure may play an important role in determining when a road is upgraded, this factor has not been added to the list because it is difficult to quantify. The factors on the list were included because over an extended planning period they affect road-upgrading decision making in one way or another. For example, traffic loads, maintenance policy, roadway surface type, and weather factors all affect road surface condition, which in turn affects upgrading costs, routine maintenance costs, and vehicle operating costs. Because the list developed was too lengthy to be used in its entirety in the modeling process, it was reduced in size by combining some factors into fewer categories and by eliminating other variables.

PROBLEM APPROACH

The basic approach to achieving the objectives outlined earlier is shown in the flowchart in Figure 1. The first step in the procedure is to identify the set of road links under study along with the physical and environmental characteristics and operational status of each link. The planning period (in years) is also established. Using the decision-making framework to be described here, those links that are, or may soon become, deficient are identified using the candidate link identification model. These links are considered candidates for the upgrading and rehabilitation funds. Knowing the candidate links and their deficiencies, a number of feasible alternative link investment strategies can be generated. A link deterioration model is needed at this point to determine how the various road links will degrade over time, given certain climatic and soil characteristics and a specified maintenance or upgrading strategy. This deterioration may have to be estimated from local experience because at the present time there is no universally applicable roadway deterioration model.

As noted by Harral et al. *(8)*, road deterioration is a function of original surface design, material types, volume and axle load configuration of traffic, climate, and maintenance policy. Although extensive research has been conducted in North America, Europe, and Australia into the performance of

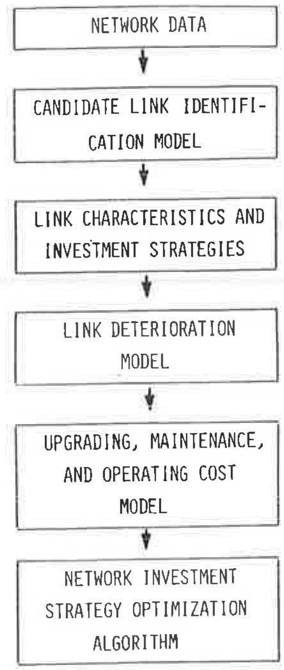

FIGURE 1 Form of approach taken to address optimal timing problem.

high-standard pavements, only limited research has been carried out on low-standard pavements. Deterioration of unpaved roads is measured in terms of surface roughness, rutting, depth of loose surface material and, for gravel roads, loss of gravel. Deterioration is caused by two factors: traffic and time-related weathering effects. Only limited data are available relative to isolating the time-related weathering effect from the traffic effect.

Similarly, the impacts of different levels of maintenance expenditures on road condition and subsequent deterioration, and, hence on road user costs, have only recently been measured scientifically. Such relations are not yet well established for the complete range of maintenance activities, traffic, and environmental conditions found throughout the United States. Considerable progress has been made in recent years through the research process. Some of the results have been reported in the proceedings of the Third International Conference on Low-Volume Roads *(9)*.

With the deterioration data, costs of implementing each link investment strategy can be estimated for the set of candidate links, including upgrading and vehicle operating costs. These two major elements of the economic evaluation are difficult to determine exactly. Thus, the experience, competence, and judgment of the engineers play a key role in system management. The total net present value of each category of costs associated with each link investment strategy is computed. Using these costs as input to a zero-one integer programming model, the network investment strategy, that is, the set of strategies that minimizes the total costs for a given budget, is identified.

IDENTIFYING LINKS FOR UPGRADING

An effort was made to refine the approach just described and apply it to roads within the Monongahela National Forest in

West Virginia. However, even before local deterioration models or appropriate integer programming models could be developed, it was believed that a better decision-making process was needed for identifying road links that were candidates for upgrading. Of most value to engineers and planners would be some type of guided decision-making scheme using specific objective criteria and based on link information already available.

The list of factors in the road-upgrading decision compiled from the published literature was reviewed with Forest Service engineers. These discussions identified other variables and quantitative criteria for road upgrading. Thus, a final list of conditions warranting upgrading was prepared. A flowchart format appeared to be the most appropriate way to adapt this information to practitioner needs. Using this format, a decision-making guide was developed. By structuring the analysis process, the format permits doing with the computer what has previously been done manually.

The flowchart aids in identifying common deficiencies characteristic of road links in the Appalachian region that would indicate that a link should be considered as a candidate for upgrading. Information on the following link characteristics was included in the flowchart:

- Stream siltation,
- Gating,
- Forecasted use,
- Surface type,
- Surface condition,
- Number of lanes,
- ADT,
- Drainage,
- Horizontal curvature,
- Sight distance,
- Turnouts,
- Roadway width,
- Bridge adequacy, and
- Subgrade soils.

Note that most of the information included is of the type with which the analyst would be familiar based on the analyst's experience with the road system or that could be acquired through standard condition surveys.

By considering one link at a time and answering yes or no questions about the characteristics noted, the engineer or planner branches through the flowchart until reaching one of two possible outcomes: (a) upgrading is not warranted, or (b) upgrading appears warranted and the link should be included in the network optimization model. Output is a list of those road links in a jurisdiction that are candidates for upgrading or rehabilitation.

A draft version of the flowchart was prepared and reviewed by Forest Service engineers. Suggestions made for improving the flowchart were incorporated into the final form of the model. The decision-making flowchart is shown in Figure 2.

Caution must be used in interpreting output from the model. There may be links for which the model indicates upgrading is not warranted when in fact it should be considered and vice versa. Experience of the engineer plays a major part in determining how effectively the flowchart meets its intended objectives. It must also be kept in mind that the flowchart has been developed for the Appalachian region. Users elsewhere may find some sections inappropriate or feel a need to include some additional capabilities. Because it is relatively easy to make such modifications, the model's flexibility as a decision-making aid is enhanced.

The logic of the process, shown in flowchart form in Figure 2, was such that it was relatively easy to develop an interactive microcomputer program to implement the model. Both an Applesoft BASIC for the Apple II computer and a Microsoft BASIC for the IBM PC are available from the author. The former operates on a 48K Apple II microcomputer with one disk drive under the DOS operating system. The MS BASIC version requires an IBM PC or compatibility with at least 128K RAM, one disk drive, and MS-DOS.

Once the candidate links and their deficiencies have been identified, the analyst can generate several different feasible alternatives for upgrading each link. For example, given a road that needs to be surfaced with gravel, a strategy must be considered that reflects different schedules of when the graveling is to take place.

The zero-one integer programming optimization algorithm (work on which is still in progress) requires as input costs of different link design and maintenance options, including different time-staging strategies. Costs associated with each investment strategy are those for the upgrading activities, recurring maintenance activities, and vehicular operation. These costs, which will be the basis for making upgrading decisions, are dependent primarily on the rate of deterioration of the road. Additional discussion of integer programming is beyond the scope of this paper. Interested readers are encouraged to consult texts on operations research for more information about integer programming and available computer programs for handling such problems.

CONCLUSIONS AND RECOMMENDATIONS

The candidate link identification flowchart and the microcomputer program can help engineers and planners identify road links that warrant upgrading. It is an easy-to-use interactive program that can be used by persons with little or no computer background. However, the model does require that the user be familiar with the links being evaluated. Although not a panacea, the program forces the user to think in a logical step-by-step fashion about the upgrading needs for a particular link. When used with experience and judgment, the model should result in decision making that is improved over previously used subjective approaches. The program should not be applied blindly; it is intended to be a flexible tool, really a starting point, that can be modified, changed, or enhanced based on local conditions and the experience of the user.

The guided decision-making model for identifying links warranting upgrading was developed for the Appalachian region. Although the microcomputer program has been used by Forest Service engineers in Monongahela National Forest, a formal evaluation has not been conducted. It is recommended that the flowchart be applied to a low-volume road network so that its usefulness can be evaluated. Undoubtedly, certain modifications will need to be made. The applicability of this tool to forest roads in other areas of the country should be investigated.

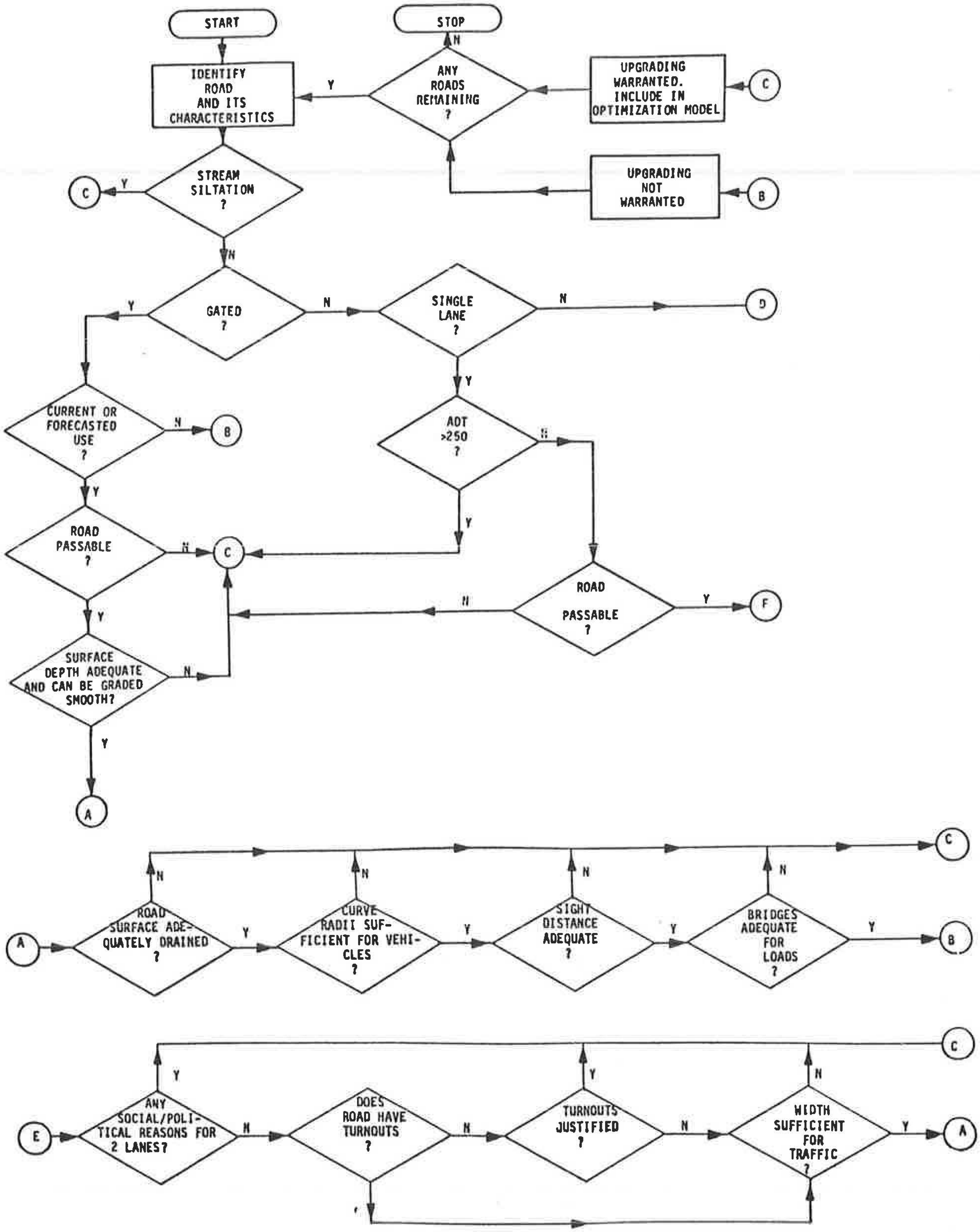

FIGURE 2 Decision-making process for identifying road links in Appalachian region warranting rehabilitation.

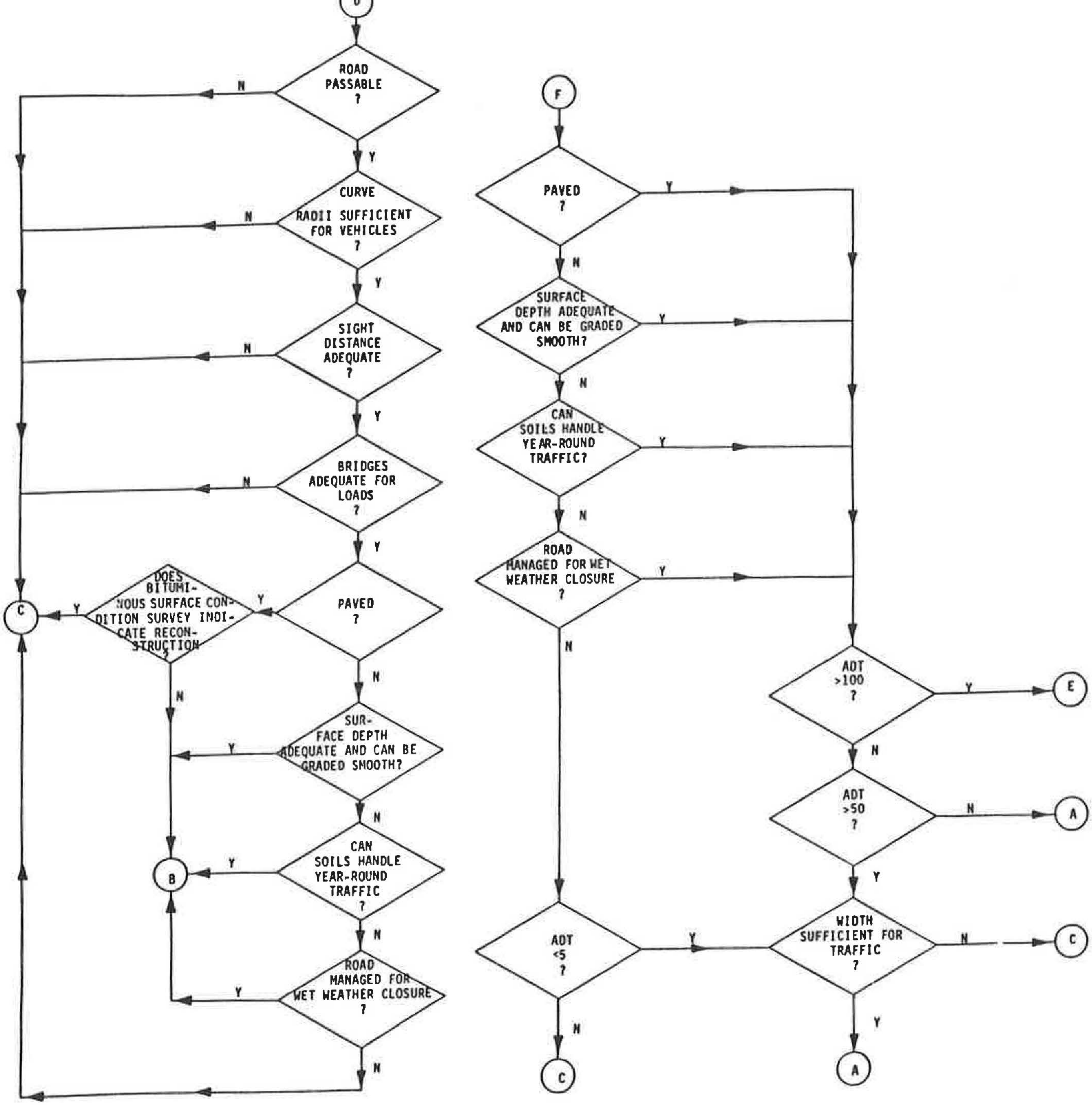

FIGURE 2 *continued*

No approach to the problem of optimum timing for road upgrading can be considered complete without some sort of link deterioration model. Such a model uses various input data to predict the deterioration of a road surface as time passes and as vehicles travel over the road. This is vitally important in decision making because vehicle operating costs are significantly affected by road surface condition. Likewise, the life of the roadway and future rehabilitation costs are heavily dependent on the level and timing of maintenance, which in turn is a function of road deterioration. The approach developed herein lacks this component because at present, there is no suitable forest road surface deterioration model for the Appalachian region.

Assuming that the optimization model currently under development can be implemented successfully and that a link deterioration model can be developed, it would be desirable to assemble a complete package of computer models for a comprehensive approach to the problem. The link identification model has already been implemented on a microcomputer. The link deterioration model and optimization algorithm would also be computer based. Development of a computerized costing algorithm and linkages between the models would be the only items needed to provide a complete computer package for low-volume road maintenance management.

ACKNOWLEDGMENTS

This paper is based on research supported by funds provided by the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Special thanks are extended to Randall Burks who worked on the network investment strategy optimization algorithm. Appreciation is also expressed to the staff of Monongahela National Forest and the Northeastern Forest Experiment Station for their assistance and cooperation throughout the study.

REFERENCES

1. J. C. Glennon. *NCHRP REPORT 214: Design and Traffic Control Guidelines for Low-Volume Rural Roads.* TRB, National Research Council, Washington, D.C., Oct. 1979.
2. *Transportation Technology Support for Developing Countries, Compendium 11—Decision Methodology for Maintenance and Upgrading: Costs, Traffic, and Benefits.* TRB, National Research Council, Washington, D.C., 1980.
3. R. Robinson, H. Hide, J. W. Hodges, J. Rolt, and S. W. Abaynayaka. *A Road Transport Investment Model for Developing Countries.* TRRL Report 674. Transport and Road Research Laboratory, Crowthorne, Berkshire, Great Britain, 1975.
4. L. L. Parsley and R. Robinson. *The TRRL Road Investment Model for Developing Countries (RTIMZ).* TRRL Report 1057. Transport and Road Research Laboratory, Crowthorne, Berkshire, Great Britain, 1982.
5. M. R. Howlett. *Special Report 160: Managing A 200,000-Mile Road System: Opportunity and Challenge.* TRB, National Research Council, Washington, D.C., 1975, pp. 53–61.
6. W. R. Hudson, T. G. McGarragh, and A. Pelzner. *Special Report 160: A Pavement Management Concept for Low-Volume Roads.* TRB, National Research Council, Washington, D.C., 1975, pp. 230–244.
7. J. L. Koger. *Factors Affecting the Construction and Cost of Logging Roads.* Technical Note B–27. Division of Forestry, Fisheries and Wildlife Development, Tennessee Valley Authority, Norris, Tenn., Dec. 1978.
8. C. G. Harral, P. Fossberg, and T. Watanatada. *Evaluating the Economic Priority of Highway Maintenance.* Transportation Department, World Bank, Washington, D.C., 1977.
9. Low-Volume Roads: Third International Conference. In *Transportation Research Record 898,* TRB, National Research Council, Washington, D.C., 1983.

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Rating Bridges on Low-Volume Roads

CARL E. KURT

The rating of an existing bridge on a low-volume road can be a very labor-intensive assignment. Because most bridges on low-volume roads are located in local jurisdictions, resources for computers and bridge inspections and repairs are limited. Therefore, to increase the productivity and improve the rating procedure, a software system has been developed to run on microcomputers. This system is made up of two programs, KU-SBAR and KU-STAR, written to rate simple and continuous span girder-type and simple truss bridges. Both programs follow AASHTO rating procedures. Five standard AASHTO trucks and one user-defined truck are supported. A wide range of output options is provided to the user. These include a rating summary, moments, shears and reactions, member stresses, and nodal deflections. The system was run on microcomputers with two different microprocessors. One was found to run approximately 2.5 times faster than the other. It was demonstrated that analyzing and rating existing bridges on low-volume roads is feasible with the aid of a microcomputer. Although the analysis and rating phase is only a portion of the entire rating process, the use of the bridge rating system described is one means of improving productivity and rating options for transportation officials and engineers.

The Code of Federal Regulations *(1)* requires each bridge in the United States to be inspected and rated every 2 years. In this paper a bridge is defined as a structure that carries moving traffic and has an opening measured along the center of the roadway of more than 20 ft between undercopings of abutments, spring lines of arches, or extreme ends of openings for multiple pipes. There are approximately 586,000 bridges in the United States; nearly 270,000 are on the Interstate or state road systems. The remaining 317,000, or 56 percent, are city, county, or township bridges *(2)*. The majority of these bridges are located on low-volume roads, although many of them do have heavy volumes of traffic.

In rural areas, these bridges may not be subjected to any higher loads than a large pickup loaded with hay or feed. However, during harvest time, very large trucks with heavy loads travel to the area. These bridges must be properly rated and signed. Because most bridges on low-volume roads are located in local jurisdictions, resources for computers and bridge repairs are limited. With the high-technology products on the market today, the price of microcomputers is within the budgets of most organizations. The computing power of these machines, which are compact enough to sit on the desk of the user, is often as high as the mainframes of a few years ago. These microcomputers are relatively easy to use. What is required for these computers to be useful to transportation officials and engineers responsible for inspecting and rating low-volume bridges is well-designed software. This need was the motive for the development of the bridge analysis and rating system described in this paper.

This system was developed to aid local transportation officials and consulting engineers in rating single- and continuous-span girder-type and simple-truss bridges. Other objectives were to eliminate the tedious calculations required to rate an existing bridge and to provide for better estimates of the allowable rating for these bridges.

RATING PROCEDURES

Throughout the development of this system, the analysis and rating procedures given by AASHTO *(3, 4)* have been followed as closely as possible. AASHTO permits each highway bridge to be rated at two levels. The lower level, inventory rating, is the load level that can safely use an existing structure for an indefinite period of time. The higher level, operating rating, is defined as the absolute maximum permissible load level that can be safely carried by an existing bridge. Bridges posted at the operating rating are safe to carry trucks at that weight level, but the life of these bridges could be reduced because of fatigue considerations. To estimate the reduction in useful life when increasing the allowable load, the existing fatigue design criteria found in the "Standard Specifications for Highway Bridges" *(4)* can be modified. For bridges on low-volume roads, the volume of traffic is often so low that fatigue is not a serious consideration in the rating decision.

AASHTO provides two methods for rating an existing bridge: the working stress method, in which the stresses induced in the bridge members should not exceed the allowable stress for that member, and the load factor method, in which the rating of a bridge is based on a strength criterion; that is, that the sum of the appropriate loads multiplied by load factors shall not exceed the strength of the bridge member. Both methods have their advantages and disadvantages. They also provide slightly different rating values. The system described in this paper is based on the working stress method. However, it would not be difficult to expand the system to allow the user to select either method for rating an existing bridge.

The primary loads considered when rating an existing bridge on a low-volume road are dead, live, and impact loads. These loads cause stresses in each bridge member. For each load type, the loads in an individual member can be expressed in the following general formula:

$$SF = DL + W \times LL \times RE \times DF \times (1 + I) \quad (1)$$

where

SF = structural function for bending moment, shear, reaction, and axial forces;

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DL = structural function due to dead loads;
W = truck weight;
LL = structural function due to a unit-live-load truck;
RE = reduction factor for multilane bridges;
DF = distribution factor; and
I = impact factor.

The reduction factor, RE, accounts for the fact that every lane of a multilane bridge is not loaded with trucks of maximum weight. Therefore, AASHTO permits a reduction in member live loads for these multilane bridges. The reduction factor is equal to 1 for one- or two-lane bridges. A 10 percent reduction is permitted for three-lane bridges and a 25 percent reduction is permitted for bridges with four or more lanes, that is, RE = 0.90 and 0.75, respectively. Most bridges on low-volume roads are rated for one or two lanes of traffic.

To determine influence of a truck wheel on an individual member, AASHTO *(4)* developed a table of distribution factors. For girder bridges, the distribution factor is a function of the following bridge parameters: bridge girder material, deck material, number of traffic lanes, and girder spacing. AASHTO requires that different distribution factors be used for interior and exterior girders. For each condition, a formula is given to calculate the distribution factor. If the girder spacing is large, the distribution factor is calculated from simple statics.

In rating a bridge on a low-volume road, it is a matter of judgment whether the bridge should be rated for one or two lanes. For typical girder spacing, the distribution factor for bridges designed for one traffic lane is from 7 to 27 percent lower than the distribution factor for bridges designed for two or more lanes. Although these differences in distribution factors are small, they could have a significant impact on the resulting allowable truck rating weight.

AASHTO provides some guidance for determining if the bridge should be designed for one or two traffic lanes. For roadway widths less than 18 ft, the bridge will carry only one traffic lane. For roadway widths greater than 18 ft, the bridge should carry at least two traffic lanes. However, there is an exception that is applicable to low-volume roads. It states that when "conditions of traffic movement and volume would warrant it, fewer traffic lanes than specified by AASHTO may be considered" *(3)*. This exception allows the engineer to use some judgment with regard to the correct distribution factor. If the bridge is narrow and two trucks can pass, it is unlikely that they will be traveling at maximum legal speeds. Thus, the impact factor may be too high if a two-lane distribution factor is used. If the bridge is narrower than the roadway surface, one vehicle usually allows the other to cross the bridge before proceeding.

For truss bridges, the distribution factor is a function of centerline truss spacing, roadway width, and number of traffic lanes. A formula for this distribution factor can be found in the "Manual for Maintenance Inspection of Bridges" *(3)*. For both bridge types, the distribution factor defines the percentage of the wheel loads carried by an individual member or truss.

The last general parameter to be discussed is the impact factor. Because trucks move as they cross a bridge, a dynamic interaction between the truck and the bridge occurs. Because of this dynamic interaction, additional loads called "impact loads" are induced in bridge members. These impact loads are expressed as a percentage of the loads introduced by the truck weight. The primary bridge parameter needed to calculate the impact load is the bridge length. The impact factor is calculated from the AASHTO formula

$$I = \frac{50}{L + 125} \quad (I \leq 0.3) \tag{2}$$

where L is span length *(4)*.

The impact load does not need to be larger than 30 percent of the truck load. For all bridges, the impact factor is 0.30 if the bridge length is below 41.6 ft. Many low-volume bridges are shorter than 41.6 ft and, therefore, are rated with a 30 percent impact factor. When evaluating the negative moments over interior support of continuous bridges, the span length, L, is the average length of the two adjacent spans. Although not a part of the current system, the impact factor for timber bridges can be neglected.

SYSTEM CAPABILITY

The bridge rating system developed can evaluate two types of bridge structures. KU-SBAR, a program of the system, is designed to analyze and rate single and continuous, up to three-span, girder-type bridges. These bridges are typically found on low-volume roads. KU-SBAR can accommodate noncomposite steel girders, composite steel girders, and concrete T-beam bridges.

KU-STAR, the other program of the system, is designed to analyze and rate simple steel truss bridges. Although five-truss configurations are automatically supported, the program has the flexibility to support truss bridges with any generalized configuration.

Although these two programs support different types of bridges, they were developed with many common features. Both programs were written in BASIC. Although computer graphics was not a major factor in the development of this system, graphic displays are used to improve user understanding and efficiency.

One common feature of the programs is the way loads are handled. Because impact loads are developed from live loads, only dead and live loads must be determined to rate most low-volume bridges. Dead loads are those loads associated with the dead weight of the bridge and include the dead weight of the main structural members, floor beams, stringers, deck, guard rails, and overlays. If there is dirt or gravel on the bridge deck, an allowance for the dead weight of this material should be included.

Live loads are those loads associated with bridge use. These loads consist of one or possibly several trucks placed in each bridge lane. The second condition is called a lane load. In general, the single-truck condition is critical for shorter bridges and the lane load condition is critical for longer bridges.

Five standard AASHTO-defined truck configurations can be used to rate a bridge system. They are H, HS, 3, 3S2, and 3-3. Trucks H and HS are the primary trucks used in the design of new bridges. The distribution of the axle weights and spacing are important parameters that affect bridge member loads.

These parameters are shown in Figure 1 for the five standard AASHTO trucks.

In the HS truck, the distance between the second and third axles is permitted to vary. The location of the third axle used to rate an existing bridge is the position between the extreme values that causes the maximum structural function to occur. In KU-SBAR, this third axle is placed within the extreme values in 2-ft increments. In KU-STAR, this load is placed at every node along the roadway within its allowable spacing.

For H and HS trucks, lane loads must also be considered. These lane loads are approximated by a uniform load and a concentrated load. Both types of loads are placed on the bridge so that the extreme values of the structural function (plus and minus) occur.

For negative moments over an interior support of a continuous bridge, AASHTO *(4)* requires that a second concentrated load be placed on an adjacent span so that maximum negative bending moment occurs over the support. The magnitude of the concentrated loads are lower for moment calculations than for shear and reaction calculations.

To determine the maximum structural functions, each truck is moved across the bridge in steps. For girder-type bridges, the front axle is placed at 10 intermediate stations along each span. In addition, the truck is placed so that the front axle is off the bridge with only the back axles located on the bridge. This truck placement, which is important for short bridges on low-volume roads, is especially important if the weight on the back axles is large. For simple-truss bridges, the truck is placed so each axle is at every node along the roadway.

When the truck has moved across the bridge facing one direction, both programs automatically turn the truck around and move it in the opposite direction. For each member or

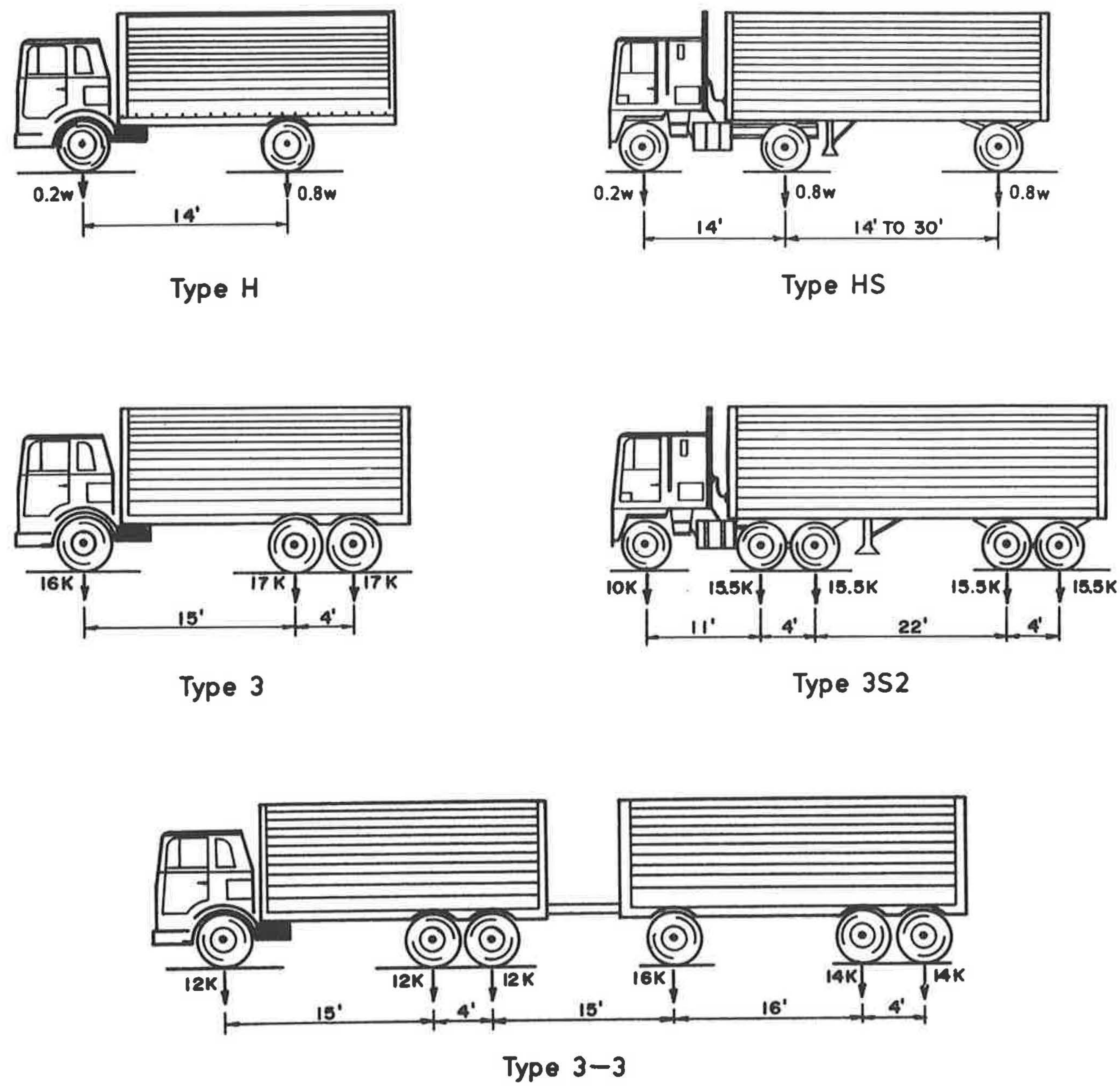

FIGURE 1 Standard AASHTO trucks.

station, the maximum and minimum structural functions are identified. These extreme member loads are important when the rating procedure is conducted.

The next important features to be discussed are the properties of the bridge materials. Because the two bridge types handled by this bridge rating system are so different, each program is described separately. For specific information about the programs, the user is referred to the corresponding users' manuals *(5, 6)*.

KU-SBAR

Analysis and rating of simple and continuous girder bridges of up to three spans are carried out by KU-SBAR, which currently supports noncomposite steel girders, composite girders, and concrete T-beams. A typical cross section of each bridge type is shown in Figure 2. Because the cross-sectional properties may vary along a span, the program was written to accommodate prismatic and nonprismatic girder members.

If the member is prismatic, the member properties are requested only once for each span. If the member properties in a span vary, the user has several options for entering cross-sectional properties. First, the user may individually define the member properties at 10 different locations along the span. If the member has a prismatic section, KU-SBAR requires the input of member properties for that prismatic section only once. The program automatically generates the section properties for the other stations in the prismatic region. This approach significantly reduces the amount of work required by the user, and it provides flexibility for treating changes in cross section when determining bridge properties and internal loads.

The section modulus and moment of inertia of the steel girder are the only section property data required for the noncomposite steel girders. For composite steel girders, more data are required to describe the properties of the cross section. The moment of inertia, depth, and area of the steel girder alone are required. Haunch depth, deck thickness, and the area of the top and bottom coverplates, if present, are also requested from the user. If the section has coverplates, KU-SBAR will request the coverplate thickness. To calculate the modular ratio for the concrete deck, the ultimate strength, f_c' is also requested. From this information, the program automatically looks up the modular ratio given in the AASHTO manual *(4)*.

When evaluating a composite steel girder, the effects of creep must be considered for calculating the stresses due to that portion of dead loads that acts on the composite cross section. This is accommodated by calculating the moment of inertia and section moduli for two modular ratios, n and $3n$.

To calculate the moment of inertia of the composite sections, the effective width of the concrete deck is automatically determined using the AASHTO criteria *(4)*. When using these section moduli to calculate stresses, the procedure is to use the one that predicts the larger composite dead load stress. The section moduli are calculated for the steel girder alone. They are also calculated for the composite sections at the concrete, and top and bottom of the steel girder. The composite section properties are calculated for both modular ratios.

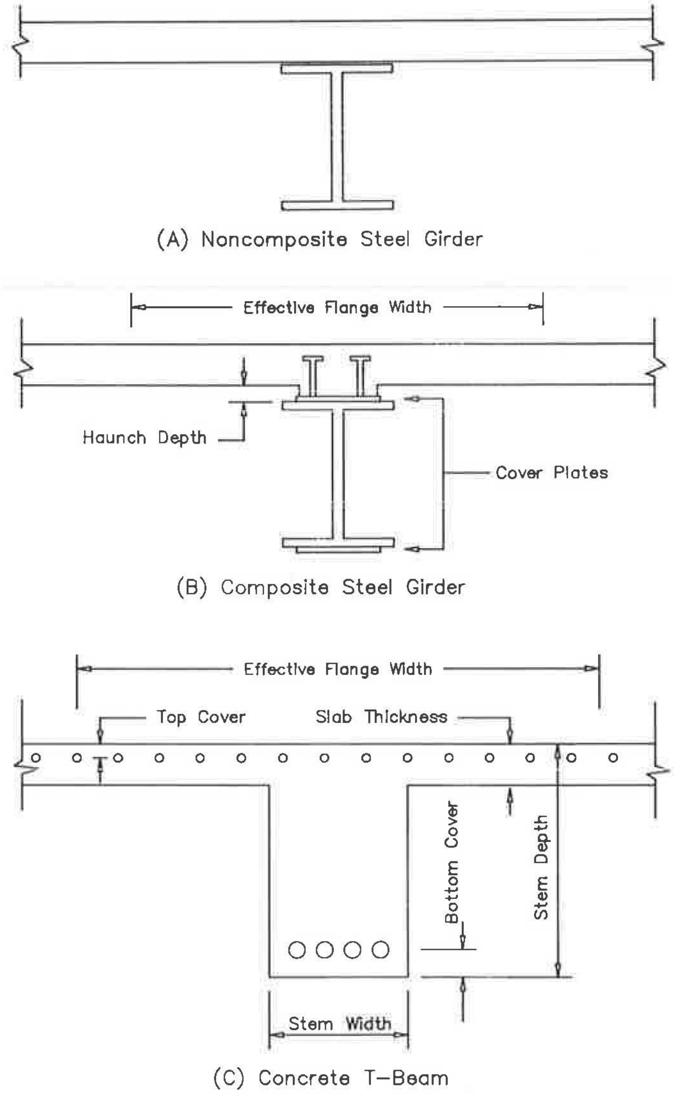

FIGURE 2 Cross sections for KU-SBAR bridges.

The data required for concrete T-beams include deck thickness, stem width, stem depth, area of bottom and top reinforcement, and reinforcement cover. With these data, the moment of inertia of the bridge can be calculated for each station.

After all data have been entered for nonprismatic spans, KU-SBAR automatically generates inertial properties at intermediate stations located midway between the 10 stations. These properties are used to calculate the flexibility coefficients described in the analysis section of the paper.

KU-STAR

KU-STAR supports the following standard bridge trusses: Pratt, Warren, Parker, deck Warren, and K-truss (Figure 3). Once the user responds to the prompts for number of panels, panel width, and panel height for these standard trusses, KU-STAR automatically generates all joint coordinate and member incidences. This feature eliminates the tedium of setting up the structural definition of the truss to be rated.

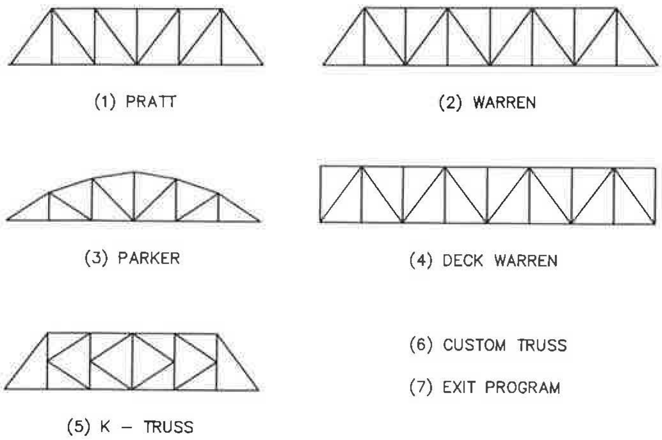

FIGURE 3 Standard KU-STAR-supported trusses.

KU-STAR also supports the nonstandard bridge truss, for which the program prompts the user for joint coordinates and member incidences for each node and member.

Each member of the truss has cross-sectional properties and allowable stresses. The original area of the member is required. To account for the deterioration of each member, a reduction in percent of original area is requested. For the rating section of the program, the allowable inventory stress in tension and compression is also required. The allowable operating stresses are automatically calculated from the inventory stresses.

To minimize user effort, only one set of member property data for each member type is required. The supported member types are top and bottom chords, verticals, and diagonals. If the members do not have similar properties, the same data are prompted for each member.

In addition, a sophisticated editing procedure is also supported by KU-STAR. This feature permits general data to be entered for each member type and then edited for those members that require modification.

METHODS OF ANALYSIS

Because the bridge types to be rated are significantly different, the system has two analysis methods. The more efficient method may be selected for each bridge type. This procedure minimizes the amount of computer time required to rate a bridge.

For truss bridges, the stiffness method was selected for analysis. Because of the wide range of configurations found in truss bridges, no generalized truss system can be defined in advance. Once the geometry and member properties are defined, the stiffness matrix can be easily generated. To improve the numerical efficiency of the solution process, symmetry of the stiffness matrix is considered. The memory requirements are minimized by storing the stiffness matrix as a banded matrix. Influence line coefficients are calculated for each member as a unit load goes to each node along the roadway. This analysis procedure can be found in most textbooks on matrix procedures of structural analysis *(7, 8)*.

For the continuous-span bridges, the flexibility method was selected for two reasons. First, the nonprismatic member capability of the program can be easily incorporated. It is easier and more efficient to calculate flexibility coefficients than stiffness coefficients for these members. They are calculated by breaking each span into 20 segments. Second, the number of unknowns for these bridge girders is always less than the number of unknowns for the stiffness method. For a three-span bridge, the number of redundants is only two.

Once these internal support moments are calculated, only simple equations of statics are required to determine influence line coefficients for the structural functions at 10 locations along the beam.

Influence line coefficients were calculated for a unit load at each node. The structural functions were calculated for each member or at 10th points along each span. For the girder bridges, an axle load placed between two adjacent nodes was distributed between the two nodes on a percentage basis.

After the influence line coefficients are calculated and the rating truck is defined, each program goes into a subroutine to march the truck across the bridge in both directions. While these trucks are moving across the bridge, the maximum and minimum values for the appropriate structural functions are retained. Lane loads are also evaluated for H and HS trucks.

OUTPUT

The output is similar, for the two programs. When possible, the output format is compatible between the two programs. Each program provides the user with two different output options. If the user wants to display the data on the computer monitor, then no action is required. If a hard copy is desired, the user selects the print menu. which directs all output to the printer. The print menu and display menu are identical and have the following configuration for the two programs.

The output menu for KU-SBAR is

DISPLAY MENU

BRIDGE GEOMETRY SUMMARY
RATING SUMMARY
MOMENTS, SHEARS, & REACTIONS
MEMBER STRESSES
RETURN TO TRUCK SELECTION MENU
NEW BRIDGE

The output menu for KU-STAR is

DISPLAY MENU

TRUSS DATA SUMMARY
RATING SUMMARY
MEMBER STRESSES
NODAL DEFLECTIONS
RETURN TO TRUCK SELECTION MENU
NEW BRIDGE

The bridge geometry summary and truss data summary provide the user with a record of the input data. These options are useful for verifying input data and for making permanent records.

The rating summary option provides the user with the allowable inventory and operating rating for the truck configuration chosen. Based on the allowable inventory stress previously defined, the programs determine the allowable weight of the current configuration truck. For example, the Type 3-3 truck weighs 40 tons. If the dead load and the Type 3-3 truck induce stresses in the bridge that exceed the allowable inventory stress in any member, the weight of the truck is reduced until the total stresses just reach the allowable inventory stress. Although the allowable inventory truck may weigh 20 tons, the distribution of the 20-ton Type 3-3 truck is identical to the 40-ton Type 3-3 truck, except the axle loads are one-half the values given in Figure 2. For the concrete T-beam and composite steel girder bridges, the stresses in the steel and concrete are checked.

In addition to the inventory rating, the operating rating is also calculated. Although the operating stresses may be only 25 to 40 percent higher than the inventory stresses, the ratio of operating to inventory rating may be significantly higher. This phenomenon was observed because the dead load stresses are constant for the two rating procedures.

Because of the differences in the type of members and stresses in the bridge configurations, the member stresses are displayed or printed differently. Both programs request the user to specify the weight of the current truck. This approach provides the user greater flexibility to use the data for other applications.

KU-SBAR has similar stress formats for each of the three girder material types. The stresses are calculated at 10 locations along each span. The simplest format is for the noncomposite steel girders. Stresses caused by dead loads, truck loads, and lane loads are displayed. In addition, the maximum total stresses are displayed for the extremes of the moment envelope.

For composite steel girders, bending stresses are presented for the concrete for compression only, and at the top and bottom of the steel beam. Stresses are calculated for dead loads that act on the steel beam alone and on the composite section and for truck and lane loads. For dead load stresses acting on the composite cross section, the smallest section modulus at each location is used in the stress calculations. In addition, the maximum total stresses are calculated at each location for the moment envelope values.

For concrete T-beams, the bending stresses are presented for the reinforcement and concrete. They are calculated for dead, truck, and lane loads. Again, maximum and minimum total bending stresses are also presented.

In truss bridges, KU-STAR has a different format for output of axial stresses. As for KU-SBAR, the axial stresses are calculated from dead, truck, and lane loads. The total stresses are also presented based on the member load envelopes. For fatigue calculations, stress reversals for each member are calculated. Although fatigue is not an important rating criterion for low-volume roads, these values are useful when the effects of fatigue must be considered.

An output format similar to the member stress section was used for the moments, shears, and reactions option in KU-SBAR. The bending moments for dead, truck, and lane loads are presented for 10 stations along each span. The total moments required to draw a moment envelope are also presented. To improve the usability of this section, the user is requested to specify the weight of the truck before calculating the live-load structural functions.

The maximum positive and negative shears are presented for each end of all spans. In addition, the maximum reactions are also presented for all loading conditions.

EXAMPLES

The following examples are presented to illustrate the capability of the bridge rating system.

Example 1

A three-span concrete T-beam bridge (40 ft, 50 ft, 40 ft) with five concrete T-beams spaced at 7 ft 0 in. is to be rated for two lanes of traffic. An overhang of 1 ft 0 in. is found on both sides of the bridge. The width of the stem is 26 in. and it has a uniform depth of 50 in. The deck thickness is 7.5 in. The deck and T-beams are made from concrete with an ultimate strength of 4,000 psi, resulting in an inventory stress of 1,600 psi and an operating stress of 2,240 psi for the concrete. The inventory and operating stresses for the steel reinforcement are 20 and 28 ksi, respectively. To make the example as simple as possible, the steel reinforcement is assumed to have a constant area over the bridge length. The bottom steel area consists of eight no. 10 bars for a total area of 10.12 $in.^2$. The top steel consists of eleven no. 9 bars for a total area of 11 $in.^2$ The cover for the top and bottom reinforcement is 2 in. Determine the allowable ratings for all five standard AASHTO truck configurations based on an interior girder.

An estimate of the dead load for this bridge was 3.0 kip per linear foot. This load was placed on each span. From KU-SBAR, the following inventory ratings were calculated for this bridge from the rating summary option: H16.2; HS16.2; Type 3, 31.2 tons; Type 3S2, 27.2 tons; and Type 3-3, 36.0 tons. The operating ratings for the five trucks were H42.2; HS42.2; Type 3, 81.0 tons; Type 3S2, 70.9 tons; and Type 3-3, 93.8 tons.

The behavior of this bridge under a variety of trucks can be understood from the output available from KU-SBAR. Because the concrete T-beams were underreinforced, the stresses in the steel reinforcement were critical for all loading conditions. In particular, the critical section for each truck was over the interior support. If the bridge has different span lengths, the location of this critical section may change.

Moment envelopes and bending stresses for concrete and steel reinforcement were available for each truck. Although the allowable operating stress for the steel reinforcement is only 40 percent higher than the allowable inventory stress, the operating rating for each truck is 2.6 times higher than the inventory rating. This discrepancy occurs because the dead-load moment over the interior support is approximately 57 percent of the total moment capacity of the cross section. This ratio of operating rating to inventory rating for an existing bridge is always higher for bridges with relatively high dead-load moments.

Although the rating for the H and HS trucks is identical, the total weight of an HS16.2 truck is approximately 29 tons. These ratings were identical because the lane load condition was the most severe loading condition for this bridge. In general, this condition does not occur.

Other interesting observations can be made from the rating summaries. The inventory and operating ratings increase as the length of the truck increases. The shortest trucks were the H and Type 3 trucks and the longest were the HS, Type 3S2, and Type 3-3. For many-simple span bridges, the Type 3 truck is critical. However, for this continuous bridge, the critical section was over the interior support. In addition, the back two wheels are heavily loaded and only 4 ft apart. Thus, the negative moment over the interior support is not as severe for this truck configuration as it is for some of the other truck configurations. This Type 3 truck configuration does cause a more severe positive moment condition at the midpoint of the longer center span.

After a review of the output, a better feel for the behavior of the bridge can be determined. For all bridges, the engineer must use good judgment to determine the allowable truck loads. Federal regulations require the bridge to be posted if the bridge operating rating is below the legal load limit for that jurisdiction *(1)*. During field inspections particular attention should be given to those stations where maximum stresses occur. If severe deterioration is found at these locations, a reduced truck load may be appropriate. A discussion of the times required to run these five cases is presented later.

Example 2

A four-panel Warren truss was selected for the second example. Each panel is 10 ft wide and 20 ft high. A sketch of the truss, with member numbers, is presented in Figure 4. Because the Warren truss is supported by KU-STAR, all joint coordinates and member incidences were automatically generated. The overall length of the bridge is 60 ft. Member properties, degree of deterioration, and allowable inventory stresses in tension and compression are given in Table 1. The width of the roadway is 20 ft, and the centerline distance between the two trusses is 22 ft. The weight of the deck, floor beams, stringers, and so forth, is 1 kip per linear foot. The dead weight of the truss, including a 10 percent allowance for connection weight, is automatically calculated by KU-STAR.

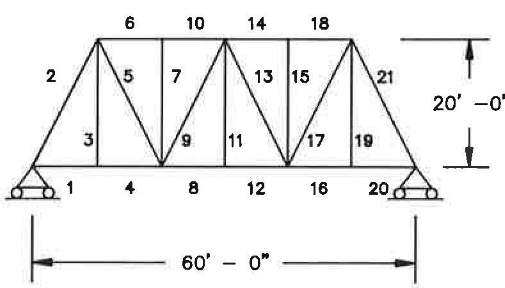

FIGURE 4 Four-panel Warren truss members.

The inventory ratings for the five standard-AASHTO defined trucks are H27.3; HS23.5; Type 3 38.5 tons; Type 3S2, 52.9 tons; and Type 3-3, 66.2 tons. The corresponding operating ratings for this bridge are H41.7; HS36.0; Type 3, 58.8 tons; Type 3S2, 80.9 tons and Type 3-3, 101.3 tons. The most critical members of the truss are Members 8 and 12. Because these members are tension members, they should receive extra attention during the field inspection. This is especially true if the members are not redundant. The connection between these two members also warrants additional attention during the field inspection.

TABLE 1 MEMBER PROPERTIES AND ALLOWABLE STRESSES FOR WARREN TRUSS

Truss Member Group	Original Area (in.^{2})	Area Reduction (%)	Allowable Inventory Stress: Tension (ksi)	Allowable Inventory Stress: Compression (ksi)
Top chord	12	0	18	14
Bottom chord	5	5	18	3
Diagonal	10	2	18	12
Vertical	6	5	18	3

For truss bridges on low-volume roads, fatigue of the bridge members is not usually a significant consideration. However, if heavy-truck traffic is critical, then the stress reversals from KU-STAR are useful for evaluating the fatigue characteristics of each member.

If desired, maximum nodal deflections are available. Dead-and-live load deflections can be obtained.

COMPUTER EFFICIENCY

As previously stated, the method of analysis varied between the two bridge types supported by the bridge rating system. Both examples were run on HP Vectra and Zenith 158 microcomputers operating at an 8-MHz clock speed. The HP Vectra had a 80286 processor, and the Zenith a 8088 processor. Both machines operated under MS-DOS version 3.10. The two programs were run in interpretive mode. The total run time for the five trucks on the three-span bridge (Example 1) was approximately 19 min with the HP Vectra. The fastest run time, 2:27 min, was for the H truck. The longest run time was 5:41 min for the Type 3-3 truck. When the number of numerical calculations required is considered, the improved efficiency of engineers and transportation officials due to the microcomputers is significant. In addition, a better idea of the behavior of this bridge is obtained.

For the simple-span, four-panel Warren truss bridge, the total run time for the five truck configurations was approximately 13 min on the HP Vectra. Again, the shortest run time of 0:41 min was found for the H truck. The longest run time was for the HS truck. Because the location of the third axle is permitted to vary, additional time was required. For the Type 3-3 truck, the run time was only 2:10 min.

The run time for the 8088-based Zenith 158 microcomputer was approximately 2.5 times longer than for the 80286-based HP Vectra microcomputer. Although slight variations in run times have been observed for different microcomputer manufacturers, the biggest factor is the type of processor. The 80286 processor is even faster than the 8088 processor. The use of the microcomputers will improve the efficiency and productivity of the engineers responsible for rating bridge structures.

CONCLUSIONS

The productivity and capability of transportation officials and engineers responsible for rating the 586,000 bridges in this country may increase with the development of the bridge rating system described in this paper. This system was designed to assist in the rating and evaluation of girder and truss bridges. The system, written in BASIC, was developed to operate on microcomputers. Computer graphics were used on a limited basis to improve user understanding of input data.

The system prompts the user for all information required to define the bridge. The manner of inputting data was chosen to minimize user effort. When appropriate, the user is given the opportunity to edit the data after they are entered.

Noncomposite and composite steel girders and concrete T-beams are supported for simple and continuous girder bridges. Simple-truss bridges are also supported. Both programs support the five standard AASHTO trucks and one user-defined truck. A wide range of output options is provided for the user. This output can be displayed on the monitor or printed on a printer for a permanent record.

An efficient software package has been developed for microcomputers. With the capabilities provided in this system, transportation officials and engineers are no longer required to simplify actual conditions to fit the conditions available for tables found in the literature. With this system, better estimates of bridge ratings are obtainable, especially for low-volume roads, where these bridges are loaded at their maximum weights only a few times per year. In addition, a better environment and credibility should result when a bridge must be posted.

The 80286-processor-based microcomputers were approximately 2.5 times faster than the 8088-processor-based microcomputers. For the three-span bridge, the five standard trucks took approximately 19 min on the 80286-based microcom puter. For the four-panel Warren truss bridge, the run time for the five standard trucks was approximately 13 min.

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REFERENCES

1. *Code of Federal Regulations.* Title 23—Highways, Part 650.300, Subpart C.
2. Better Roads 1985 Bridge Inventory. *Better Roads,* Vol. 55, No. 11, Nov. 1985, p. 23.
3. *Manual for Maintenance Inspection of Bridges.* American Association of State Highway and Transportation Officials, Washington, D.C., 1983.
4. *Standard Specifications for Highway Bridges.* 13th ed. American Association of State Highway and Transportation Officials, Washington, D.C., 1983.
5. K. V. Boldt and C. E. Kurt. *Kansas University—Simplified Truss Analysis and Rating—User's Manual.* Department of Civil Engineering, University of Kansas, Lawrence, 1985.
6. C. E. Kurt. *Kansas University—Simplified Bridge Analysis and Rating—User's Manual.* Department of Civil Engineering, University of Kansas, Lawrence, 1986.
7. R. B. Cook. *Concepts and Applications of Finite Element Analysis.* 2nd ed., John Wiley and Sons, New York, 1981.
8. C. K. Wang. *Intermediate Structural Analysis.* McGraw-Hill, New York, 1983.

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A Microcomputer Program to Evaluate the Benefits and Costs of Alternative Investment Strategies on Low-Volume Local Rural Roads

GREGORY R. PAUTSCH AND C. PHILLIP BAUMEL

The physical condition of local rural roads and bridges is deteriorating. Many roads have not been reconstructed since they were first surfaced; many bridges are 50 to 100 years old. At the same time, the money available to local governments to maintain and rebuild the system is declining. Some observers believe that the local road system must be restructured by reducing the number of miles of road and by paving some roads, reconstructing others, and reducing maintenance levels on still other roads. Residents living on or farming land on roads considered for abandonment, reduced maintenance, or conversion to private drives argue that these policies increase their transportation costs in amounts exceeding the savings to local governments. At the present time, local government officials have no methods of evaluating the changes in travel and investment costs associated with changing the number of miles and types of local rural roads. Described in this paper is a microcomputer program designed to enable county engineers and other local officials to estimate the change in travel and investment costs from alternative investment strategies on local rural roads and to compute benefit-cost ratios for the alternative investment strategies.

The local rural road system, defined as those roads that are under the jurisdiction of county and township governments, contains 71 percent of the 3.2 million mi of rural roads in the United States. The large number of miles and the rectangular regularity of the local rural road system date back to the Ordinance of 1785, which established townships and the 1-mi survey grids. The objective of Congress was to open the land for settlement.

Precise data on the present condition of the local rural road system are not available. However, there is ample evidence that the system is deteriorating rapidly. In a recent Illinois survey, farmers and agribusiness representatives rated about half the Illinois local rural roads as needing more than regular maintenance, and more than 20 percent of these roads were rated as needing major repair. Common complaints about the local rural roads in many states include the following:

1. Overweight vehicles are breaking up road surfaces.
2. Lack of hard surfaces creates dust and rideability problems.
3. Road widths and other design characteristics are inadequate for today's large farm equipment and heavy trucks.
4. Narrow lanes create safety problems.

Although local road deficiencies are significant, the condition of local bridges is also of great concern. On January 1, 1985, 184,977 bridges, or 61 percent of all the off-federal-aid bridges that had been inventoried, were deficient. In addition, 118,390, or 39 percent of the 306,388 off-federal-aid system bridges, are posted, or should have been posted, at less than legal weight limits. However, even this understates the magnitude of the problem. Bridges under 20 ft long were not included in the inventory, and there are thousands of structures under 20 ft in length that need replacement or rehabilitation.

The distribution of deficient bridges among states indicates that the local bridge problem is national in scope. States with the largest number of deficient bridges are Arkansas, Illinois, Indiana, Iowa, Kansas, Mississippi, Missouri, Nebraska, North Carolina, Oklahoma, Tennessee, and Texas. States in the northeast, midwest, southeast, and southwest are included in the groups with a high percent or a large total number of deficient bridges.

To a large extent, the county road system faces many of the same problems that the railroad system encountered in the late 1960s and early 1970s. The physical condition of the county road system is deteriorating. The continuing increase in farm size results in heavier vehicles traveling on these roads and causing more damage to the system; at the same time, the available money, in real terms, to maintain and rebuild the system is declining. Although federal and state motor fuel taxes have increased sharply in recent years, there is increasing pressure to reallocate a larger share of these funds to roads that are under city and state jurisdiction. Moreover, a substantial share of the funds to maintain local rural roads comes from property taxes. The recent decline in rural property values places downward pressure on this source of funds for rural roads. In addition, funds from federal revenue sharing are declining and are likely to continue declining in the future. The decline in the amount of federal general revenue sharing funds is likely to force local governments to reallocate some road funds to meet mandated expenditures such as mental health care. In short, the problem is lack of money to properly

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maintain the existing system for the quantity, sizes, and types of vehicles that are traveling on the roads.

Public debate about county roads has focused mainly on the deteriorating condition of the system. The implicit assumption behind much of this debate is that the system should be maintained "as is." However, an increasing number of observers believes that the number of miles of local rural roads could be reduced by either abandonment or conversion to private drives. A 1976 editorial in the *Des Moines Register* states

> County roads that served dozens of farms forty years ago may be serving only two or three farms today. Many roads that were once vital to a county's well-being have become, in effect, private roads, although the county is responsible for their upkeep. Such roads no longer belong in a county road system.

Some observers suggest additional investment alternatives should be considered including converting selected gravel or dirt roads to low-level maintenance roads—sometimes referred to as B level roads, simultaneously paving selected roads while abandoning other roads, upgrading bridges, and moving field or household driveways to increase the number of roads that could be considered for abandonment without landlocking property. Residents living on and operating farms on roads considered for abandonment, for conversion to private drives, or as low-level maintenance roads argue that these policies will force them to travel longer distances and incur higher travel costs and that the additional travel and maintenance costs will exceed the cost savings from removing these roads from the public system.

At present, local government officials have no methods of evaluating the changes in travel and investment costs associated with changing the number of miles and types of local rural roads. The microcomputer program described in this paper is designed to enable county engineers and other local officials to

1. Estimate the change in travel costs to the traveling public from alternative investment strategies on low-volume, local rural roads. The investment strategies include abandoning roads, converting roads to private drives, paving gravel and dirt roads, converting roads to low-maintenance B level roads, and upgrading bridges.
2. Estimate the change in investment costs from the alternative investment strategies.
3. Compute benefit-cost ratios for the alternative investment strategies.

The program, written in FORTRAN, can be executed on an IBM or IBM-compatible personal computer with at least 300K of storage. The personal computer must have a fixed disk of at least 3 megabytes (MB) of storage and be equipped with DOS version 3.0. The underlying logic of this program is described by Baumel et al. *(1)*.

DATA REQUIREMENTS

Road and Bridge Network

The first data set to be created for the local rural road evaluation program is the road network. A network consists of a set of nodes connected by a set of arcs. A node represents a point where trips originate, are relayed, or terminate. Arcs represent the roads that allow traffic to flow between the nodes. Each arc in the network is described by

- A beginning node,
- An ending node,
- A distance,
- A weight constraint,
- A width constraint,
- The length of any bridge on the arc,
- The width of any bridge on the arc, and
- A road surface code.

The program requires five types of arcs to be created in a complete rural road and bridge network. The first type of arc is called a study area arc. A study area arc is created by dividing the roads in the study area into half- or quarter-mile segments. In Figure 1, the roads in a 1-mi by 1-mi study area are divided into half- and quarter-mile segments. A node is placed at each intersection and at the end of each road segment. The node numbers must start at one and be sequential; a number cannot be skipped. All of the nodes on study area arcs should be assigned numbers before numbers are assigned to the nodes on all other types of arcs. The nodes on the study area arcs in the Figure 1 study area begin at 1 and move sequentially to 10. The road segment connecting Node 1 with Node 5 is represented by two arcs. The arc allowing traffic to flow from Node 1 to Node 5 has a beginning node number of 1 and an ending node number of 5, whereas the arc allowing traffic to flow from Node 5 to Node 1 has a beginning node number of 5 and an ending node number of 1.

The distance of study area arcs must be an integer. Because the road segment between Nodes 1 and 5 is 0.5 mi long, the distance for the two arcs representing this 0.5-mi road segment is equal to 50. The distance for a 1-mi road segment is 100, and the distance for a quarter-mile segment is 25. In Figure 1, a bridge is located on the road segment connecting Nodes 5 and 7. The distance of any arc that has a bridge is given a distance of 25. Hence, a node must be placed one-eighth mile away from both ends of the bridge.

The weight constraint of an arc is the weight of the heaviest vehicle that the arc can carry, whereas the width constraint is the width of the widest vehicle that the arc can accommodate. Both the weight and width constraints must be integers. The weight constraint is measured in tons, whereas the width constraint is measured in feet. The length and width of any bridge on an arc must be integers and both are measured in feet. If an arc does not have a bridge, the bridge length and width of that arc are set at zero.

The surface code of a study area arc can be any of the following numbers:

Type of Road	*Code*
Paved county road	1
Gravel county road	2
Dirt county road	3
Paved noncounty road	4

A paved noncounty road is a state or Interstate highway located in the study area.

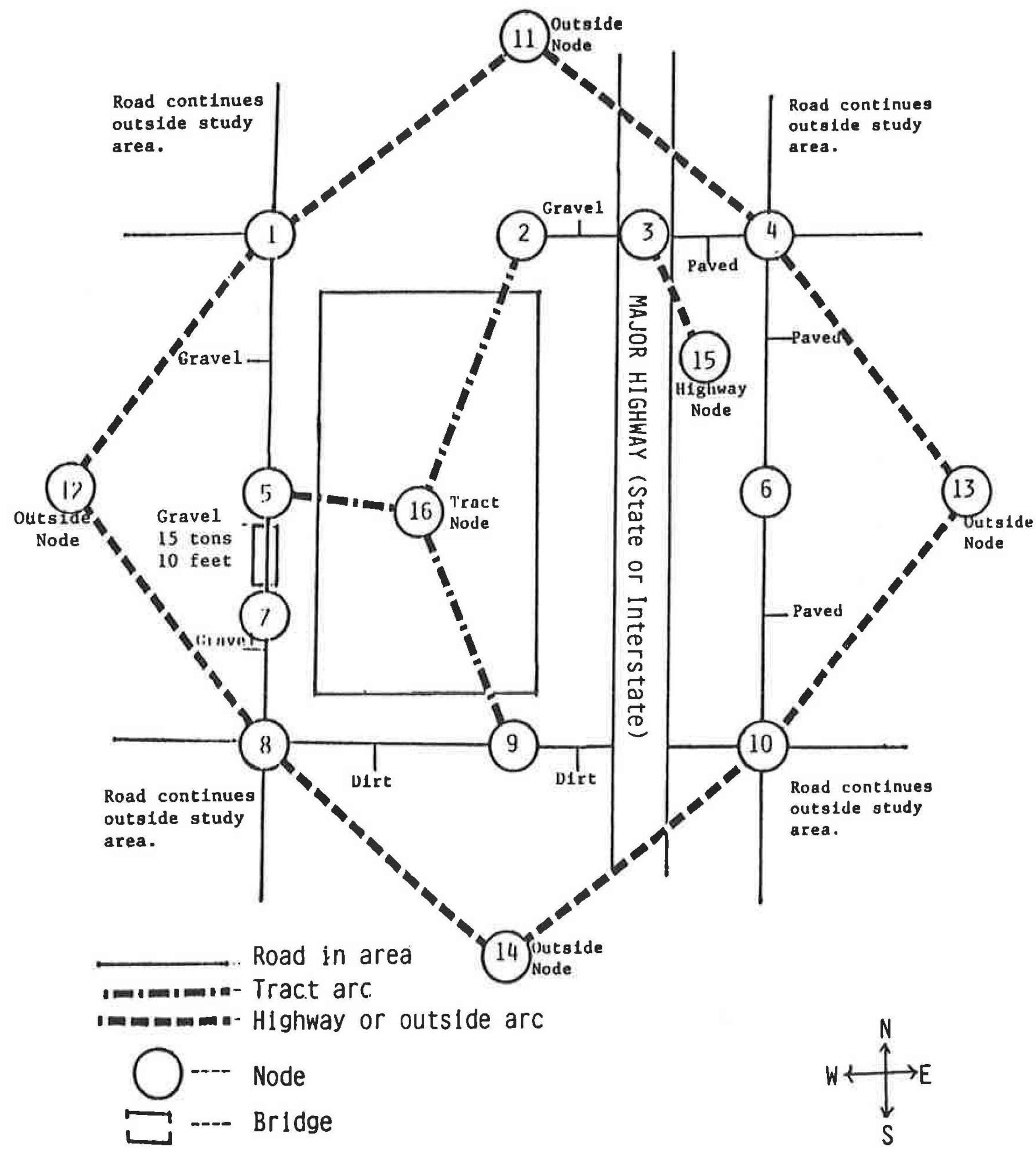

FIGURE 1 A sample network of a 1-mi by 1-mi study area divided into half- and quarter-mile segments.

The second type of arc to be created is an outside arc. Outside arcs allow the computer to route vehicles through the study area when they travel to destinations outside the study area. Outside nodes are placed north, south, east, and west of the study area. The node number for the outside nodes must start with the next number following the last number assigned to a study area arc and move sequentially. In Figure 1, the nodes placed on the study area arcs start at 1 and continue to 10. Hence, the numbers assigned to the outside nodes start at 11 and continue to 14.

Outside arcs are formed by connecting the outside node to the nodes on the edge of the study area that allows traffic to leave the study area. In Figure 1, the west outside node is connected to Nodes 1 and 8 because they allow travel westward out of the study area. The west outside node is not connected to Nodes 5 and 7 because they do not allow travel westward out of the study area. Hence, if a farmer has a tract of land located west of the study area, it would be given the west outside node as the destination. Any trip to that outside tract is routed from the origin node within the study area to the west outside node. This allows for the calculation of within-study-area travel costs to destinations outside of the study area.

The third type of arc to be created is a highway arc. Highway arcs connect the highway node to the within-study-area nodes serving as access points to the highway. Thus, a highway node is placed on each state or Interstate highway in the study area. The numbers assigned to the highway nodes follow the last number assigned to an outside node and move sequentially. In Figure 1, the highway node is assigned the value of 15 because the last number assigned to an outside node is 14. Only Node 3 serves as an access point to the highway; hence, only Node 3 is connected to Node 15. Highway arcs allow trips to distant locations under the assumption that travel to and from distant locations maximizes the use of state or Interstate highways. Therefore, the destination of any out-of-state trip is the highway node. The computer routes the trips to the closest access to a state or Interstate highway that is in the general direction of the true destination.

The distance of all outside arcs and highway arcs is set at 10,000 and the surface code is equal to 5. The weight and width constraints of outside arcs and highway arcs are set at a value so that all legal-sized vehicles are able to travel over these arcs. The program does not consider bridges on outside arcs and highway arcs; hence, the length and width of bridges on outside arcs and highway arcs should be set at zero.

The next type of arc to be created is a tract arc. The origin or destination of many farm trips is tracts (fields) of farmland. Tracts of farmland often have multiple-access points. In most cases, the access used depends on the origin of the trip. Each tract of land within the study area is assigned a tract node. The numbers assigned to tracts follow the last number assigned to a highway node and continue sequentially. A tract arc is formed by connecting the tract node to the nodes in the study area that serve as access points to the tract of land. Hence, in Figure 1, the tract node—Node 16—is connected to Nodes 2, 5, and 9 because these nodes serve as access to the tract of land. When a farmer travels from tract to tract, the origin and destination should be coded as each tract node number. The computer finds the cost-minimizing route between the two tracts by finding the optimal access points to use for each trip.

The final type of arc to be created is a new arc. New arcs allow for new access points to tracts of farmland to be inserted into the county road network. Because abandoning a road segment or a group of road segments may landlock some property, new arcs placed on a remaining road adjacent to the tract allow the farmer to travel to his tract of farmland. A new arc is formed by connecting the tract number to the node number representing the location of the new access point.

The distance for tract arcs and new arcs is set at 10,000 so only trips that have the tract node as an origin or destination are routed over the arc. This high distance value prevents overhead traffic from "driving through the field." The surface code for tract arcs is 6, and the surface code for new arcs is 8. The weight and width constraints of tract arcs and new arcs must be set at a value such that all vehicles are able to travel over these arcs. The length and width of any bridge on tract arcs and new arcs is set at zero because bridges are not located on these arcs.

Trip Information Data

The second data set to be created is the trip information data set. The trip origin node number, destination node number, number of trips, and vehicle type code number must be entered into this data set. The various vehicle code numbers for various types of vehicles are given in Table 1. The sample study area in Figure 2 includes three households numbered 1, 2, and 3. Suppose they furnished the following trip information, assuming all trips are one-way, that is, they do not include return trips:

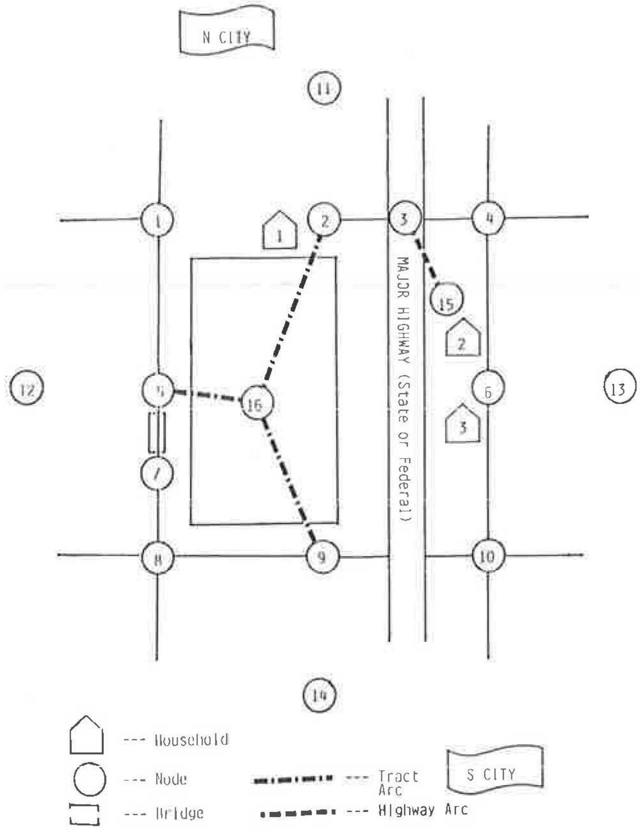

FIGURE 2 Sample study area.

TABLE 1 VEHICLE CODE NUMBERS

Vehicle Code Number	Vehicle Description
1	Automobile
2	Commercial van
3	Pickup
4	Single-axle truck, half-loaded
5	Tandem-axle truck, empty
6	Tractor pulling equipment
7	Tractor pulling equipment with timeliness
8	Pickup pulling trailer
9	Garbage truck
10	Commercial semitrailer, empty
11	Tractor
12	Combine, 2-row
13	Combine, 4-row
14	Combine, 6 or 8-row
15	Tractor pulling 125-bu wagon, empty
16	Tractor pulling 250-bu wagon, empty
17	Tractor pulling 350-bu wagon, empty
18	Tractor pulling 450-bu wagon, empty
19	Tractor pulling 550-bu wagon, empty
20	Tractor pulling two 350-bu wagons, empty
21	Tractor pulling two 450-bu wagons, empty
22	Single-axle truck with pup, empty
23	Farm semitrailer, empty
24	Tandem-axle truck with pup, empty
25	Single-axle truck pulling 250-bu wagon, empty
26	Single-axle truck pulling 350-bu wagon, empty
27	Tandem-axle truck pulling 450-bu wagon, empty
28	Tractor pulling grain buggy, empty
29	Tandem-axle truck pulling 550-bu wagon, empty
30	Tandem-axle truck pulling two 350-bu wagons, empty

TABLE 1 *continued*

Vehicle Code Number	Vehicle Description
31	Tandem-axle truck pulling two 450-bu wagons, empty
32	Commercial semitrailer, loaded
33	Tandem-axle truck, loaded
34	Farm semitrailer, loaded
35	Single-axle truck with pup, loaded
36	Tandem-axle truck with pup, loaded
37	Tractor pulling 125-bu wagon, loaded
38	Tractor pulling 250-bu wagon, loaded
39	Tractor pulling grain buggy, loaded
40	Tractor pulling 350-bu wagon, loaded
41	Tractor pulling 450-bu wagon, loaded
42	Tractor pulling 550-bu wagon, loaded
43	Tractor pulling two 350-bu wagons, loaded
44	Tractor pulling two 450-bu wagons, loaded
45	Single-axle truck pulling 250-bu wagon, loaded
46	Single-axle truck pulling 350-bu wagon, loaded
47	Tandem-axle truck pulling 450-bu wagon, loaded
48	Tandem-axle truck pulling 550-bu wagon, loaded
49	Tandem-axle truck pulling two 350-bu wagons, loaded
50	Tandem-axle truck pulling two 450-bu wagons, loaded

Household 1—

Five trips per week to N city in a car,

Four trips per month to N city in a pickup truck,

Two trips per day to the field (Node 16 in the figure) in a pickup truck,

Two trips per day to the field during fall harvest in a tractor pulling a 450-bu wagon,

Five trips to the field in a 6-row combine during harvest, and

Five trips per year from S city in a tandem-axle truck pulling a pup trailer.

Household 2—

Ten trips per week to S city in an automobile,

One trip per month to N city in a pickup truck,

Two trips per year to a distant location in an automobile using a major highway, and

Three trips per week to a neighbor, Household 1, in a pickup truck.

Household 3—

Fifteen trips per week to a city east of the study area in an automobile,

Five trips per year to N city in a commercial semitrailer, and

Four trips per year from S city in a single-axle truck.

In smaller study areas, many trips originating within the study area go to outside locations, and many trips to locations within the study area begin at origins outside the study area. A complete description of trip data for a given household must include information on all trips to and from locations inside and outside the study area.

Once trip data have been collected for all households in the study area, the three steps in adjusting the data for the local rural road evaluation program are as follows:

Step 1. First, trip information must be converted to common units, such as number of trips per year. Because there are 52 weeks in a year, 12 months, or 365 days, and one-quarter of these per season, the following conversions should be used:

1 trip per day = 1×365 = 365 trips per year.
5 trips per week = 5×52 = 260 trips per year.
1 trip per month = 1×12 = 12 trips per year.
1 trip per day per season = $1 \times 365 \times 1/4$ = 91 trips per year.

Step 2. Origin and destination nodes are next assigned to each trip, that is, for the requested route. Each household is given a location node based on the closest node in the study area. A household located exactly between two nodes is assigned to the node nearest the middle of the arc on which it lies. In the example, Household 1 is located near Node 2, whereas Households 2 and 3 are closest to Node 6. Hence, travel originating at Household 1 is given an origin node of 2. Travel originating in the field in the sample study area is assigned an origin node of 16, the node of that tract of land. Travel originating outside the study area is given the appropriate outside node as its origin, or if travel originated at a distant location, the major highway node, Node 15. Similarly, a destination node for each requested route is assigned. Trips to Household 2, for example, have Node 6 as destination node. Trips to N city are assigned Node 11 as destination node, because N city is outside and north of the study area, and Node 11 is the north outside node.

Step 3. The third step is to assign vehicle code numbers to each vehicle, based on the numbers given in Table 1. For example, the code of 1 is assigned to the automobile. School buses and postal vehicles are excluded from Table 1. School bus and postal service vehicles are routed based on larger geographic areas, and any change in school bus and postal travel costs must be calculated by hand. Table 2 presents a list of the coded travel information given for the sample study area in Figure 2.

TABLE 2 CODED TRAVEL INFORMATION FOR SAMPLE STUDY AREA

Origin Node No.	Destination Node No.	Yearly Trips	Vehicle Code No.
2	11	520	1
2	11	96	3
2	16	1,460	3
2	16	183	18
2	16	183	41
2	16	10	14
14	2	5	24
14	2	5	36
6	14	1,040	1
6	11	24	3
6	15	4	1
6	2	312	3
6	13	1,560	1
6	11	5	32
6	11	5	10
14	6	8	4

Vehicle Grouping Information

Another required data set is vehicle groupings. Vehicle groupings allow several vehicles to be routed together to increase the efficiency of the computer. The vehicles in each grouping should have similar weight and width characteristics and the ratios of costs per mile of traveling over a gravel surface to a paved surface, the costs per mile of traveling over a dirt surface to a paved surface, and the costs per mile of traveling over a B level road surface to a paved surface must be similar. For each vehicle grouping, the following information is required:

- The representative weight (tons),
- The representative width (ft),
- The representative ratio of cost per mile of traveling over a gravel surface to that over a paved surface,
- The representative ratio of cost per mile of traveling over a dirt surface to that over a paved surface,
- The representative ratio of cost per mile of traveling over a B level road surface to that over a paved surface, and
- The total number of vehicles in the grouping.

In addition, the vehicle code numbers in Table 1 and the variable cost in cents per mile of traveling over a paved surface must be entered into the vehicle grouping data set.

The representative weight and width of a vehicle grouping must be an integer value. The weight is expressed in tons, and the width is expressed in feet. The three representative ratios are rounded to two decimal places. The variable cost in cents per mile of traveling over a paved surface for a vehicle is rounded to one decimal place. The total number of vehicles in a vehicle grouping can be any integer value of 15 or less.

Road and Bridge Maintenance, Reconstruction, and Resurfacing Costs

The next type of data required is the road maintenance, reconstruction, and resurfacing cost data set. This data set requires that maintenance costs be separated into fixed and variable maintenance cost per mile of gravel, dirt, paved, and B level roads. The variable maintenance cost of a road is a function of the average daily traffic (ADT) level of the road. The fixed maintenance cost of a road is the maintenance cost required, independent of traffic levels. If the variable maintenance cost of paved roads is calculated using kip loads, zero is inserted for the paved-road variable maintenance cost. An explanation of using kip loadings to calculate variable maintenance cost of paved roads is presented later in the text.

The method used to calculate reconstruction and resurfacing costs for the local rural road evaluation program is based on Iowa data. Data sources in other states may vary, and the procedure used to calculate reconstruction and resurfacing costs may need to be modified according to the available data. The method for calculating reconstruction and resurfacing costs and the number of years between reconstructions and resurfacings for Iowa roads is described by Baumel et al. *(1)*.

Reconstruction and resurfacing costs for highway group Numbers 3–8 in Hamilton County, Iowa, are given in Table 3. Reconstruction costs on gravel and dirt roads are spread over a 60-year period. The frequency at which reconstruction and resurfacing costs are charged to paved roads is coded in the program.

The real interest rate, bridge maintenance cost per square foot, cost for inserting a new access point into the road network, per-acre rental value of farmland in the county, and the cost of converting the right-of-way into agricultural production

TABLE 3 RECONSTRUCTION AND RESURFACING COSTS PER LANE MILE BY HIGHWAY GROUP NUMBER, HAMILTON COUNTY, IOWA

Highway Group No.	Reconstruction[a] Costs ($)	Resurfacing[a] Costs ($)
3	183,687	32,877
4	123,505	30,094
5	58,141	25,881
6	26,121	17,454
7	12,399	6,621
8	7,824	4,213

[a]Calculated from *(2)*.

are additional information needed in the maintenance, reconstruction, and resurfacing data set. The annual per-acre farmland rental values can be estimated in two steps. First, the average rental rate per acre of the crop-reporting district is calculated as a percent of the average land value in the crop-reporting district. To obtain the estimated county land rent per acre, the year's average county farmland value is multiplied by the percent that the average crop-reporting district rental rates are of farmland value.

The estimated value of the cost of converting the right-of-way into agricultural production by type of terrain for Iowa data is presented in Table 4. The bridge maintenance cost per square foot is the annual square foot cost of keeping the bridge in the current condition.

TABLE 4 ESTIMATED VALUES OF CONVERTING THE RIGHT-OF-WAY INTO AGRICULTURAL PRODUCTION BY TYPE OF TERRAIN FOR IOWA DATA

Type of Terrain	Cost per Mile ($)
Flat, minimal side ditch and grade	700
Rolling, little if any end-haul dirt to move	1,000
Flat, good cross section of ditches and centerline profile	8,500
Rolling, substantial end haul, good cross section of centerline profile and ditches	16,000

Paved County Road Information

The final data set concerns paved county roads. The following information is required in the paved county road data set:

- Beginning node of each paved county road segment,
- Ending node of each paved county road segment,
- Number of years since each paved county road segment was reconstructed,
- Whether the road segment is paved of rigid or flexible pavement,
- Structural number or slab thickness of each paved county road segment,
- Design term of each paved county road segment, and
- Average annual paved-road variable maintenance cost.

If the road segment is rigid pavement, the slab thickness can be any integer between 6 and 11. The design term can be any

TABLE 5 VEHICLE AXLE WEIGHTS BY TYPE OF VEHICLE IN POUNDS

Vehicle Description	No. of Axles	Individual Axle Loadings (lb)[a]					
		First	Second	Third	Fourth	Fifth	Sixth
Automobile	2	1,750	1,750	–	–	–	–
Commercial van	2	2,800	2,400	–	–	–	–
Pickup	2	1,750	1,750	–	–	–	–
Single-axle truck, half-loaded	2	6,150	13,300	–	–	–	–
Tandem-axle truck, empty	2	6,900	11,700T	–	–	–	–
Tractor with equipment	3	3,800	12,800	4,000	–	–	–
Pickup with trailer	3	1,750	1,750	6,000T	–	–	–
Garbage truck	2	7,000	29,000T	–	–	–	–
Commercial semitrailer, empty	3	9,000	13,400T	9,500T	–	–	–
Tractor	2	3,800	12,800	–	–	–	–
Tractor with equipment	3	3,800	12,800	4,000	–	–	–
Combine, 2-row	2	8,000	3,000	–	–	–	–
Combine, 4-row	2	12,615	3,700	–	–	–	–
Combine, 6-row	2	13,926	4,640	–	–	–	–
Tractor, empty wagon							
125 bu	4	3,800	12,800	500	500	–	–
250 bu	4	3,800	12,800	520	520	–	–
350 bu	4	3,800	12,800	730	730	–	–
450 bu	4	3,800	12,800	1,070	1,070	–	–
550 bu	4	3,800	12,800	2,190	2,190	–	–
Two 350 bu	6	3,800	12,800	730	730	730	730
Two 450 bu	6	3,800	12,800	1,070	1,070	1,070	1,070
Tractor/grain buggy, empty	3	3,800	12,800	7,240	–	–	–
Truck, empty							
Single axle with pup	3	5,500	6,600	6,640T	–	–	–
Farm semitrailer	3	9,000	13,400T	9,500T	–	–	–
Tandem axle with pup	3	6,900	11,700T	6,640T	–	–	–
Truck/wagon, empty							
Single axle/250 bu	4	5,500	6,600	520	520	–	–
Single axle/350 bu	4	5,500	6,600	730	730	–	–
Tandem axle/450 bu	4	6,900	11,700T	1,070	1,070	–	–
Tandem axle/550 bu	4	6,900	11,700T	2,190	2,190	–	–
Tandem axle/two 350 bu	6	6,900	11,700T	730	730	730	730
Tandem axle/two 450 bu	6	6,900	11,700T	1,070	1,070	1,070	1,070
Trucks, loaded							
Commercial semitrailer	3	9,800	28,800T	29,400T	–	–	–
Tandem axle	2	20,000	34,000T	–	–	–	–
Farm semitrailer	3	9,800	33,000T	33,000T	–	–	–
Single axle with pup	3	6,800	20,000	24,000T	–	–	–
Tandem axle with pup	3	20,000	34,000T	24,000T	–	–	–
Tractor, loaded wagon							
125 bu	4	3,800	12,800	4,000	4,000	–	–
250 bu	4	3,800	12,800	7,520	7,520	–	–
Auger wagon	3	3,800	12,800	20,000	–	–	–
350 bu	4	3,800	12,800	10,530	10,530	–	–
450 bu	4	3,800	12,800	13,670	13,670	–	–
550 bu	4	3,800	12,800	17,590	17,590	–	–
Two 350 bu	6	3,800	12,800	10,530	10,530	10,530	10,530
Two 450 bu	6	3,800	12,800	13,670	13,670	13,670	13,670
Truck/wagon, loaded							
Single axle/250 bu	4	6,800	20,000	7,520	7,520	–	–
Single axle/350 bu	4	6,800	20,000	10,530	10,530	–	–
Tandem axle/450 bu	4	18,660	34,000T	13,670	13,670	–	–
Tandem axle/550 bu	4	14,820	30,000T	17,590	17,590	–	–
Tandem axle/two 350 bu	6	10,000	27,880T	10,530	10,530	10,530	10,530
Tandem axle/two 450 bu	6	10,000	15,000T	13,670	13,670	13,670	13,670

[a]T indicates a tandem axle, otherwise the axle is single *(1)*.

number between 6.5 and 13.9 rounded to one decimal place. If the road segment is of flexible pavement, the structural number can be any integer between 1 and 6, whereas the design term can be any number between 2.0 and 4.7 rounded to one decimal place.

The basic assumption underlying the maintenance cost for a paved road is that a portion of the cost varies directly with the number of axle loadings passing on the road. Therefore, the first step in estimating the maintenance costs is to express all vehicles in terms of equivalent 18,000-lb (18-kip) axle loadings that the road sustains through one pass by each vehicle.

Pavements are designed to withstand the projected number of 18-kip loadings during the expected life of the road, usually 20 years. An increase in the projected number of 18-kip loadings within a given period of time increases the maintenance cost of the road surface.

The measure of pavement condition used is the pavement serviceability index (PSI). This surface roughness index ranges from 5.0 downward to 0.0 with the upper limit being the indication of the best condition possible.

The design term relates the number of passes of a standard 18,000-lb axle load to the load-carrying capacity of the various pavement layers. The design term indicates the number of standard axle loads that can pass over a pavement before the roughness (PSI) reaches 2.0 for each flexible or rigid pavement thickness. The design term for each paved road should be computed from pavement type and thickness information supplied by the county and the state department of transportation records.

Table 5 indicates the number and type of axles and the loading on each axle for all vehicles used in the local rural road evaluation program. The program calculates the number of 18-kip equivalent loads that each vehicle applies to a pavement. The 18-kip equivalent number is multiplied by the vehicle yearly traffic level on the road to obtain the total number of 18-kip loadings the vehicle applies to the road. Summing over all vehicle types yields the annual number of 18-kip loadings applied to a road.

The Iowa Department of Transportation reports an average total annual paved-road maintenance cost. This number is multiplied by an area cost factor to obtain the average total annual paved-road maintenance cost per mile. The annual paved-road fixed-maintenance cost per mile is subtracted from average total annual paved-road maintenance cost per mile to yield the average annual paved-road variable maintenance cost. For a more complete discussion on how to use kip loadings to calculate paved-road variable maintenance cost, see Baumel et al. *(1)*.

CREATING THE DATA SETS

Creating the Network Data Set

The data set name for the network must be called NET. Each arc in the network requires one line of data. The column fields are shown in Table 6. All values must be justified to the right so that only blanks precede the value in its column field.

TABLE 6 COLUMN FIELDS FOR THE NETWORK DATA SET

Information	Column Field
Beginning node of the arc	1–5
Ending node of the arc	6–10
Distance of the arc	11–20
Weight constraint of the arc	21–30
Width constraint of the arc	31–40
Length of any bridge on the arc	41–45
Width of any bridge on the arc	46–50
Surface code of the arc	51–55

TABLE 7 COLUMN FIELDS FOR THE TRIP INFORMATION DATA SET

Information	Column Field
Beginning node	1–10
Ending node	11–20
Number of trips	21–30
Vehicle code number	31–40

Creating the Trip Information Data Set

The name for the trip information data set is TRIP. The column fields for the data set are given in Table 7. All values must be justified to the right so that only blanks precede the value in its column field.

Creating the Maintenance, Reconstruction, and Resurfacing Cost Data Sets

The data in Table 8 show the estimated values of the information required in the maintenance, reconstruction, and resurfacing cost data set for Hamilton County, Iowa. The name of the data set for the maintenance, reconstruction, and resurfacing cost is MRR. There are 10 lines in MRR, and each piece of information must be placed on a specific line and in a specific column field. Table 9 gives a list of the information required for each line and the specified column fields in which each piece of information is placed. Each piece of information is justified to the right in the column field, so there are only blanks preceding the number, not trailing the number, in the column field. Because data sources in other states may vary, the format for the MRR data may need to be modified according to the available data.

Creating the Vehicle Group Data Set

The vehicle grouping data set is called VEHGROUP. Each vehicle grouping requires three lines of data. Table 10 provides a list of the information required for each line and the specified column field in which each piece of information is placed. The number of vehicle groupings can be any value. As the number of vehicle groupings increases, the number of data lines in VEHGROUP increases. Table 11 gives a list of the relevant information pertaining to each vehicle grouping, assuming the first vehicle group consists of an automobile, a commercial

TABLE 8 ESTIMATED VALUES OF THE DATA REQUIRED IN THE MAINTENANCE, RECONSTRUCTION, AND RESURFACING COST DATA SET FOR HAMILTON COUNTY, IOWA

	Cost ($)
Fixed maintenance cost per mile of road	
Gravel	2,376.00
Dirt	2,206.00
Paved	1,160.00
B Level	505.00
Variable maintenance cost per ADT per mile of road	
Gravel	4.70
Dirt	1.52
Paved	0.00
B level	0.00
Reconstruction cost per lane-mile for Highway Group	
3	183,867.00
4	123,505.00
5	58,141.00
6	26,121.00
7	12,399.00
8	7,824.00
Resurfacing cost per lane-mile for Highway Group	
3	32,877.00
4	30,094.00
5	25,881.00
6	17,454.00
7	6,621.00
8	4,213.00
Annual rental value of farmland per acre	140.91
Cost per mile of converting right-of-way into agricultural production	700.00
Real interest rate (percent)	5.60
Annual bridge maintenance cost per square foot	0.80
Time between reconstructions of gravel and dirt roads (years)	60
Cost for a new access point	470.00

van, a pickup, and a pickup pulling a trailer, whereas the second vehicle group consists of a loaded tandem-axle truck, a loaded commercial semitrailer and a loaded farm semitrailer.

TABLE 9 INFORMATION REQUIRED FOR EACH LINE AND THE SPECIFIED COLUMNS FOR EACH PIECE OF INFORMATION IN THE MRR DATA SET

Line	Column	Information
1	1–10	Fixed maintenance cost per mile of gravel road
	11–20	Fixed maintenance cost per mile of dirt road
	21–30	Fixed maintenance cost per mile of paved road
	31–40	Fixed maintenance cost per mile of B level road
2	1–10	Variable maintenance cost per mile of gravel road
	11–20	Variable maintenance cost per mile of dirt road
	21–30	Variable maintenance cost per mile of paved road
	31–40	Variable maintenance cost per mile of B level road
3	1–15	Reconstruction cost per lane-mile of Highway Group 3
	16–30	Resurfacing cost per lane-mile of Highway Group 3
4	1–15	Reconstruction cost per lane-mile of Highway Group 4
	16–30	Resurfacing cost per lane-mile of Highway Group 4
5	1–15	Reconstruction cost per lane-mile of Highway Group 5
	16–30	Resurfacing cost per lane-mile of Highway Group 5
6	1–15	Reconstruction cost per lane-mile of Highway Group 6
	16–30	Resurfacing cost per lane-mile of Highway Group 6
7	1–15	Reconstruction cost per lane-mile of Highway Group 7
	16–30	Resurfacing cost per lane-mile of Highway Group 7
8	1–15	Reconstruction cost per lane-mile of Highway Group 8
	16–30	Resurfacing cost per lane-mile of Highway Group 8
9	1–10	Annual rental value of farmland per acre
	11–20	Cost of converting the right-of-way to farmland
	21–25	Annual bridge maintenance cost per square foot
	26–30	Annual interest rate
10	1–5	Number of years between reconstruction of gravel roads
	6–10	Number of years between reconstruction of dirt roads
	31–40	Cost for a new access point

Creating the Paved County Road Data Set

The paved county road data set is called PAVEMENT. Table 12 gives a list of the information required for each line and the specified columns in which each piece of information is placed. If a paved-road segment was reconstructed 30 years ago or more, a 1 is placed in Column 15. A 2 is placed in Column 15 if the paved road segment was reconstructed more than 15 but less than 30 years ago, while a 3 is placed in Column 15 if the paved road segment was reconstructed 15 years ago or less. If a road segment is paved of rigid pavement, a T is placed in Column 20; if paved of flexible pavement, an F is placed in Column 20. The number of data lines in the PAVEMENT data set depends on the number of paved county road segments in the study area. Table 13 gives an example of the information for the paved county roads in the sample network shown in Figure 1.

HOW TO RUN THE LOCAL RURAL ROAD EVALUATION PROGRAM

The disk provides three data sets and three execute files. The three data sets NAMES, TABLES, and VEHICLES, along with

TABLE 10 INFORMATION REQUIRED FOR EACH LINE AND THE SPECIFIED COLUMNS FOR EACH PIECE OF INFORMATION IN THE DATA SET VEHGROUP

Line	Column	Information
1	1–75	Number of vehicle groupings
2	1–10	Representative weight for Grouping 1
	11–15	Representative width for Grouping 1
	21–35	Representative ratio of cost per mile of travel over a gravel surface to a paved surface for Grouping 1
	36–50	Representative ratio of cost per mile of travel over a dirt surface to a paved surface for Grouping 1
	51–65	Representative ratio of cost per mile of travel over an Area B surface to a paved surface for Grouping 1
	66–75	Total number of vehicles in Grouping 1
3	1–5	First vehicle code number in Grouping 1
	6–10	Second vehicle code number in Grouping 1
	11–15	Third vehicle code number in Grouping 1
	16–20	Fourth vehicle code number in Grouping 1
	21–25	Fifth vehicle code number in Grouping 1
	26–30	Sixth vehicle code number in Grouping 1
	31–35	Seventh vehicle code number in Grouping 1
	36–40	Eighth vehicle code number in Grouping 1
	41–45	Ninth vehicle code number in Grouping 1
	46–50	Tenth vehicle code number in Grouping 1
	51–55	Eleventh vehicle code number in Grouping 1
	56–60	Twelfth vehicle code number in Grouping 1
	61–65	Thirteenth vehicle code number in Grouping 1
	66–70	Fourteenth vehicle code number in Grouping 1
	71–75	Fifteenth vehicle code number in Grouping 1
4	1–5	First vehicle's variable cost per mile of traveling over a paved surface in Grouping 1
	6–10	Second vehicle's variable cost per mile of traveling over a paved surface in Grouping 1
	71–75	Fifteenth vehicle's variable cost per mile of traveling over a paved surface in Grouping 1
5		Pertains to Grouping 2 and is formatted the same as Line 2
6		Pertains to Grouping 2 and is formatted the same as Line 3
7		Pertains to Grouping 2 and is formatted the same as Line 4
8		Pertains to Grouping 3 and is formatted the same as Line 2
9		Pertains to Grouping 3 and is formatted the same as Line 3
10		Pertains to Grouping 3 and is formatted the same as Line 4

the user-created data sets, are placed on the fixed disk of the microcomputer. The three execute files are named PASS1.EXE, PASS2.EXE, and PASS3.EXE.

To begin the local rural road evaluation program, type PASS1 on the keyboard. The command PASS1 initiates the execution of the first step of the local rural road evaluation program. The following question then appears on the screen:

> IS THIS RUN FOR THE BASE SOLUTION? (Y/N)

To run the base solution with all the roads in their present condition, type Y for yes. To run an alternative solution with an alternative investment strategy, type N for no.

TABLE 11 AN EXAMPLE OF VEHICLE GROUPING INFORMATION

Vehicle Group	Description		Typical Value
1	Representative weight (tons)		4
	Representative width (ft)		6
	Representative ratio of cost (cents per mile) of travel over a gravel surface to that over a paved surface		1.39
	Representative ratio of cost (cents per mile) of travel over a dirt surface to that over a paved surface		1.77
	Representative ratio of cost (cents per mile) of travel over a B level to that over a paved surface		1.98
	Total number of vehicles		4
	Vehicle cost (cents per mile) of travel over a paved surface		
	Code	*Vehicle*	
	1	Automobile	20.2
	2	Commercial van	40.2
	3	Pickup	24.4
	8	Pickup pulling trailer	35.3
2	Representative weight (tons)		40
	Representative width (ft)		8
	Representative ratio of cost (cents per mile) of travel over a gravel surface to that over a paved surface		1.48
	Representative ratio of cost (cents per mile) of travel over a dirt surface to that over a paved surface		1.96
	Representative ratio of cost (cents per mile) of travel over a B level to that over a paved surface		2.16
	Total number of vehicles		3
	Vehicle cost (cents per mile) of travel over a paved surface		
	Code	*Vehicle*	
	33	Loaded tandem-axle truck	42.4
	34	Loaded farm semitrailer	37.4
	32	Loaded commercial semitrailer	55.4

Running a Base Solution

After Y is typed to the first question, the following message appears on the screen:

> ENTER THE NAME OF YOUR STUDY AREA

The study area name, which must start with a letter and consist of no more than 15 characters, is then typed on the

TABLE 12 INFORMATION REQUIRED FOR EACH LINE AND THE SPECIFIED COLUMNS FOR EACH PIECE OF INFORMATION IN THE DATA SET PAVEMENT

Line	Column	Information
1	1–5	Beginning node of the first paved county road segment
	6–10	Ending node of the first paved road segment
	15	One if the road was reconstructed 30 or more years ago Two if the road was reconstructed more than 15 years but less than 30 years ago Three if the road segment was reconstructed 15 years ago or less
	20	T if the road segment pavement is rigid, or F if the road segment pavement is flexible
	21–25	Structural number if the road segment pavement is flexible, or the slab thickness of the road segment is rigid
	26–30	Design term of the paved county road segment
2		Pertains to the next paved county road segment and is formatted the same as Line 2
Last line	1–25	Average annual paved road variable maintenance cost

keyboard. When PASS1 is completed, the following message appears:

> PASS ONE COMPLETED

After this message appears on the screen, type PASS2 on the keyboard. The command PASS2 initiates the second step of the local rural road evaluation program. When PASS2 is completed, the following message appears:

> PASS TWO COMPLETED

After this message appears on the screen, type PASS3 on the keyboard. The command PASS3 initiates the final step of the local rural road evaluation program. When PASS3 is completed, the following message appears:

> PASS THREE COMPLETED

The output of the base solution is then found in the data set called "RESULTS."

Running a Reduced Solution

A reduced solution is run to evaluate an alternative investment strategy. After N is typed to the first question, the following message appears on the screen:

> ENTER THE NUMBER OF ROAD SEGMENTS TO BE ABANDONED

Type the number of road segments to be abandoned; if there are no road segments to be abandoned, type zero. The computer then asks for the beginning node (BN) and the ending node (EN) for each road segment to be abandoned. Type in the BN and EN for only one (not both) of the arcs representing the road segment. Remember that each road segment is represented by two arcs. For example, the road segment connecting Node 1 to Node 5 in Figure 1 is represented by an arc with a beginning node of 1 and an ending node of 5 and by an arc with a beginning node of 5 and an ending node of 1. If the road segment connecting Node 1 to Node 5 is to be abandoned, then type, for example, BN = 1, EN = 5. After the BN and EN for all the abandoned road segments are entered, the following message question appears on the screen:

> ENTER THE NUMBER OF ROAD SEGMENTS TO BE UPGRADED

Type the number of road segments to be upgraded. If there are no road segments to be upgraded, type zero. The computer then asks for the BN and EN for each road segment upgraded. Again, type the BN and EN for only one of the arcs representing the road segment. The computer then prints out the present weight limit, width constraint, and surface code, and asks for new values for the weight limit, width constraint, and surface code for each road segment. If a characteristic of the road segment is not changed from the base network, simply type the present value for the new value. For example, if a bridge on a gravel road segment is to be upgraded to legal limits, type 40 for the new weight limit, 20 for the width constraint, and 2 for the new surface code. The computer then asks for the total upgrading cost for the road segment. If a road segment is to be paved, the computer asks for the design terms and whether the new pavement type is rigid or flexible. If the new pavement is rigid, the computer asks for the slab thickness number; if the new pavement is flexible, the computer asks for the structural number. After these questions are answered, the following message appears on the screen:

> ENTER THE NUMBER OF ROADS TO BE CONVERTED TO B LEVEL SERVICE

Type the number of road segments to be converted to B level service. If there are no road segments converted to B level service, type zero. The computer then asks for the BN and EN for each road segment converted to B level service. Type in the BN and EN for only one of the arcs representing the road segment. After these questions are answered, the following message appears on the screen:

> ENTER THE TOTAL NUMBER OF NEW ACCESS POINTS PUT INTO THE ROAD SYSTEM

Type the total number of new access points to be put into the road system. If there are no new access points, type zero. The computer then asks for the tract number and the new access location for each new access point put into the road system. After these questions are answered, the following message appears on the screen:

> ARE THERE ANY ROAD SEGMENTS TO BE CONVERTED TO PRIVATE DRIVES? (Y/N)

Type Y for yes if there are road segments to be converted to private drives. Type N for no if there are no road segments converted to private drives. If there are road segments to be converted to private drives, the following series of messages appears on the screen:

TABLE 13 AN EXAMPLE OF THE INFORMATION FOR THE PAVED COUNTY ROADS IN THE STUDY AREA PRESENTED IN FIGURE 1

Road Segment			Slab Thickness or		
Beginning Node	Ending Node	Pavement	Structural Number	Design Term	Years Since Last Reconstruction
3	4	Flexible	1	2.1	15
4	6	Rigid	6	6.6	20
6	10	Rigid	7	6.5	31

NOTE: Average annual paved road maintenance cost = $170.65.

TABLE 14 PRIVATE DRIVE MAINTENANCE COST CODE BY TYPE OF ACCESS

Type of Access	Private Drive Maintenance Cost Code
Residence only	1
Small to medium farm	2
Large farm	3
Field access only	4

TABLE 15 FORMAT OF THE "RESULTS" DATA SET

Annual Costs of Providing the System	Current	Previous	Change
Annual costs to the county			
Total variable maintenance cost			
Total fixed maintenance cost			
Total reconstruction cost			
Total resurfacing cost			
Total upgrading cost			
Total bridge maintenance cost			
Total cost for new access points			
Annual cost to the county			
Annual cost to private drives			
Total maintenance cost			
Total reconstruction cost			
Total bridge maintenance cost			
Annual cost of private drives			
Annual net value of land			
Changes in annual cost of providing the system			
Annual costs to the traveling public			
Total annual travel cost			

> ENTER THE NUMBER OF ROAD SEGMENTS TO BE CONVERTED TO PRIVATE DRIVES

Type the number of road segments converted to private drives. The total number of road segments converted to private drives cannot exceed 22. The computer then asks for the BN and EN for each converted road segment. Again, type the BN and EN for only one of the arcs representing the road segment. The computer then asks for the private drive maintenance code for each converted road segment. Table 14 presents the values of the private drive maintenance cost code by type of access.

After these questions are answered, the following message appears on the screen:

> PASS ONE COMPLETED

After this message appears on the screen, type PASS2. The command PASS2 initiates the second step of the local rural road evaluation program. When PASS2 is completed the following message appears on the screen:

> PASS TWO COMPLETED

After this message appears, type PASS3. The command PASS3 initiates the final step of the local rural road evaluation program. Each new solution is compared with a previous solution, either the base solution or an alternative solution. The computer then requests the following information concerning the previous solution:

> ENTER THE TOTAL VARIABLE MAINTENANCE COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL FIXED MAINTENANCE COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL RECONSTRUCTION COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL RESURFACING COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL VALUE OF LAND FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL BRIDGE MAINTENANCE COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL TRAVEL COST FROM THE PREVIOUS SOLUTION

> ENTER THE PRIVATE DRIVE MAINTENANCE COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL UPGRADING COST FROM THE PREVIOUS SOLUTION

> ENTER THE TOTAL COST FOR NEW ACCESS POINTS FROM THE PREVIOUS SOLUTION

> ENTER THE PRIVATE DRIVE RECONSTRUCTION COST FROM THE PREVIOUS SOLUTION

> ENTER THE PRIVATE DRIVE BRIDGE MAINTENANCE COST FROM THE PREVIOUS SOLUTION

All of the information from the previous solution is found in the output for that solution. After this information is entered, the following message appears on the screen:

> PASS THREE COMPLETED

The output of an alternative solution is found in the RESULTS data set. The format of the RESULTS data set is given in Table 15. The annual cost of providing the system consists of the annual costs to the county, the annual cost of private drives, and the annual net value of land. The annual cost to the traveling public is the total annual travel cost. The column headed "current" represents the costs associated with the investment strategy, whereas the column headed "previous" gives the costs before the investment strategy was implemented. The column headed "change" presents the difference between current costs and previous costs.

The RESULTS data set identifies the benefits and costs of the investment strategy. The benefits of an investment strategy are defined as a reduction in either the annual cost of providing the system or the annual travel cost, whereas the costs of an investment strategy are defined as an increase in either the annual cost of providing the system or the annual travel cost. A benefit-cost ratio is calculated and interpretation of the ratio is presented in the RESULTS data set.

A disk containing the microcomputer program to evaluate the benefits and costs of alternative investment strategies can be obtained by mailing a check for $12.50 made out to Iowa State University to: C. Phillip Baumel, Department of Economics, Iowa State University, Ames, Iowa 50011.

REFERENCES

1. C. P. Baumel, C. A. Hamlett, and G. A. Pautsch. *The Economics of Reducing the County Road System: Three Case Studies in Iowa.* DOT/OST/P-34/86/035. U.S. Department of Transportation, Jan. 1986.
2. *Quadrennial Need Study Report on Highways, Roads and Streets for Study Years 1982 through 2001.* Vol. I. Iowa Department of Transportation, Ames, July 1983.

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Corps of Engineers Low-Volume Road Design

JOHN C. POTTER, RAYMOND S. ROLLINGS, AND WALTER R. BARKER

The U.S. Army Corps of Engineers' pavement design procedures are particularly appropriate for low-volume road applications because they were developed from traffic tests using relatively low traffic volumes and thin pavement sections on low-strength subgrades. The large loads and low volumes of traffic used in their development are especially analogous to situations encountered in mining, logging, and similar industrial applications, or in port facilities. The flexible pavement criteria are most appropriate for thin asphalt concrete pavements in granular base courses and subbases. Generally, rigid pavements have not been associated with low-volume roads because of their cost. However, development of roller-compacted concrete pavement construction has made rigid low-volume pavements feasible in many situations, and the corps design method is capable of addressing roller-compacted concrete pavement characteristics. These design procedures, published in Army technical manuals, have also been computerized. The Corps of Engineers' design criteria can now be applied quickly and efficiently, even by pavement engineers unfamiliar with the corps criteria or programs, to design economical pavements for military installations and other low-volume facilities.

The U.S. Army Corps of Engineers design procedures for roads and streets have been developed for application to the low traffic volumes generally associated with military installations. A central facet of the design criteria for both rigid and flexible pavements is a rational consideration of the structural requirements for pavements expected to experience limited traffic over their design life.

These design procedures have long been described in the various Army technical manuals. Now they have also been computerized. The computerized versions of the technical manuals allow faster and more error-free design. A wider range of structural design alternatives also becomes practical.

SCOPE

The design procedures for rigid and flexible pavements is the primary focus of this paper. These procedures were developed from traffic tests using relatively low traffic volumes and thin pavement sections on low-strength subgrades. The large loads and low volumes of traffic used in their development are especially analogous to situations encountered in mining, logging, and similar industrial applications, or in port facilities. The flexible pavement criteria are most appropriate for thin asphalt concrete pavements on granular base courses and subbases. Generally, rigid pavements have not been associated with low-volume roads because of their cost. However, development of roller-compacted concrete pavement construction has made rigid low-volume pavements feasible in many situations, and the corps design method is capable of addressing roller-compacted concrete pavement characteristics. Unsurfaced or aggregate-surfaced roads subject to heavy loads generally require continuous maintenance, even for low traffic volumes. The corps criteria for these roads are also less sophisticated than for rigid and flexible pavements and have not been computerized.

ROADS AND STREETS

A major element in any pavement design is the characterization of the anticipated traffic and selection of a design traffic loading. This task has been simplified in the corps criteria by use of a design index. The design index is a measure of the total lifetime traffic for the pavement in terms of equivalent 18-kip axle loads. Each design index corresponds to a range of equivalent 18-kip axle loads such as those given in Table 1. Pavements subjected to loads from vehicles such as forklift trucks or heavy aircraft, which are significantly greater than the 18-kip axle load, are designed separately. The use of 18-kip axle equivalents is not sufficiently accurate for these loads.

TABLE 1 FLEXIBLE PAVEMENT DESIGN INDEX AND RANGE OF EQUIVALENT 18-KIP AXLE COVERAGES

Flexible Pavement (DI)	Range of Equivalent Coverages	
	Minimum	Maximum
1	0	2,400
2	2,400	10,500
3	10,500	47,000
4	47,000	207,000
5	207,000	908,000
6	908,000	4,000,000
7	4,000,000	18,000,000
8	18,000,000	79,500,000
9	79,500,000	355,000,000
10	355,000,000	1,600,000,000

NOTE: DI is design index.

The design index is determined in the same manner for both rigid and flexible pavements, except that the ranges of

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equivalent 18-kip axle coverages for each design index are different. (Here, a coverage is defined as a sufficient number of movements or passes of the design vehicle to cover the entire traffic lane with at least one stress repetition.) Traffic typical of a particular traffic category and facility class has been converted to equivalent 18-kip axle loads so that the appropriate design index can be selected knowing only the type of traffic (category) and roadway class. Additional guidance is provided, if needed, for selecting the category and class for a particular design.

The rural "road" or urban "street" class is a function of the design hourly volume (DHV), for the 25-year service life, as indicated in Table 2. The DHV is assumed to be 15 percent of the average daily traffic (ADT) for rural roads and 12 percent of the ADT for streets in built-up areas. Various geometric design constraints, appropriate for the traffic intensity, also apply to each class. Parking area design is based on Class E traffic.

TABLE 2 DESIGN HOURLY VOLUME AND ROAD/STREET CLASS

	DHV	
Class	Road	Street
A	≥ 900	≥ 1,200
B	720–899	1,000–1,199
C	450–719	750–999
D	150–449	250–749
E	10–149	25–249
F	< 10	< 25

The traffic category is governed by the number per day and gross weight of tracked vehicles, if any. Otherwise, the traffic category is based on the percentages of 2- and 3-axle trucks in the traffic mix. The descriptions for each category, and the design index corresponding to those categories for each class, are given in Table 3.

Thickness adjustment for traffic level has long been a part of Corps of Engineers pavement design. Both the rigid and flexible pavement design procedures are based on extensive full-scale, accelerated traffic testing to failure in a wide range of climates using a wide range of pavement structures and load configurations. These procedures have been highly refined for pavements subject to heavy aircraft loads and have been transferred to the design procedures for more lightly loaded pavements. These adjustments are based on actual field performance rather than laboratory tests. Environmental effects such as joint behavior, temperature and moisture cycles, and gradients and material variability, not normally accounted for by laboratory-determined design values, are implicitly incorporated.

Flexible Pavements

The flexible pavement design procedure is based on the California bearing ratio (CBR) equation and uses a thickness adjustment factor called the load-repetitions factor. Figure 1 shows the load-repetitions factor, α, as a function of 18-kip axle coverages. The coverage level corresponding to the middle of the range of equivalent 18-kip axle loads for a particular design index (Table 1) is used to determine the appropriate α-factor.

Rigid Pavements

The Corps of Engineers' rigid pavement design method is based on a fatigue analysis. Tensile stress for the design load is calculated by using the Westergaard edge-loaded analytical model. When traffic loads will not actually "traffic" the free edge of a slab such as in parking areas or on airfields, these calculated stresses are reduced 25 percent to account for load transfer between adjacent slabs. Twenty five percent was selected as an appropriate design value from model and full-scale tests on pavements by using load transfer devices that met corps criteria. Pavements such as those on most roads and streets carry traffic loads adjacent to the outside free edge, and no reduction in stress is allowed for these.

The Corps of Engineers defines design factor as the modulus of rupture of concrete divided by the design tensile stress. Full-scale accelerated traffic tests were used to develop the fatigue relation between design factor and coverages shown in Figure 2. The failure criteria used in these tests, which is the basis of the Corps of Engineers fatigue relationship, is the development of one or more structural cracks in one-half or more of the trafficked slabs. This analysis approach is used to select a pavement thickness to resist the fatigue effects of the desired design repetitions of traffic load. The design factor corresponding to a given design index is chosen as with the α-factor, but using a coverage level corresponding to the midrange of the values given in Table 4. Additional adjustments are used in the design procedure for special cases such as subgrade pumping protection, high strength subgrades, frost action, and so forth.

Roller-compacted concrete is of particular interest for use on low-volume roads. The economics of using it are in the construction method rather than in reduced materials cost, and it has the potential of providing reduced-cost pavements at the expense of increased roughness and poorer appearance. To date there is no indication that the fatigue properties of roller-compacted concrete are any different from conventionally placed portland cement concrete. Consequently, the regular Corps of Engineers' rigid pavement design procedures can be used to design roller-compacted concrete with one restriction. The current methods of construction for roller-compacted concrete do not provide reliable load transfer across joints between slabs. Therefore current design aids, such as those published in technical manuals or the microcomputer programs, would provide erroneous results for a case in which roller-compacted concrete is used for a parking area unless the user was aware of the adjustments needed.

Computerization

Rigid pavement design for roads and streets (including vehicular parking areas) is covered in *Rigid Pavements for Roads, Streets, Walks, and Open Storage Areas (1)*. Flexible pavements are addressed in *Flexible Pavements for Roads, Streets, Walks, and Open Storage Areas (2)*. A complete design also

TABLE 3 PAVEMENT DESIGN INDEX

Traffic Category	Pavement Design Index for Road or Street Classification A	B	C	D	E	F
I (< 1% two-axle trucks)	2	2	2	1	1	1
II (≤ 10% 2-axle, no 3-axle trucks)	3	2	2	2	2	1
III (≤ 15% trucks, ≤ 1% 3-axle trucks)	4	4	4	3	3	2
IV (≤ 25% trucks, ≤ 10% 3-axle trucks)	5	5	5	4	4	3
IVA (≥ 25% trucks or ≥ 10% 3-axle trucks)	6	6	6	5	5	4
V (60-kilopound (kip) track-laying vehicles):						
500/day	7	7	7	7	7	*
200/day	6	6	6	6	6	*
100/day	6	6	6	6	6	6
40/day	6	6	6	5	5	5
10/day	5	5	5	5	5	5
4/day	5	5	5	5	4	4
1/day	5	5	5	4	4	4
VI (90-kip track-laying vehicles):						
200/day	9	9	9	9	9	*
100/day	8	8	8	8	8	8
40/day	7	7	7	7	7	7
10/day	6	6	6	6	6	6
4/day	6	6	6	6	6	6
1/day	5	5	5	5	5	5
1/week	5	5	5	4	4	4
VII (120-kip track-laying vehicles):						
100/day	10	10	10	10	10	10
40/day	9	9	9	9	9	9
10/day	8	8	8	8	8	8
4/day	7	7	7	7	7	7
1/day	6	6	6	6	6	6
1/week	5	5	5	5	5	5

* Traffic limited to 100 vehicles per day.

TABLE 4 RIGID PAVEMENT DESIGN INDEX AND RANGE OF EQUIVALENT 18-KIP AXLE COVERAGES

Rigid Pavement Design Index	Range of Equivalent Coverages Minimum	Maximum
1	1	45
2	45	600
3	600	13,000
4	13,000	130,000
5	130,000	800,000
6	800,000	3,500,000
7	3,500,000	14,000,000
8	14,000,000	40,000,000
9	40,000,000	110,000,000
10	110,000,000	300,000,000

requires use of appropriate material from the technical manuals *Pavement Design for Seasonal Frost Conditions (3)* and *General Provisions and Geometric Design for Roads, Streets, Walks, and Open Storage Areas*. Having a working knowledge and understanding of the intricacies of these procedures are formidable tasks for a new corps employee or consultant designing a pavement for the Corps of Engineers. Errors of interpretation or application of the criteria or omissions of valuable options and considerations are easily committed. The scrupulously precise logic of a computer program offers the potential for reducing errors of this kind. The increased computational speed makes consideration of a large number of potential pavement systems feasible.

The Corps of Engineers now has a series of computer programs for microcomputers that constitutes a high speed, friendly, interactive alternative to the technical manuals. Rigid pavement design for roads is covered by the RRD computer program, and flexible pavement design for roads is covered by the FRD program.

The two computer programs were developed specifically to operate on IBM PC's or compatible microcomputers using FORTRAN 77. Each of the programs has been uploaded to mainframe computers with only minimal effort. The computer programs were written to follow the design manual in a logical stepwise procedure. Questions are asked that must be answered so that all aspects of the design must be considered by the designer. In areas in which questions are not completely clear, accompanying information is provided. Also, when necessary, guidance in the selection of design data will be provided. The computer programs provide for a data review and a method of changing any design data before execution of the particular design problem. The programs determine pavement thicknesses and other pertinent design information that is consistent with the design manuals. The product from the program is first output to the screen and a disk file. The operator may then direct the output from the disk file to the printer.

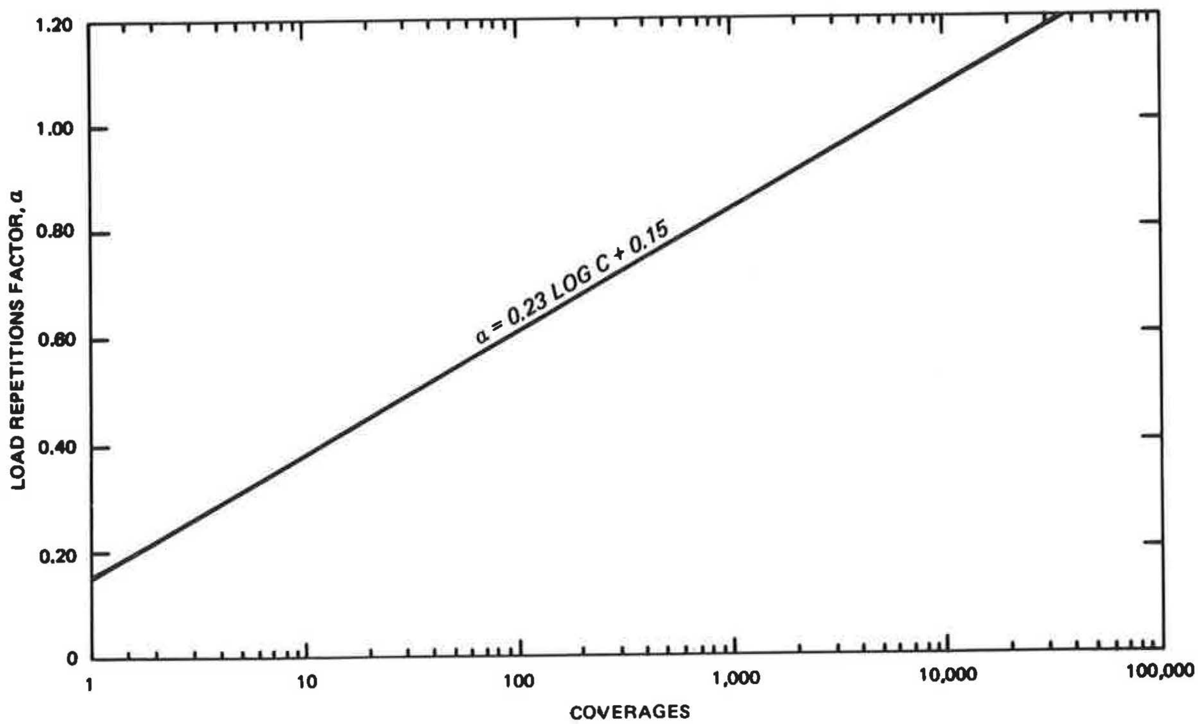

FIGURE 1 Load repetitions factor versus coverages.

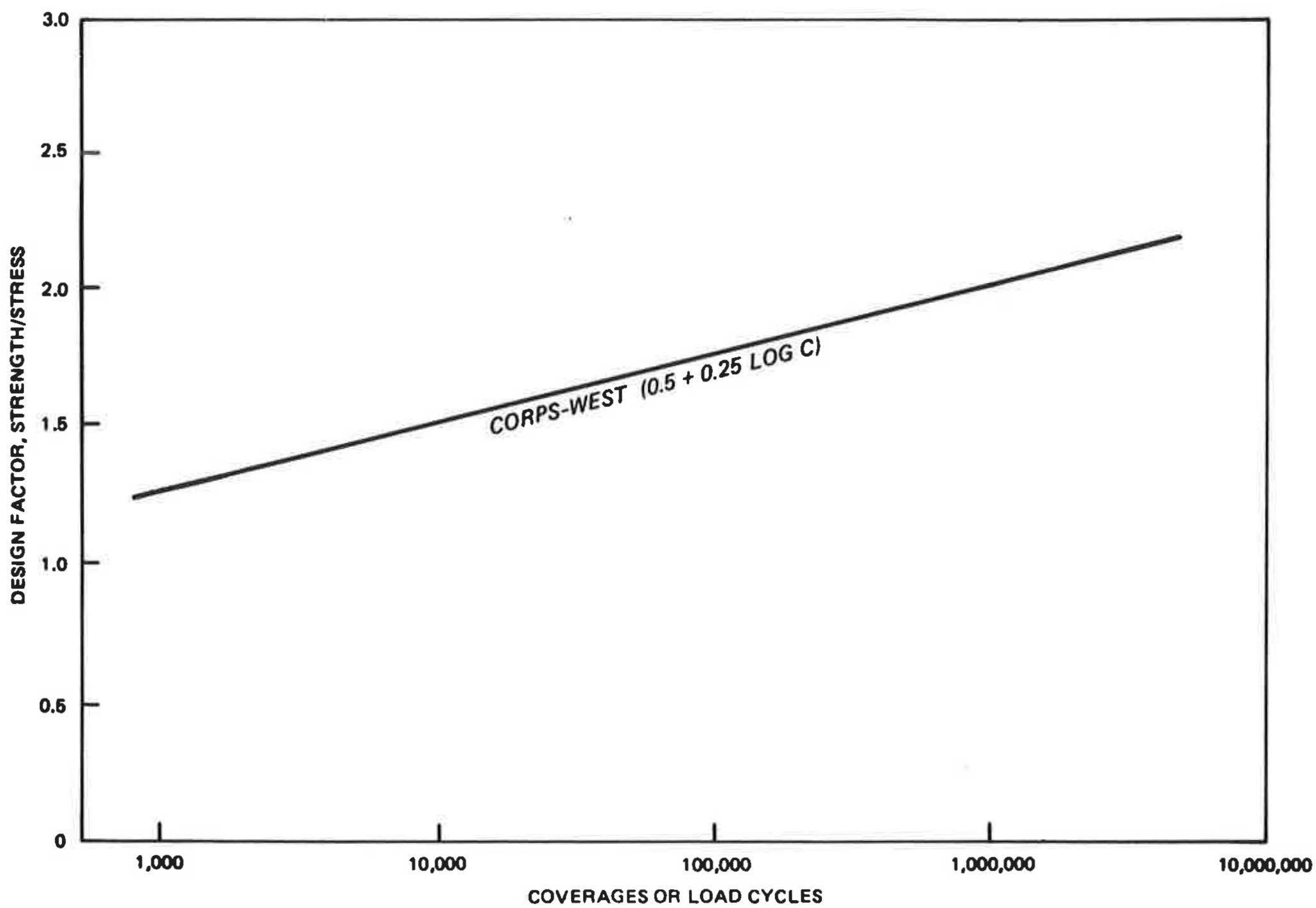

FIGURE 2 Design factor versus coverage.

CONCLUSIONS

The Corps of Engineers design criteria are appropriate for low-volume roads, especially if subjected to large wheel loads. The criteria can be used to design both flexible and rigid pavements, including roller-compacted concrete construction. Although the corps criteria are relatively complex, they have been incorporated into flexible and rigid pavement computer programs. These programs can be used on the microcomputer at the design engineer's desk to quickly design a selection of alternative pavement sections from which to choose the most economical section, confident that the Corps of Engineers design criteria are satisfied by each of the alternatives.

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REFERENCES

1. *Rigid Pavements for Roads, Streets, Walks, and Open Storage Areas.* Technical Manual 5-822-6. Department of the Army. U.S. Government Printing Office, Washington, D.C., April 1977.
2. *Flexible Pavements for Roads, Streets, Walks, and Open Storage Areas.* Technical Manual 5-882-5. U.S. Government Printing Office, Washington, D.C., Oct. 1980.
3. *Pavement Design for Seasonal Frost Conditions.* Technical Manual 5-818-2. U.S. Government Printing Office, Washington, D.C., Jan. 1985.
4. *General Provisions and Geometric Design for Roads, Streets, Walks, and Open Storage Areas.* Technical Manual 5-822-2. U.S. Government Printing Office, Washington, D.C., April 1977.

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