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CONTENTS

FOREWORD

Because highway maintenance does not seem to be as glamorous or productive as highway construction, there is a tendency to ignore maintenance costs when new roads are programmed for construction. Yet maintenance costs persist long after construction is complete. After the Interstate System is completed, many states will be spending more to maintain roads than they did to build them. That this is now beginning to create problems is apparent. The Federal Highway Administration recently felt constrained to tell state highway departments that they should keep open rest area facilities constructed with federal-aid funds even though some state highway departments did not feel they could afford the expenditures involved in maintaining them.

This problem, serious as it may be in developed countries, is felt even more strongly in undeveloped countries where expenditure for national development of transport ranks first or second among all classes and the money for development is provided by lending agencies. Yet these lending agencies expect borrowers to continue to maintain facilities with little or no aid. A similar problem exists in the United States where no direct federal-aid money is available for maintenance.

The paper by Hall addresses the problem of inventorying the road system in Sudan. Bauman and Betz develop a method of estimating maintenance requirements and costs as developed for a transportation system planning activity in Sudan.

Stone offers a procedure for simulation modeling of highway maintenance operations. In this particular application, a mowing model was developed that facilitates decision-making related to mowing operations. However, the program developed for the mowing model is a utility program that can be extended to other highway maintenance operations such as road patching, snowplowing, or ditching operations.

The paper by Doom reports on a search for answers to equipment maintenance and utilization questions posed by top management of the Virginia Department of Highways. As a result of the study, specific recommendations were made and implemented that resulted in estimated savings amounting to $450,000 annually in the form of reduced unit costs.

Two defects considered of paramount importance, separation of a concrete bridge slab into two or more approximately horizontal layers and poor quality concrete, are being investigated by the Texas Transportation Institute because most structural damage to deteriorating bridge decks results from one or both of these defects. Two papers report on the development of methods to evaluate the extent of this deterioration in bridge decks. One report by Moore describes an instrument to detect delamination and includes an evaluation of the device; the other study by Moore, Swift, and Milberger examines delamination detection, corrosion potential, acoustic velocity, Windsor probe, Schmidt rebound hammer, and direct tensile strength.

SUDAN ROAD SURVEY: THE FIELD INVENTORY AND ITS SUGGESTED MAINTENANCE OF LOW-VOLUME TRACKS

Kenneth M. Hall, Memphis State University

In 1966 Lockheed Aircraft International, Inc., began a comprehensive plan for upgrading the transportation system of the Democratic Republic of the Sudan. Because there were few historical data, a field survey was undertaken to obtain information on soils, drainage, aggregate availability, and vehicle operating costs. This paper delineates and discusses the planning and prosecution of the survey. Particular emphasis is placed on survey procedure and related problems and evaluation of the technique. Suggestions are made for future surveys. A map of the boundaries and the classification of the major soil groups in northern and central Sudan are included. In the process of gathering data for the long-range transportation plan, data pertinent to maintenance of the existing system were obtained. This paper concludes with a discussion of maintenance techniques for extending the useful life of existing tracks into the rainy season, providing all-season vehicular transport to central and northern Sudan.

•A TRUCKER in Sudan may very well be the world's finest example of the indomitable spirit of free enterprise. Pursuing his livelihood, a trucker must be an extraordinary driver, a master mechanic, a freight agent, a conductor (because he will carry both freight and passengers), a policeman, a banker, an entrepreneur, and, at times, a prophet. He must function continuously for long periods of time under the most adverse trucking conditions imaginable. During the year, the trucker's business will take him over windswept sands where temperatures above 120 F are not uncommon, over giant clay plains where the earth tracks become endless ribbons of corrugations, and occasionally over metamorphic landscapes where the terrain, because of its ruggedness, appears to be extraterrestrial. When the rains come, the valleys and the giant clay plains become seas of mud. Add to these geographic conditions a scarcity of spare parts, and the problem reaches such magnitude that one can only marvel that trucks operate at all in Sudan. But, operate they do—and at a profit.

Sudan is located in the northeastern section of Africa, bordered on the north by Egypt and bordered on the east by the Red Sea and Ethiopia (Fig. 1). Geographically, the country is the largest in Africa, about 1 million square miles. Its current population is estimated at 13 million people. Generally, Sudan is a gigantic plain with some isolated mountainous areas. The most important of these are the Red Sea Hills, which parallel the Red Sea coast, the Jebel Mara Complex in Western Darfur Province, the Nuba Hills in Kordofan Province, and the highland area of the southeastern border.

Sudan has a tropical continental climate. The country has a consistent gradation in the rainfall from north to south. Generally, the area north of latitude 19 North can be classified as desert. South of this is a semidesert region with a short rainy season. The amount of rain and the length of the season increase as the distance to the equator decreases. In the southern extreme of the country, there is an area of dense vegetation where rain falls in various amounts for 9 or 10 months a year.

The most important geographical feature of the country is the Nile River system. The Nile system provides water for habitation and irrigation for much of the country

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and is essential to its economy. It has also provided a traditional transport link. The river winds through the entire length of the country and has played a historic role.

The White Nile rises in Lake Victoria and enters Sudan at Nimule. There it goes over a series of rapids and enters the great plain of Sudan. For the next 400 miles it winds through a swamp known as the Sudd, which covers thousands of square miles in Upper Nile and Bahr El Ghazal Provinces. The swamp accounts for a high loss of water by evaporation, which is vitally needed in the dry northern areas, and has been a great hindrance to transportation. The Sudd has been such a substantial barrier that it prevented the identification of the source of the White Nile until the modern era. The Blue Nile drains Lake Tana in Ethiopia, 1,000 miles by river from Khartoum. Unlike the White Nile flowing placidly from the Sudd, the Blue Nile is torrential and highly variable. Of the total annual discharge of the Nile north of Khartoum, 85 percent comes from Ethiopia with only 15 percent through lower Sudan. The main Nile north of Khartoum contains the historic cataracts that inhibit river transportation to the present day. Also north of Khartoum there are few tributaries, and of these only the Atbara flows continuously. The Nile flows into Lake Nasser about 50 miles from the Sudanese-Egyptian border.

Although there are no major mountainous areas and most of the country is a great plain, Sudan is virtually without a constructed road system in the northern and middle portions of the country. These areas contain the irrigated cotton schemes that are the economic base of the country.

A mixture of land, water, and air facilities will be needed to produce an optimum transportation network. Much of the country is uninhabited or traversed by seminomadic peoples. This paper discusses a field survey conducted by the personnel of the Engineering Research Center, Arizona State University, under contract to Lockheed Aircraft International, Inc. Lockheed's objective was the development of a long-range transportation plan for Sudan. The purpose of the Arizona State University subcontract was to develop the basic engineering and economic data for road design and cost estimation for road improvements and maintenance. Specifically the function of the field survey was the accumulation of fundamental soil, drainage, aggregate availability, water, and vehicle operating cost information. The survey was conducted between January 1966 and May 1967. Thus, it represented 16 consecutive months of effort by Arizona State University personnel in Sudan.

PLANNING THE SURVEY

There is nothing unique about collecting engineering data, but it is rarely attempted on such a scale as occurred in Sudan. Most on-the-ground surveys are oriented toward design rather than toward general feasibility or systems planning. The goal of this study was to survey the country so that basic levels of improvement of the existing tracks, maintenance, and operation costs could be estimated for inclusion in a systems analysis. Approximately two-thirds of the country, the central and northern portions, were surveyed. This included more than 5,500 route miles. It is estimated that the crew traveled about 9,000 miles during the survey including backtracking.

At the time the survey was conducted, there were less than 50 miles of hard surface rural roads and less than 2,000 miles of all-weather rural roads of any type. Of these 2,000 miles, more than 1,900 miles were located in the laterite area of the southern three provinces and were gravel-surfaced. The vast majority of the country had no all-weather, motorized transport. Historical road-building experiences of any magnitude simply did not exist. It was necessary to develop all the parameters for construction and maintenance estimates based on the data to be gathered by the reconnaissance team.

Data gathering began with an analysis of existing maps and other information. Extensive use was made of recollections and diaries kept by people who had traveled in Sudan. The country is made up of rather distinct geological areas: "fixed" sand dunes, referred to as Qoz; clay plains, ironstone or lateritic; and large rock masses covered with thin, superficial soil deposits. Each of these areas requires different types of road improvement and maintenance, and each causes unique problems to existing transport. The survey was planned to delineate these areas and to gather data pertinent to each. To do so, a 50-mile nodal system was laid out in accordance with the existing tracks. That is, a series of points approximately 50 miles apart was selected in such a way that, by traveling among them, boundaries of the various areas could be determined. The routes were selected to obtain the widest possible coverage of the developed, or potentially developable, areas of the northern six provinces. (Permission to survey the three southern provinces, Equatoria, Bahr El Ghazal, and Upper Nile, was denied because of political conditions existing at that time.) Virtually all the routes selected were unimproved tracks.

In northern and central Sudan it is almost always warm and generally hot. In the central portion, which includes most of the survey activity, the rains begin in May and extend through September. The months of July and August are usually the wettest. By November the country again exhibits desert conditions. Field work was scheduled around the rainy season. In the planning state, it was anticipated that two U.S. engineers would perform the survey. One would handle the organizational and administrative chores and log pertinent data. The second would sample and test the soil. An interpreter and one or more drivers would complete the team. The survey area extended approximately 1,000 miles in the east-west direction and approximately 800 miles in the north-south direction.

PROSECUTION OF THE SURVEY

Because of contract delays, the team could not enter the field immediately after the rainy season. Instead the team was assembled in Khartoum in January. Equipment was ordered, and it began arriving in February. Some of the equipment was severely delayed. Two trucks ordered through a dealer in Khartoum did not arrive until April. Between January and the beginning of the survey at the end of April, additional information was obtained, equipment procured and modified, and a crew assembled.

It became apparent shortly after arrival in Khartoum that the original plans for prosecuting the work must be modified. Travel between population centers was found to be much slower than anticipated, and there was considerably less public accommodation than had been reported by previous travelers in Sudan. Also, when the survey area was determined (in conference with the U.S. Agency for International Development and the Sudanese government), it included areas of very sparse population with considerable distance between villages. Consequently, the crew had to be self-sustaining in the field. It was necessary to provide more supplies and parts than had been anticipated. Originally, it was anticipated that a four-wheel drive personnel carrier and two four-wheel drive pickup trucks would be required. Upon "first-hand" appraisal of the finalized survey area, a third (used) pickup truck was purchased. Thus, the crew was supported by and traveled in a convoy of four vehicles. One of the pickup trucks was equipped with a soil auger that was used to drill exploratory holes. The second carried laboratory equipment, spare parts, and auxiliary fuel. The third pickup truck carried camp supplies and food and pulled a 250-gal water trailer to provide necessary water. Before the two new pickup trucks arrived, some short shakedown runs were conducted.

The crew could not remain indefinitely in the field. Major repairs and resupply of some spare parts could be obtained only in Khartoum. To overcome this problem "loops" had been laid out in such a way that the survey began and ended in Khartoum. Even then, at the farthest point the crew would be more than 700 miles from Khartoum. It was expected that the survey crew would be back in Khartoum within 45 days. In the prosecution of the project, considerable variation and modification occurred because of variable weather and major automotive breakdown.

The crew was composed of four technical personnel and from three to five support personnel. Technical personnel were composed of two U.S. engineers, a young Sudanese engineer who assisted the party chief and acted as interpreter, and a technician who helped with the soil sampling and testing. While in the field, the crew also included from two to four drivers and one or two cooks. The Sudanese personnel, with exception of the cooks, were assigned by the Sudanese government.

The survey crews spent the months of May and June in the field. Early in July the crew returned to Khartoum because of increased difficulty of travel due to the rain.

Although the rains were slow in coming that year and the roads were still passable, one vehicle had lost its front-wheel drive, and the party chief feared that the heavy rains could possibly strand the team hundreds of miles from Khartoum.

Motoring about Sudan is unbelievably difficult. From the start, the trip was a continual repair job. Although no actual record was kept for the allotment of time, it is possible that more time was spent on vehicle repair than on the survey itself. Fortunately, the initial work was near Khartoum, and vehicles could be towed to repair shops in Khartoum.

SURVEY PROCEDURE

The survey followed set procedures. Upon departure from Khartoum a continuous detailed log of the trip was kept. A road inventory was made of conditions of the roads, and distances were recorded to features such as villages, intersections, drainage facilities, and streams. Cross-sectional measurements were made of watercourses. In addition to the road inventory, considerable effort was exerted in the search for construction material, which is scarce in most of the area surveyed. Each source of aggregate encountered was inspected, and its potential quality and approximate quantity (when the deposits were small) were recorded. Areas where there was potential for, or actual production of, brick, lime, and/or cement were also recorded. Wells and other sources of water were logged. Villages encountered were described and their size estimated. Comments on the character of the area traversed were recorded including items such as relative economic conditions, density of population, type and amount of agriculture, and location of any industry. At 5-mile intervals and at visual changes of soil, exploratory holes were drilled. These holes were ordinarily drilled to a depth of 6 ft. The soil was examined and visually classified.

Major exploratory holes were drilled at the predetermined 50-mile node and when unusual soils were encountered. These holes were drilled to a depth of 20 ft or to refusal. The holes were visually logged, in-place moisture content and density determined, and samples taken for later testing in the Khartoum laboratory. The laboratory testing included grain-size distribution, Atterberg limits, and compaction tests. Typical samples from the clay plains and the Qoz sands were collected and shipped to the Arizona State University laboratories for intensive testing and stabilization studies. The data from the soil survey were published in a series of strip maps; a typical example is shown in Figure 2.

Careful records of operating costs were kept. Each evening upon arrival at the campsite, daily maintenance was performed and the vehicles fueled. The amounts of fuel, oil, etc., were entered in the log along with the description of any repairs to be made. The same was true for repairs made en route. This was especially important with regard to tires. Before beginning each loop, all vehicles were serviced and all tires carefully cleaned and weighed. Upon return to Khartoum the tires were again carefully weighed, and loss of rubber was related to the mileage shown for the tire during the trip.

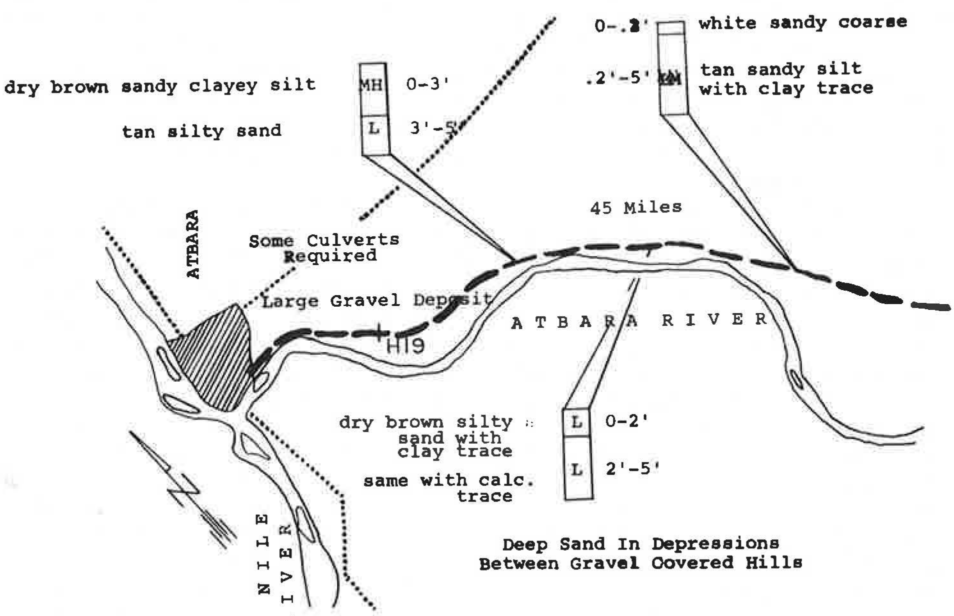
In addition to logging fuel consumption as the survey progressed, special fuel consumption tests were conducted in each of the major geographical areas: northern desert, Qoz sands, and clay plains. These tests were conducted over courses typical of the terrain. Several trips were made over each course. Throughout each trip over the course, the drivers maintained as near as possible a constant speed. The various trips were made at different speeds concluding with the fastest safe speed.

EVALUATION OF SURVEY TECHNIQUES

The survey performed its function in the time originally allotted even though delayed by 4 months due to late arrival of equipment. There was, however, considerable modification to the plan as the survey progressed. The plan as prosecuted worked very well. The original plan with the 50-mile nodal system was used throughout. Fifty miles per day was possible when no serious breakdowns occurred. Camping as we did at the 50-mile nodal points, the major test hole could be drilled and the sampling and testing performed while the cooks were setting up camp and preparing the evening meal. Also,

Figure 1. Northeast Africa.

Figure 2. Example of strip map.



during this time the other vehicles were serviced and tire and vehicle repairs made. In the mornings, food was prepared and everything quickly packed away for the day's march. When circumstances prevented completion of 50 miles of route, the team made every effort to reach the location of the next major drill site and then backtracked as necessary the following morning. Generally, this was done before breakfast: The survey team returned to the morning meal at the campsite, and then the day's march commenced. By using this procedure, a great deal of "catching up" could be accomplished.

At the completion of the job, the team was functioning smoothly. This was primarily the result of rotation of personnel until compatibility was obtained coupled with rather extensive training. The Sudanese engineer and soil technician assigned were admirably suited to the program and were with the team from the date of their appointment until its conclusion (the first loop was conducted before their assignment). Considerable difficulty was encountered, however, with the assigned drivers. The field survey was conducted from sunup to sundown, 7 days per week, while the team was in the field. This was a rather drastic change from chauffeur duty in Khartoum. In Khartoum the duty was easy and the hours short. Joining the survey meant leaving family and the comforts of home behind. In short, long, rough hours at the wheel coupled with rigorous maintenance and repairs, rewarded sparsely, led to very poor morale among the drivers. The first couple of days out things would go well. Then perhaps a large town would be reached, and the drivers would want to partake of the local life. Denied a night (and a day) on the town, morale began to sink. When entering the major villages, time off was granted, but this generally led to even worse morale problems upon leaving.

On the road the drivers were paid per diem, and they took care of their own personal needs including food and bedding. If we had been working the regular Sudanese day, with afternoons off, morale might not have been a serious problem; however, working throughout all the daylight hours and often into the night to maintain schedules was a hardship on the men. Before entering the field after the rainy season, a mechanic was hired. Because he could double as driver in emergencies, one less driver was included in all subsequent trips.

Operating crews in Sudan and probably in other emerging nations are little different from those in the United States. The same problems of morale are faced, and the same sorts of incentives are applicable. For efficient operation it is imperative that all the personnel be under the direction of the party chief, and the party chief must be in a position to reward exemplary service and to replace those who are disruptive forces. Support facilities must be available to all personnel. It is especially important that refreshments and food be of a high quality, readily available, and adaptable to the desire of the various segments of the crew.

The loop concept worked admirably. This allowed deposit of soil samples at the Khartoum laboratory, restocking of supplies, and repairs of the equipment. More importantly, however, it allowed a restoration of spirit. Team members could visit their families, see to personal needs, and rest up for the next trip. The loops for such a large country cannot be small, but best results were obtained when the period in the field did not exceed 30 days. Longer periods resulted in shortage of parts and supplies and consequent reduction of morale. For future surveys, should the loops require more than 45 days, it is recommended that midloop breaks be scheduled.

The vehicles performed with mixed success. The most dependable of our vehicles was the Universal Jeep, CJ-5. The used pickup truck proved to be a tough vehicle, and it performed reasonably well throughout the survey even though it had more than 60,000 miles on the odometer when it was obtained. The two new pickup trucks were trouble from the very beginning. Almost everything that could go wrong did go wrong. They were equipped with front-end winches, but almost from the beginning of the trip they failed to operate. No amount of repair seemed to suffice, and, because the jeep was equipped with a serviceable winch, the crew gave up on the pickup winches altogether. The vast majority of all vehicle repairs were on these vehicles. They simply did not seem to be tough enough to handle loads over the Sudanese terrain. Most of the vehicle problems resulted from parts being loosened by the rough ride and thereby broken or lost.

DISCUSSION OF RESULTS

The results obtained were more than adequate for planning purposes. The original assumption that large areas of the country were sufficiently homogeneous such that they could be identified in terms of their engineering properties was borne out. From the road log and exploration and testing program, it was possible to divide the country into zones of homogeneous soil conditions. The data gathered in Sudan, coupled with the extensive testing and stabilization studies conducted at Arizona State University, enabled us to outline a demarkation of zones of homogeneity of soil conditions and to gather data for economic design of roadway structures. Thus, not only did the survey data apply to planning, but they also may be used for roadway design for all except the highest type of construction and major stream crossings. Figure 3 shows the soil areas surveyed and their AASHO classification.

On the basis of the soil conditions and geological and geographical factors, the country was further divided into zones of homogeneous construction and maintenance costs. These zones were used to generate necessary cost data for optimization of the multimode transport system for Sudan.

RECOMMENDATION FOR MAINTENANCE OF LOW-VOLUME ROADS IN SUDAN

Although the primary function of the survey was to collect cost data for the estimation of the construction and maintenance of traditional types of improved roadways, in a country such as Sudan the establishment of a system of such roadways will be a most extensive investment. Because of this, it is important that consideration be given to the possibility of extending the seasonal use of the present tracks by moderate maintenance procedures. This would include the possibility of minimal upgrading by such procedures.

During the dry season, there are numerous tracks over which trucks travel in the pursuit of commerce. Tracks seem to run everywhere. During the rainy season, however, travel in a large portion of the country is radically curtailed. The most difficult area to traverse in Sudan during the rainy season is the great plains composed of brown silty clay. This soil experiences great volume change under the cyclic climatic conditions that prevail, and when saturated its shear strength approaches zero. Most of the year, water is scarce except along the rivers. For construction, large quantities must be hauled when building high-quality fill during the dry season. During the rainy season, supplying other construction materials is virtually impossible. Naturally occurring aggregate is scarce, and skilled labor of the type required for heavy construction is limited. All of these conditions increase the cost of traditional construction.

Some of the properties that are so detrimental to building and maintaining primary highways may be used to advantage if traffic volumes are low. The phrase "up out of the mud" is the key to the creation of a network of all-season (as compared to all-weather) roads. The critical item is the fill. (Most of Sudan is so flat that no cuts are involved.) In the clay areas, fill should be built high enough and with sufficient crown to enable motoring after the rainy season begins. Because of its extremely low coefficient of permeability, negligible quantities of water will flow through the fill. Immediately after a rain, traffic will experience considerable inconvenience because of the slippery surface, but this is temporary because the hot African sun quickly dispels the water. No specific cross section or specific technique need be defined as the improvement technique. Rather, considerable latitude should be allowed, enabling engineers in the field to utilize the total resources at their command.

It is possible to develop feeder roads without purchasing heavy equipment abroad. The local population should be enlisted to develop the roads using every available means. Local leadership is probably the most important ingredient. Improvement of roads as outlined is not road construction in the usually accepted sense. It is more akin to maintenance (i.e., maintenance implies a continual, time-dependent process), and for this reason real advances come from employment of indigenous personnel.

Rigid specifications should be shunned. Superior tracks can be constructed by raising their elevation and compacting the material at or on the wet side of optimum; however,

Figure 3. Sudan road survey soils map.

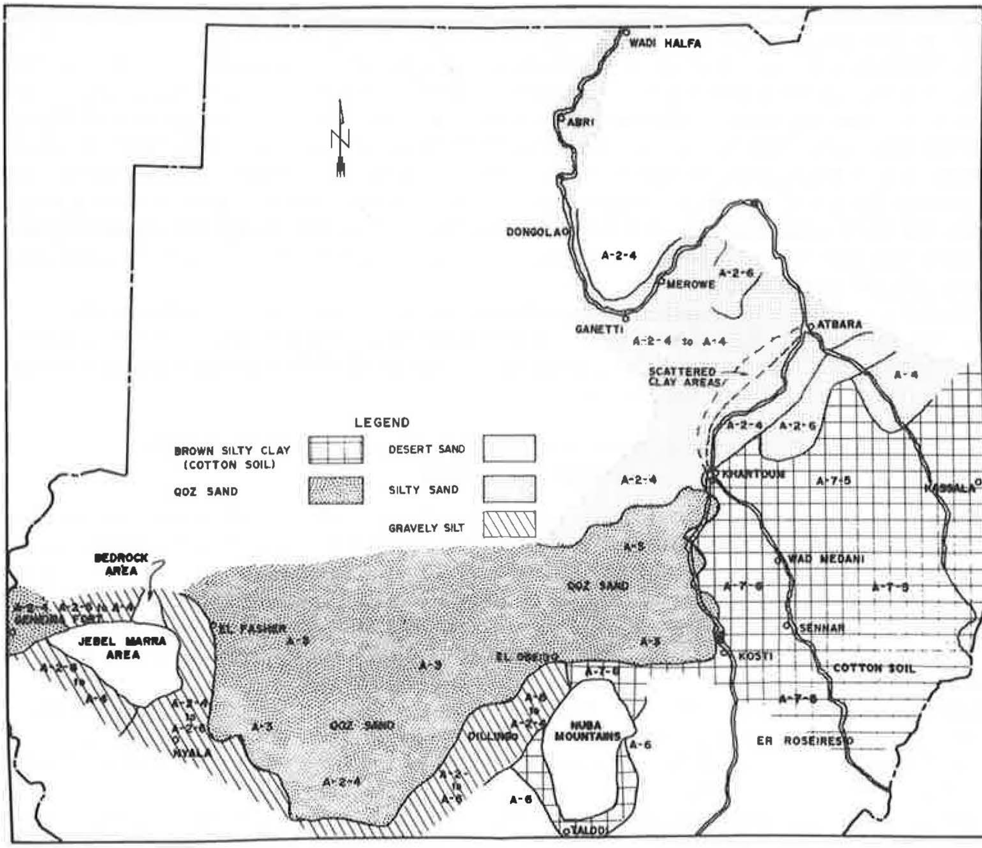


Table 1. Classification test for soil in areas of reduced corrugations.

Sample Number	Atterberg Limits: Liquid Limit (percent)	Atterberg Limits: Plastic Limit (percent)	Plasticity Index	Sieve Analysis: Sieve Size	Sieve Analysis: Percent Retained
1	40	23	17	No. 10	0
				No. 40	25
				No. 200	33
				Pan	42
2	44	18	26	No. 10	0
				No. 40	22
				No. 200.	24
				Pan	54

if the required equipment is not available, the lesser quality fill should be built and allowed to consolidate under use. For crossing watercourses, concrete or masonry cast-in-place culverts or both are recommended because they can be built with local labor, little capital, and insignificant foreign exchange. Properly graded ditches will greatly enhance the road, but complete absence of ditches may be tolerated in most cases. At the onset of the rainy season, cracks that may have opened up during the dry season must be filled and sufficient crown developed (or restored) to minimize the penetration of water into the fill from the top. This is essential.

In addition to maintaining the crown and keeping the shrinkage cracks filled, consideration should be given to surfacing the tracks (beginning with the worse sections) with whatever aggregate is available. Whenever possible, crushed stone should be used. When it is not economically feasible to use crushed stone, gravel, sand from the streams, or even blow sand can be used. In the case of sand, the most advantageous time to cover the road is during the rainy season when penetration of the binder can occur. Otherwise, it may be necessary to scarify the surface and then place the sand on the loose material to prevent loss due to wind and traffic. Once the system is developed and drainage structures are in place, the local people who developed the system will be able to continue a program of maintenance. Increased quality of road normally results in an increase of traffic, and, with an increase in traffic, additional funds should become available and more permanent construction encouraged.

The feasibility of constructing such a network of roads in Sudan has already been demonstrated. The canal spoils were simply dumped adjacent to the canals with no attention given to making or maintaining them as roadways. Yet they provide all-season access where they exist. In the transition zone between sand and clay, natural mixtures of these potentially difficult materials, highly plastic clay and blow sand, have produced sufficient stability to allow all-season transport in many cases. Furthermore, the Arizona State University team observed that, when certain mixtures occurred, corrugations were greatly reduced. The sieve analysis and Atterberg limits for two typical samples are given in Table 1.

An all-season road network awaits the people's demand. Sudan has sufficient highly trained people to organize and direct part of the nation's resources, the most important of which is labor, into road improvements. Roads as discussed here ranged from improved tracks to superior earth structures with untreated soil mixtures. Funds currently available to the Sudanese government are adequate to begin development of such roads. It has been demonstrated throughout the world that once such a program of road improvement is begun it gains momentum. With road improvements comes increased economic activity, and from an expanding economy come the incentive and additional funds to further improve the roads. In the initial stages, road development using indigenous labor will be cumbersome, but as time progresses on-the-job training will increase efficiency. People thus trained become the cadre for maintenance and further expansion. Development of local labor fosters pride and new ideas that result in better and more economic transport facilities.

MAINTENANCE COSTING METHOD FOR LOW-VOLUME ROADS

Richard D. Bauman, University of Hawaii; and
Mathew J. Betz, Arizona State University

This paper summarizes the importance of maintenance as it applies to decisions regarding low-volume road system development, especially as related to economically developing countries. The importance of the decision to pave versus using local aggregates for road surfacing is presented. Specifically, the paper presents a method of estimating maintenance requirements and costs as developed for a transportation system planning activity in the Democratic Republic of the Sudan. Examples are presented of the types of cost relations established and the philosophy of developing these costs from basic considerations of equipment need and utilization rates. The paper emphasizes the fact that the total cost to the economy, in areas with limited road systems, varies with the mileage of roads of a particular surface type to be maintained. This is a consequence of economy of scale and equipment utilization. The development of fundamental input data involved 16 months of field exploration in Sudan.

•IN most parts of the world, construction costs that are incurred when a transportation facility is put into operation are considered to be expenditures for national development and form a significant portion of the operating capital of any country. In fact, among expenditures for national development in the less developed countries, transport generally ranks first or second in magnitude. Costs of constructing new transport facilities have accounted for approximately one-third of all loans made by the International Bank for Reconstruction and Development and for one-fifth of American aid for development projects. Yet the lending agencies normally expect the borrowing countries to maintain facilities with little or no aid. A similar problem exists in the United States where no federal-aid money is available for maintenance.

It is becoming increasingly apparent that, as more and more roads are constructed within a country or a state, the maintenance costs continue to accumulate long after the money that financed the road construction has been spent. These maintenance costs are sizable, usually ranging from 23 to more than 40 percent of the total highway expenditures. But as the highway system of a region expands, the maintenance costs can increase to the point that they exceed the total expenditures previously spent for highways. For example, after the Interstate System is finished, many states will annually be spending more to maintain their portions of the Interstate System than they used to spend for new highway construction.

Because the cost of maintaining roads is great but the role of maintenance is not as politically glamorous or seemingly productive as is new road construction, there is a tendency to try to ignore highway maintenance costs when new roads are programmed for construction. In fact, instances have occurred where roads have been constructed but never maintained while new road construction continued.

To schedule the costs of maintaining a road system into the budget for overall highway expenditures, we need a systematic costing method that takes into consideration

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factors that cause maintenance costs to vary from highway section to section. Such a costing method is difficult to obtain because maintenance costs are usually not kept in a manner that allows one to correlate costs with highway design, environmental factors, and traffic loads, and little or nothing is available for new roads of new design.

This paper describes a procedure developed to predict maintenance costs of a proposed road system in Sudan. The procedural concepts may have utility for estimating highway maintenance costs on systems in other portions of the world.

IMPORTANCE OF MAINTENANCE

It must be emphasized that the failure to provide adequate support for highway maintenance results in decreased quality of service and deterioration of the initial investment. Once a highway facility has been constructed, any change in maintenance procedure will affect vehicle operating costs. Moreover, the amortization period of the construction costs can be affected by the maintenance provided after construction. This is further complicated by the fact that the quantification of this interrelation has not as yet been established.

As road facilities are extended and improved, maintenance commitments accumulate. The magnitude of this is often not realized. In the feasibility study of any one facility, the annual maintenance charge, in absolute terms, will most likely be smaller than the annual construction costs or user costs. However, for nationwide systems, maintenance costs can amount to substantial sums, especially from the viewpoint of governmental road expenditures. This is due to the fact that maintenance costs are a continuing cost that accumulates as the system is improved and expanded.

In the planning for any system of low-volume roads, especially in developing countries, the importance of proper maintenance must be emphasized and its probable costs indicated. Too often, maintenance is done as needed or as funds are available. The fact that maintenance needs to be initiated upon termination of construction is seldom noted. Deferring of such maintenance can mean the deterioration of the level of service, necessity for higher future expenditures, and possible loss of investment. Thus, the planning for maintenance should have an important position in the development of low-volume road systems.

When this is done, the developing countries will necessarily realize that it is important to construct a system to a level within the countries' ability to properly maintain it. The availability of skilled and semiskilled personnel and financial considerations must be considered. Roads that are inadequately maintained can result in a poorer overall system then would be obtained by a well-maintained system of roads with an initially lower type of surface. Thus, it is realized that the decision to pave or not to pave is of primary importance in system planning.

ROAD MAINTENANCE OPERATIONS

For costing purposes, maintenance operations can be subdivided into three general categories: routine maintenance, emergency maintenance, and periodic resurfacing of the roadways. It is virtually impossible to predict or schedule emergency maintenance factors. These are due to unusual occurrences caused by flooding, earthquakes, military action, and so forth. Because of the relatively rare occurrence of these needs and the conditions under which the work is performed, there is little information concerning their costs. Therefore, this type of maintenance is not considered in this paper.

The periodic resurfacing of roads includes the addition of gravel or the addition of a bituminous surface treatment, which is required on a relatively regular basis because of the effects of time and traffic on the road surface. The methods, equipment, and costs involved are essentially the same as used during the initial construction procedure and can be costed in a similar manner.

The costing method discussed in this paper is concerned with routine road maintenance, i.e., that which has to be conducted on a continuing basis. This can be subdivided into the following operations: surface and shoulder maintenance, maintenance of drainage facilities, maintenance of the roadside, maintenance of traffic control devices, and maintenance of bridges and other major structures. Discussions of each of these as related to gravel versus paved surfaces can be found in the literature (1).

In summary, important consequences of a decision to use a bituminous-treated surface affect the necessary maintenance, the equipment to be used, the skill level of the maintenance personnel, the overall costs, and the foreign exchange costs. Generally, the maintenance of surface and shoulders of graveled roads can be accomplished with light trucks, tractors, some type of drag (which can be locally manufactured), and possibly motor graders. This work can be done by relatively unskilled personnel. The same is not true for the bituminous surface, with respect to either the day-to-day patching operation or the periodic resurfacing. For many countries, the cost of bitumen represents a foreign exchange expenditure.

The general cost of maintenance within the United States increases as one moves from a gravel to a bituminous surface roadway. The relative expenditure for surface maintenance decreases. One of the observed problems in a number of developing countries has been a tendency to concentrate almost solely on surface maintenance. Recommendations by the International Road Federation as applied to Latin America indicated the need for greater emphasis on nonsurface maintenance (2).

The decision to pave or not to pave has little impact on many nonsurface maintenance procedures but may affect the level of effort. An example is the necessity for more roadside maintenance for paved roads because of the higher expectancy levels of the public and because of the fact that the paved travel way is generally narrower than the available travel way on a gravel road (which often includes shoulder areas).

The maintenance of traffic control devices is another example of increased cost required for paved surfaces. In most of the developing countries, when roadways are paved they are relatively narrow two-lane roads. It is therefore important from a safety standpoint to properly sign and stripe the roadway. The striping represents a substantial expenditure that is incurred yearly under most conditions. Roadway paints are relatively specialized items and represent a foreign exchange cost. Figures published by the Highway Research Board for the United States indicate that the cost of materials amounts to almost 80 percent of the total cost of highway marking (3). In addition, the equipment in this operation is specialized and has to be imported. Trained operators are necessary. Trained personnel to properly maintain the equipment itself is also important.

MAINTENANCE COSTING METHODOLOGY

What follows is a description of a maintenance cost-estimating methodology developed for a major portion of Sudan. These costs along with construction and vehicle operating costs were prepared for inclusion in a total transportation analysis that led to the development of a multimode transportation plan for the country. The project was conducted by personnel at Arizona State University under subcontract to Lockheed Aircraft International, Inc. The basic engineering information was obtained in the field during a 16-month period in 1966 and 1967. The following presents an example of the type of maintenance equipment requirements and costs relations developed. As a part of the project, separate sets of these relations were presented for the various types of surface for each of the homogeneous areas identified (4).

Total road maintenance needs are a function of the road design, soil and environmental conditions, and traffic characteristics. The interrelation among these, as related to maintenance, is most complex and unquantified even for the most developed systems. In most cases, road maintenance is considered to be a function of traffic volume only, assuming both a fixed-cost and a variable-cost component. For example, Bonney (5) has derived an expression to indicate the maintenance costs of gravel roads: Total annual cost per mile = 496 + 13Q, where Q = daily traffic flow in vehicles per day. Actually, for any specific surface type, both the fixed cost and the variable costs will differ depending on the availability and quality of construction materials, the climatic conditions, and the topography of the area.

Significance of Homogeneous Cost Areas

Because the various items that make up the maintenance cost change depending on the location of the road as well as the road design, the total maintenance cost will vary from area to area within a country even if traffic volumes are equal in each area. Therefore, the first step in the maintenance costing procedure is to divide a region into areas of similar pavement design with equal cost of maintenance materials and maintenance equipment.

For Sudan, the equal cost areas were defined based on information gathered by the field team and on laboratory tests concerning soil characteristics, construction material availability, and water availability. The northern section of Sudan was divided into 13 areas as shown in Figure 1. Each area, A through M, displays homogeneous characteristics that tend to cause all construction and maintenance activities and costs in the area to be similar. Thus, within each area it was assumed that the distance between wells is constant, the distance between gravel sources is constant, and the physical design of the pavement structure is constant. Because each area is distinct, it follows that the construction and maintenance requirements in each area are different from those in other areas.

Preparation of Construction Equipment Packages

Knowing the areas of similar cost, our next step was to actually determine the costs associated with each area. The subject of road maintenance costing is only rarely discussed in the literature. Apparently nothing factual has been written concerning development of procedures for forecasting construction and maintenance costs for a road system. In many areas, future costs of road construction and maintenance can be determined by studying existing costs. This was impractical in Sudan because few roads have been constructed or maintained.

In the past, when individuals have forecast maintenance costs, most studies have used a fixed cost per mile for all maintenance on roads of a certain design. At the same time, planners have used relatively accurate costs for vehicle operation on the road. Actually, the analysis problem is as sensitive to changes in construction and maintenance costs as it is to changes in vehicle operating costs. Fixed cost-per-mile estimates lead to serious errors in the analysis because there is considerable economy of scale. For example, the cost of maintaining 1 mile of gravel road might be $2,500, whereas the cost of maintaining 40 miles of the same road might be $1,100 per mile. Within certain limits, which vary from project to project, the larger the project is the lower the unit price is. This economy of scale is most noticeable at the low production rates prevalent in most underdeveloped countries that can only afford to build and maintain a few miles of road each year. In light of this, it was concluded that maintenance cost formulation that considered the economy of scale of a project would best solve the analysis problem.

The issue was how to compute costs that would reflect economy of scale for an area with no history of costs on similar projects available. The problem was resolved by using the normal bidding procedures utilized by contractors for road maintenance projects. The procedure entailed determining the pavement design prevalent in the area, selecting a package of construction equipment required to handle the maintenance tasks, and costing the maintenance price per mile for projects of varying length.

For each homogeneous cost area shown in Figure 1, a package of construction equipment necessary to complete the maintenance activities was selected. This was done by selecting appropriate equipment units and then combining the units into groups termed equipment packages. For example, an equipment package for maintenance of an earth road could consist of two dump trucks, one rubber-tired roller, one water truck, one front-end loader, and one motor grader.

Next, the total hourly cost to own and operate each package was computed. This procedure involved obtaining hourly ownership and operating costs for each unit in the package and summing the individual costs to compute the total hourly costs. Severe depreciation rates recommended either by the Association of General Contractors Ownership and Expense Manual or by equipment manufacturers were utilized.

In most cases, a single package was not suitable for handling a wide range of production rates on a project. Large-sized units of equipment can be used to maintain a small project, but they cannot be used economically. Therefore, each package was customized to fit a specific range of project sizes, with the size and type of units in each package varying with the size of the projects.

The customizing procedure involved grouping specific sizes and types of construction units into packages and then determining the productivity-cost relations for each package. Thus, for an activity involving the maintenance of a gravel road, one package was selected for maintenance rates up to 230 miles per year at traffic volumes below 25 ADT, and the size of the package was increased as the traffic volume on the road increased. Typical packages suitable for maintaining unsurfaced roads in Sudan are given in Table 1.

Formulation of Maintenance Cost Equations

It is a much simpler procedure to estimate costs of a maintenance project for a highway that has a definite length and location than it is to estimate costs where the road length and completion time are variables. But, for planning purposes, the latter is the case. Use of the equipment package concept simplifies the costing process but also points up the economic consequences of inefficient use of construction equipment packages. As is shown in Figure 2, for a specific construction package the cost per mile decreases as the production rate increases until the operational efficiency of the package is exceeded, then the cost per mile begins to increase. The challenge is to develop equipment packages suited for the anticipated range of productivity.

For the Sudan project, maintenance costs were split into two categories: expected routine maintenance and resurfacing. Maintenance cost experience in Ghana and Nigeria found that resurfacing costs range from 30 to more than 50 percent of the total annual maintenance expenditure. The equipment package requirements for routine maintenance are different than the requirements for resurfacing.

Routine Maintenance Costs in Sudan

As previously indicated, the routine maintenance on aggregate roads is basically the maintenance of the riding surface and the elimination of road roughness. For bituminous surfaces, it involves the patching of potholes, the maintenance of signs and markings, and the general "housekeeping" of roadsides and drainage facilities. Figure 3 shows the expected typical relations between normal maintenance costs in Sudan and traffic volume for an earth, rock road. The routine maintenance costs of bituminous-surfaced roads operating at low-traffic volumes are relatively independent of traffic volume. This cost was estimated at $1,200 per mile for a surface treatment, $1,340 per mile for a road mix, and $1,130 per mile for a hot-mix road.

Resurfacing Costs

Gravel and bituminous surfaces require periodic resurfacing in order to maintain the standard of the roadway. The resurfacing operations for both gravel and bituminous surfaces are essentially the same in equipment, material, and personnel as those required for initial construction. The costs prepared assume the optimum use of the smallest particular construction package based on a 40-hour week. The costs were converted to annual costs by simple division of the resurfacing cost by the expected period of resurfacing. No interest calculations were included because the period of resurfacing is relatively short.

In the case of roads surfaced with crushed rock, it was assumed that the surface would be rebuilt every 6 years, and at that time 4 in. of new crushed rock would be added. In the case of roads surfaced with gravel, it was assumed that the surface would be rebuilt every 6 years, and at that time 6 in. of new gravel would be added. The resurfacing cost was determined by prorating the initial construction cost. General experience with gravel roads throughout Africa indicates that with moderate traffic volumes, gravel roads tend to lose about 1 in. of gravel per year. This rate of gravel

Figure 1. Areas of homogeneous construction and maintenance costs in Sudan.

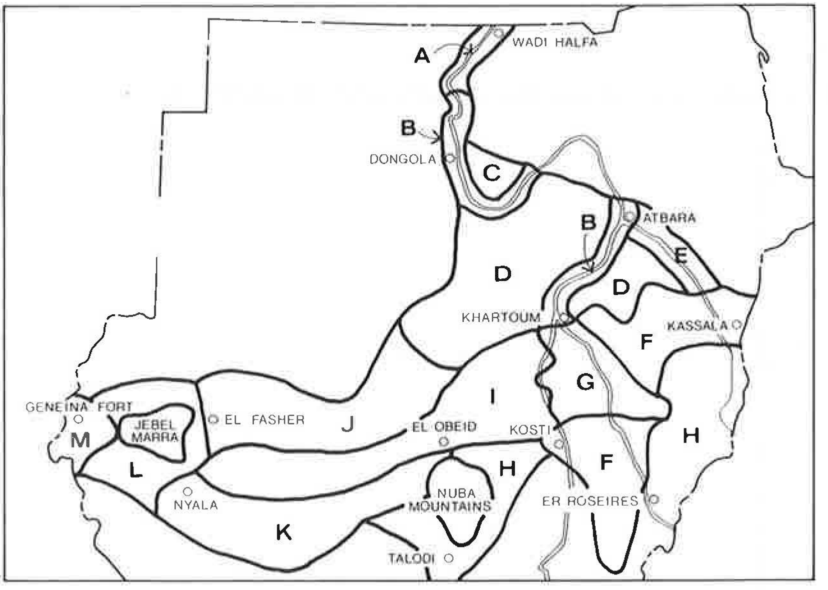


Table 1. Minimum equipment packages required for routine maintenance of unsurfaced roads.

Traffic Volume (ADT)	Road Surface		
	Earth	Gravel	Crushed Rock
0 to 24	One 5-yd truck One 2,000-gal water truck One ½-yd front-end loader One motor grader	One 5-yd truck One 2,000-gal water truck One ½-yd front-end loader One motor grader	One 5-yd truck One 2,000-gal water truck One ½-yd front-end loader One motor grader
25 to 49	Two 5-yd trucks One roller One 2,000-gal water truck One ½-yd front-end loader One motor grader	One 5-yd truck One roller One 12-ton truck One 2,000-gal water truck One 1-yd front-end loader One motor grader	Two 5-yd trucks One 2,000-gal water truck One ½-yd front-end loader One roller One motor grader
50 to 99	One 5-yd truck One 12-ton truck One 2,000-gal water truck One roller One 1-yd front-end loader One motor grader	Two 5-yd trucks Two 12-ton trucks Two rollers Two 2,000-gal water trucks Two 1-yd front-end loaders One motor grader	Two 5-yd trucks One 12-ton truck One 2,000-gal water truck One roller One 1-yd front-end loader One motor grader
100 to 399	One 5-yd truck Three 12-ton trucks Two 2,000-gal water trucks Two 1-yd front-end loaders Two rollers Two motor graders	Two 5-yd trucks Three rollers Six 12-ton trucks Three 2,000-gal water trucks Two 1-yd front-end loaders Two motor graders	One 5-yd truck Four 12-ton trucks Two 2,000-gal water trucks One 1-yd front-end loader Two rollers Two motor graders

Figure 2. Equipment package cost-productivity relation.

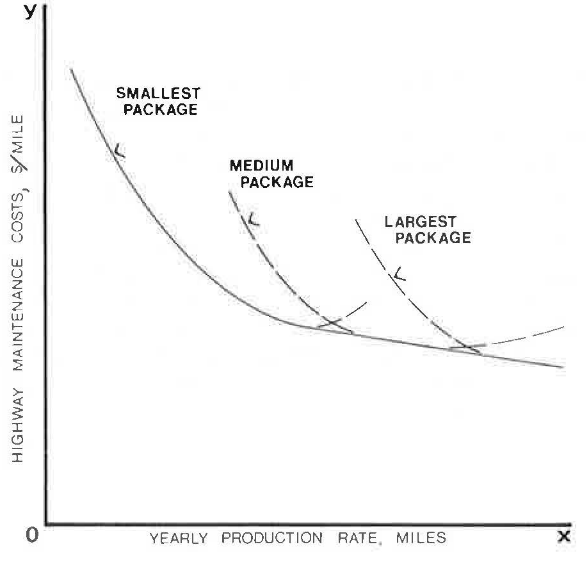
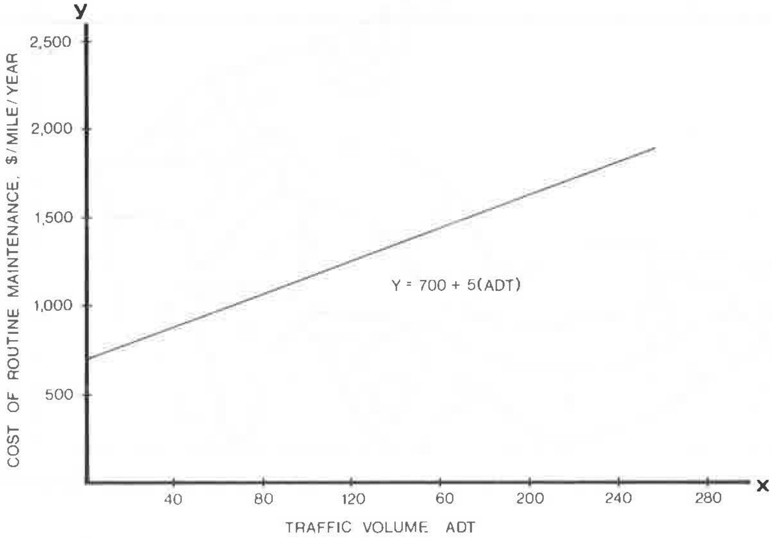


Figure 3. Routine maintenance costs and traffic volume of earth-surfaced road.



loss is relatively constant for a moderate range of traffic volumes because the dragging operation tends to have a greater effect on aggregate loss than does traffic per se. The assumption that the Sudanese crushed-rock roads will lose only ⅔ in. per year was based on the fact that the aggregate used in the construction has particle interlocking characteristics not found in natural gravel. Usually, natural gravels have rounded particles that do not provide much mechanical particle interlocking. The Sudanese crushed-rock aggregate will be highly angular, and it is therefore expected that there will be a much higher degree of mechanical interlock between particles and, therefore, a decreased rate of loss. The different annual costs for certain areas for resurfacing reflect the influence of the differential length of haul from aggregate sources.

The calculation of the resurfacing cost for bituminous roadways was based on the cost of a single surface treatment repeated every 5 years. Experience has shown that this operation generally must be repeated every 4 to 6 years to counteract the effects of both traffic and aging. These costs were estimated assuming the equipment packages were being utilized efficiently and the costs were represented on an average dollar-per-mile basis.

SUMMARY

As previously indicated, the variation of maintenance costs with basic variables is currently ill-defined although they represents a significant public expenditure. That these costs can be evaluated over time when maintenance needs are met under specific known conditions is admitted. However, Sudan at this time does not have significant experience in the road maintenance procedures within its own area to quantify any cost or productivity data. This is a situation common to most developing countries and even to some states. Due to the economy of scale associated with maintenance costs and the cost variance caused by variables such as project size, construction material availability, topography, in-place soil conditions, and productivity of the labor force, generalized fixed-cost estimates are inaccurate. The equipment package costing methodology outlined in this paper presents a technique that allows estimation of maintenance costs in areas where no maintenance cost experience is available and allows consideration of economy of scale.

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DISCUSSION

Bertell C. Butler, Jr., Byrd, Tallamy, MacDonald and Lewis, Falls Church, Virginia

Bauman and Betz's paper presents a maintenance costing methodology that should be valuable in developing maintenance cost for new highway systems. In particular, it should be very useful to planners as they develop transportation programs in developing countries.

The authors' paper has properly stressed the importance of maintenance for low-cost roads, particularly as a factor in the planning and decision process. They placed the maintenance impact on total highway expenditures between 23 and 40 percent. An examination of the maintenance expenditures made for county and township roads in the United States during the past 15 years reveals that an average of 63 percent of total highway expenditures was spent for maintenance (6). The type of road system they discuss seems closer to the county-township type of system than the state system where the maintenance percentage for the same period was 18 percent.

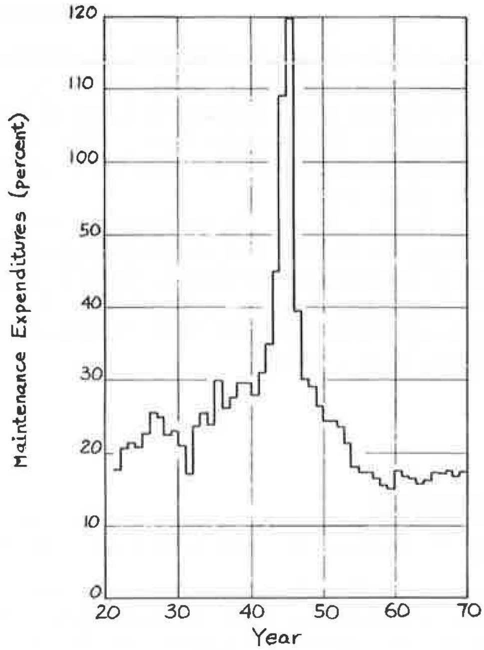
As the highway system of a region expands, the maintenance expenditures continue to increase. There also is considerable evidence in the literature to suggest that these maintenance costs further increase as traffic volumes grow. However, as a percentage of total expenditures, the picture is not so clear. Figure 4 shows the percentage of total highway expenditures for state highway maintenance in the United States. Disregarding the war years of the 1940s, there is no evidence of any general increase with time. Rather, both the capital outlay and the maintenance expenditure portions grow together.

The impact of increased traffic volume on maintenance is revealed by comparing a sampling of high- and low-volume state highway expenditures. The high-volume states averaged \$24,000 per mile on maintenance, which reflected 25 percent of total road construction expenditures. This can be compared with \$1,250 per mile and 13 percent for the low-volume states (6).

The authors were faced with the need to develop maintenance cost estimates for a total highway program budget. Realistic costing is needed to allow for variations in the physical and operational environments of the roads in various areas of the country. This was particularly critical to the Sudan study where a wide variation was expected in the mileage of a given pavement design from area to area. The estimating procedure developed responds to the need for having more than a single fixed maintenance cost that can be applied to roads in the planning process.

The authors divided Sudan into areas of similar pavement design and equal material and equipment cost. They then selected the equipment units that would be needed to maintain the pavement design assumed for an area, a given level of traffic volume, and a limited range of mileage of roads. The equipment was then placed into what the authors termed an equipment package, and the total hourly cost to own and operate the package was computed. The authors are not clear on how the entire maintenance cost

Figure 4. Maintenance expenditures as percentage of total state highway costs.



was included in their cost equation, i.e., as part of the equipment package or in support of the equipment package. In developing resurfacing costs, the authors note that the equipment package cost was based on a 40-hour week use assumption. No such notation is included for the maintenance equipment package. Therefore, the basis for developing hourly cost for the equipment is not clear. Some mention of the assumed range of use would be helpful. Also, an indication of some of the other assumptions that must have been made related to frequency of equipment assignment to each mile of road, treatment of supervisory cost, labor and material requirements, and housing and administrative costs would be useful additional information. However, it is assumed that the equipment package generated a total cost that could be converted to a per-mile maintenance cost by assuming a mileage in each homogeneous cost area. The model shown in Figure 3 was apparently the result of plotting per-mile expenditures from like areas of road design and mileage for different traffic volumes.

The method of costing presented by the authors was reportedly used to generate various matrices of unit maintenance cost by type of road surface and region for varying system mileage and traffic volume. The inclusion of such a matrix would have been a useful addition to the paper. Nevertheless, this paper should prove a valuable addition to the present literature on the maintenance of roads in developing areas.

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Better knowledge of road maintenance costs would be welcome in every country, but the relative paucity of information and the need to examine various road design and maintenance strategies in developing countries make better information on maintenance costs particularly important in these countries. In the United States and Western Europe, high traffic volumes, high values attached to motorists' time, and relatively low cost of capital usually make it more economical to incur higher initial costs to construct roads to higher standards to minimize road-user and maintenance costs. In developing countries, however, traffic volumes and values attached to motorists' time are often much lower, and capital is much costlier, so that staged construction, with lower initial design standards and higher road-user and maintenance costs, may be the optimum strategy. In some of these countries, relative labor abundance makes labor-intensive methods of construction and maintenance more feasible, which has important but relatively unexplored implications for road design and maintenance.

Thus, Bauman and Betz are quite correct in seeking to gain greater understanding of road maintenance costs in developing countries and to develop methods for quantifying and predicting them. Certainly, the approach they developed in Sudan, which is similar to the work by Soberman in Venezuela, constitutes an improvement over existing procedures in many cases where the only data are average total maintenance outlay per mile of network. Formulation of maintenance costs in the form $Y = a + b(ADT)$ does take into account the fact that there may be certain expenditures, such as the costs of administration, or other economies of scale when traffic volumes expand. Developing separate relations for different types of road in different homogeneous cost regions is a further improvement.

However, this approach does not go deeply enough to answer many of the questions that need answering. Predicting maintenance outlays in this manner implicitly assumes a given maintenance policy, when in fact we want to investigate what maintenance policy should be. If one is to examine alternative maintenance strategies, it is necessary to distinguish the physical deterioration of the road from the response to that deterioration. The effect of different maintenance standards on the physical condition of the road and the effect in turn of various road conditions on road-user costs must be established, as well as the costs of the different maintenance routines. If, in addition, one is to determine the best technology to effect a given maintenance standard, it will be necessary to generate the whole set of alternative technologies specified in terms of outputs achieved by a given set of inputs (equipment packages) and prices of the various inputs.

Measurement of the physical deterioration of roads of different designs and the effect of alternative maintenance policies thereon ultimately requires some longer term experimentation, which presumably was outside the authors' terms of reference. Least is known concerning the deterioration of earth and gravel roads (of various geological compositions), but fortunately this can be measured relatively easily because deterioration occurs rather rapidly if regular maintenance is withheld. A 2-year period of study is quite sufficient to observe significant change in the condition of unpaved roads. It is more difficult to establish deterioration relations for paved roads because deterioration occurs much more slowly. The only alternative to long-term experiments would be cross-section analysis of pavements of various ages in various degrees of deterioration. However, because of the problems in defining the original construction standards of those pavements, as well as the use and the maintenance they have received over the years previous to the study, we would not be optimistic about this approach. Thus, deterioration relations for paved roads may have to be derived from time-series analysis of observations collected over several years from roads built to carefully controlled standards and subjected to normal use.

Various approaches may be used to establish the effect of different maintenance standards on road-user costs. A direct experimental approach, involving operation of a fleet of instrumented test vehicles over experimental road sections where the condition of the road surface is measured, may provide accurate information on the effect of different maintenance standards on vehicle speed and fuel consumption. A sample survey of road users, including establishment of a well-controlled set of cost accounts for a representative sample of types of vehicles operating over roads in various states of maintenance, will yield additional information on vehicle depreciation and maintenance costs.

If one wishes to relax the assumption of a fixed maintenance technology and determine the optimum technology, it is necessary to scan the whole set of feasible alternative technologies. The authors' specification of equipment packages, or input-output vectors, is thus a step in the right direction, but it is not clear that they have systematically generated the whole set of alternative technologies (or a reasonable approximation thereto). What do they mean when they say that the equipment package was "customized to project size?" What exactly does "project size" mean? Also one would like them to specify the sources of the economies of scale they envisage. Is it simply fixities in administrative costs when either the mileage of the system or the traffic densities increase? Or do greater traffic densities or greater network mileage make different technologies with lower variable costs more economical? It is not easy to see this intuitively, but ultimately the question is an empirical one.

We at the World Bank have been very much concerned with these questions, particularly the trade-offs between road design standards and maintenance costs and the effect of different technologies thereon. Since 1969, we have been working in conjunction with other institutions to develop the methodology and empirical data necessary to determine optimum highway design and maintenance strategies for low-volume rural roads, assuming initially a fixed technology for construction and maintenance. The U.K. Transport and Road Research Laboratory, working in collaboration with the World Bank, has been conducting empirical research in Kenya since early in 1971 on road-user costs and road deterioration relations for alternative design standards and alternative maintenance policies. We hope to have completed the initial field studies of these relations by July 1973, but the study will have to be continued in order to gain longer time-series observations on paved road deterioration. At the same time, we are hopeful that similar studies may be undertaken in India and Brazil to capture a wider range of physical and economic environments. The World Bank also has under way studies on the technical and economic feasibility of alternative civil construction technologies involving different combinations of labor and equipment. An initial survey of existing evidence reached the conclusion that it is technically feasible to use labor-intensive methods of construction for most activities involved in constructing highways, including higher standard highways, and that these techniques may be economically feasible under certain circumstances in labor-abundant economies. The next phase of the study will concentrate on the adaptation of road design to labor-intensive and intermediate technologies and its implications for road design and maintenance strategies and the problems of implementing changes in technologies, design, and maintenance strategies.

Samuel F. Lunford, Arizona Highway Department

The authors discuss the importance of maintenance costs in the planning of highway systems, especially with regard to its effect on the overall economic well-being of an emerging nation. A most interesting consideration not normally imposed on the maintenance engineer-economist in this country is the major effect that foreign exchange expenditures have on the decision-making process when the physical designs to be utilized in the system are evaluated.

In the citation on the lack of formal costing knowledge of highway maintenance activities, the authors present the same general observations that others have struggled with in attempting to develop forecasting systems or formulas. For many years, maintenance cost data have been collected, summarized, and published in terms of average costs per mile of various types of designs with very little consideration of the relations among highway design, environmental factors, traffic loads, and social structure of the community. The application of such past per-mile average cost data can result in a completely inadequate financial and organizational plan for any highway system, whether considering an emerging nation without a transportation history or a highly developed community with a sophisticated network and years of experience.

The emphasis on the importance of maintenance is well made as a major element in system planning and design. The magnitude of accumulating maintenance requirements is rapidly forcing highway administrators in this country and on the international scene to focus more attention on scientific research and economic evaluations of maintenance practices. In recent years this has resulted in the so-called new maintenance management systems in many states.

These new maintenance management systems and the accompanying performance budget methods of analyzing maintenance cost factors have been highly publicized and reported in literature during the past 10 years. It was disappointing to find no mention or consideration of these highly developed techniques in maintenance costing.

In approaching the costing of maintenance operations in an environment without a past history to relate to, the authors categorize maintenance into routine, emergency, and periodic resurfacing. Emergency maintenance factors are immediately dismissed as impossible to predict or schedule. Resurfacing maintenance is analyzed as essentially the same as initial construction procedures and therefore costed in the same manner. It appears, then, that the important contribution this paper offers is a new approach to forecasting the probable costs for routine recurring maintenance under the unique conditions and limitations of an emerging underdeveloped nation and the effect of this cost on the long-range financial requirements to protect the original investment.

Although emergency maintenance might logically be a minor cost factor, it should be considered, especially with regard to the effects of natural occurrences on underdesigned highway systems. Weather history and severe seasonal weather conditions are generally well known, and the problems of maintenance operations involving design deficiencies for all weather conditions can be ordinarily recognized and can be adequately provided for by anticipating certain average activity requirements to provide capability to restore damaged or interrupted transportation services.

The costing of routine road maintenance planning values is most difficult with known existing systems. The complexities of analysis presented in this described project, to predict with confidence the cost of maintenance values for various design considerations on a nonexisting highway system, is approached in a new and unique manner. Such an approach offers a new opportunity to make further research and extend present concepts of the state of the art.

Without a history base to quantify the many variables of maintenance activities, the authors devised what might be called a system of common denominators. By grouping similar environmental characteristics, a system of homogeneous cost areas was developed in which it can rationally be assumed that all construction, maintenance, and cost factors will be similar. This same rationalization is used by several states in establishing regional performance standards for maintenance activities.

The second common denominator presented for evaluating costs was the construction equipment package. This approach is unique in concept, but it is not clearly defined in the paper, especially with regard to what activities or level of service is considered in creating the equipment packages for comparative evaluation. It would seem that a quality standard or a level of service must also be determined to establish an equipment package. The tolerance of wear or deterioration with a frequency of service requirements must certainly be involved in determining either the equipment package or the area that a given equipment package might cover. The paper intimates that such analysis was considered within the project development, but it does not dwell on how the service-level variables were constructed to determine the equipment package. Some additional development of these factors would clarify the concept of relating maintenance cost predictions on the assignment of cost factors to the hourly operation of a given equipment staffing required to perform the level of maintenance necessary to support and protect the transportation investment.

The authors have injected an analysis consideration, which provides a realistic approach to adjusting cost data, not heretofore observed by the reviewer in other maintenance cost projection exercises. The "economy-of-scale" adjustment to operational data emphasized in this paper has been observed and considered in many construction program cost estimates, but its application to maintenance cost projections may be one of the important contributions presented here and also might possibly be a subject for further research in relation to maintenance cost factors.

In summary, the project described certainly appears to have been challenging, and the approach to analysis was innovative and unique. The importance of maintenance costs to the total design considerations and financial planning of transportation systems is well presented. The homogeneous cost areas, the equipment package, and the economy-of-scale concept are analysis techniques that might be further researched for useful relations.

The paper offers an important reference background for refining the art of long-range maintenance cost predictions particularly as related to new transportation systems in emerging nations.

AUTHORS' CLOSURE

The basic elements in the discussions focus around issues concerned with assumptions used in the derivation of the equations and with appropriate policies for maintenance of a road system when funds are limited. Butler discusses the cost assumptions and raises significant questions concerning the methodology used in the derivation of the cost equations. Harral discusses important policy issues. Lanford's discussion overlaps into both policy and cost issues. This response to the discussions will attempt to clarify some of the assumptions and derivation procedures as well as comment on the policy issues.

The first major area of concern seems to relate to the cost formulation process. The process of deriving the cost formula for an equipment package was to assemble the equipment units and manpower into a package, calculate all costs on an hourly basis, expand costs to an annual basis using number of work hours per day and number of workdays per week typical in Sudan, estimate the maximum productivity of each package in terms of number of miles of two-lane road per year, and develop cost curves by holding annual equipment package costs constant and varying package productivity, thus achieving a variable cost-per-mile output. The costs used in each package were derived based on relations among hourly costs to own and operate the units of construction equipment in each package, labor costs for equipment operators and supervisory personnel, and material costs. The operational life of each unit of equipment was computed in terms of total hours of life based on manufacturer's recommendations and assuming severe operating conditions. Utilizing this technique, the economy-of-scale characteristics of an equipment package become apparent as the efficiency of utilization of the package increases.

The application of the level-of-service concept for processes concerned with routine maintenance is significant and could be used to quantify policy decisions. For the Sudan project, it was assumed that the equipment packages would operate so as to maintain all roads in their respective areas at a level sufficient to preserve the roadway in a condition as close to the original as possible. This required assumptions concerning frequency of machining, daily productivity, and material replacement based on empirical data from other studies. All assumptions are discussed in detail in the original report (4). This meant that the maintenance policy proposed for Sudan assumed a high level of service. At first glance, this assumption may not appear to be the most appropriate policy for a country with low traffic volumes on nearly all its roads and with limited funds. However, the policy for maintenance cannot be considered in an isolated context. Instead, the policy for maintenance must be considered together with the policies concerned with design and construction. If stage design techniques are properly used and a road is never overdesigned, a high level of service for maintenance appears to be the appropriate policy.

Study of the trade-offs between road design standards and maintenance policies and costs was beyond the scope of this project. But the trade-offs represent a highly significant area of concern. So the World Bank projects described by Harral, when completed, should produce some very useful data.

SIMULATION MODELING OF HIGHWAY MAINTENANCE OPERATIONS APPLIED TO ROADSIDE MOWING

Robert J. Stone, Drexel University

This paper presents a simulation model by which a mowing operation is analyzed on a day-to-day basis. Included in the model are the effect of rainfall-speed distributions for tractor-mower production as related to terrain features; hourly cost distributions for tractors, mowers, and service trucks; and time distributions for nonproduction activities that occur during the daily mowing operation. The speed and time measurements were observed on 169 acres of a 10.6-mile section of I-95 in the New Castle maintenance district in Delaware. The simulation model is described in the general purpose simulation system language. Output showing the simulated variation in total project times and costs for 20 observations of various amounts of assigned mowing area are shown. The model provides a tool by which the highway maintenance engineer can evaluate short- and long-range planning decisions that involve a series of highly variable time-consuming activities. Suggestions of other highway maintenance operations to which the model can be applied are presented.

•WITH the growing size and complexity of the nation's highway system and ever-increasing traffic volume, it is necessary that highway maintenance be given more attention in the overall development of the highway system to ensure safety and driving ease for the motoring public.

The highway maintenance engineer, as any other engineer, is dedicated to satisfying the needs of society by using modern planning and decision-making techniques that not only improve day-to-day operations but also provide for long-range planning to reduce the cost of highway maintenance operations.

Operations research techniques are not used in the highway maintenance field to anywhere near their full potential for cost reduction. Yet the problems of maintaining a highway are not significantly different from other types of maintenance operations to which operations research techniques have been successfully applied. An effort to apply linear programming for the optimal assignment of tractor-mower units for roadside mowing was developed in 1966 (1), but the model was incomplete in its development and thus is not used today for highway maintenance planning (2).

One of the most significant improvements for updating the planning and budgeting of highway maintenance operations has been obtained through the standardization of quality, quantity, and production that was initiated only 4 to 5 years ago (3, 4, 5).

Several state highway departments and the Federal Highway Administration have made comprehensive studies in an effort to determine a procedure for evaluation of the time and cost associated with grass cutting (6-17). The results of the studies indicated that the times and costs were highly variable. Thus, the use of average values of time and cost for budgeting and equipment assignment led to erroneous decisions.

Many questions to which quantitative comparisons can be applied for management decisions related to mowing can be answered quickly and at a relatively low cost with a simulation model. Simulation is a process by which logic models, which are too complex for an analytical solution, can be solved numerically. The simulation process in-

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volves the performing of controlled experiments on the model and observing the performance of the model under a given set of conditions.

Among the questions that might be proposed are the following:

1. What would be the expected change in time and cost if a different size and/or type of mower was used to cut the grass?
2. What would be the expected savings in time and cost if all 3:1 side slope mowing were eliminated?
3. What would be the expected time and cost for cutting grass on a new section of highway?

The mowing simulation model developed in this study can be represented by a block diagram (Fig. 1) showing the logical flow of the activities that an operator of a tractor-mower unit performs in a daily mowing operation. The simulated operator has associated with him attributes in the form of frequency distributions obtained from field measurements that, through random number generators, describe the probabilistic status of the operator at any point in time during the working day. The simulated speed of the mower is controlled by randomly sampling the speed distributions that are associated with various terrain features of the highway right-of-way. Included in the model are travel times, delay times, equipment operating costs, and speeds that relate to the production capacity of the mower.

The computer programming language used for the model is the general purpose simulation system (GPSS) language, which is applicable to the IBM 360 series of digital computers. The output of the computer program provides the following information about a mowing operation:

1. The total completion time of the project including the effect of rainfall;
2. The total time to complete the project excluding the effect of rainfall (sometimes called the scheduled completion time of the project);
3. The total production time in the project;
4. The total project cost including equipment, transportation, and labor;
5. The total cost in the project for the tractor-mower unit;
6. The total cost in the project for transportation to and from the field; and
7. The subsection of the highway where the tractor-mower unit stopped cutting each day.

The model can be used effectively to determine the expected cost for mowing the grass cover on new sections of highway, analyze highway beautification programs in which only certain portions of the grass cover are to be cut, compare the differences in expected times and costs related to various cutting assignments using different sizes and/or types of tractor-mower units, analyze the effects on production time if more management control of the field operation is provided, and aid in the establishment of mowing standards for sections of highway.

Data for the model were obtained from field studies of tractor-mower production speeds and nonproductive time-consuming activities as observed on I-95 in Delaware. The study encompassed 169 acres of mowed grass area that was divided into seven subsections with each subsection having six terrain classifications related to the mower production speeds.

The model was used to predict the expected times and costs for a 6-ft flail type of mower to mow the grassed areas associated with the northbound lane, southbound lane, and median.

SIMULATION MODEL

The simulation model consists of a core program and four data packs. The data packs, which contain information relevant to determining mowing project costs and times, are as follows:

1. Speed functions that relate mower production to terrain features,
2. Cost functions that relate to hourly equipment costs,
3. Delay functions that are associated with nonproductive activity times, and

4. Area distribution functions that describe the subsections of the highway right-of-way and the respective percentages of each type of terrain classification.

The core program, through random number generators that select random variables from cumulative probability density functions within each of the data packs, determines mowing project times and costs.

The model considers the probability of rainfall delays, and variations in daily nonproductive times such as travel to and from the field, preventive maintenance, personal delays, and equipment breakdowns.

OPERATION OF THE MODEL

The model contains six speed functions relating to the production capacity of the mower, three cost functions that reflect equipment cost, 16 functions of nonproductive time activities occurring during a normal workday, and seven functions that relate to the proportional amounts of area to be mowed under each of six speed distributions (Table 1).

Random variables were selected from the functions listed in the program by means of eight pseudorandom number generators. The generators were assigned sequentially to the functions because they were listed at the beginning of the program to make the entire model random.

Simulation began by setting the simulated clock time within the program to zero. The simulated time unit in the model was equivalent to 1 min of actual time.

As a transaction, which represented the driver of a tractor, proceeded from one component to another in the system, the clock time was updated by variate time increments that were added to the clock time.

The simulation model accrued time on a day-to-day basis until all grass areas within the section of highway were mowed. This approach required that a sufficient number of daily work sequences be run to ensure that all the grass areas were cut. From previous observations of mower production in the example study and several trial runs with the computer program, it was established that 12 cycles of daily work sequences per observation of project completion time was adequate.

At the end of every 12 cycles, the clock time was reset to zero. Also, all "savevalues" that serve to retain the values of attributes such as total project time, total project cost, total equipment cost, and other times and costs associated with morning and afternoon production in the simulation model, were reset to zero except for those "savevalues" that designated the areas of the subsections and terrain classifications.

The seeds of the eight random number generators were not reset. Thus, each 12-cycle run was an independent observation of the project completion time.

Three time interruptions within a daily work sequence were instituted from field studies. The first interruption was the time to stop cutting in the morning and go to lunch. The second was the time to leave the field and return to the maintenance division headquarters. The third was the time at which the transaction was to leave the system.

As shown in Figure 1, the first consideration in the model was to ascertain if rain had occurred. Rain determined whether the driver was sent to the field or assigned to another task. On the first of each 12 cycles, the probability was 0.73 that a clear day would randomly occur. A random variable was selected by means of a random number generator and compared with the probability of 0.73. If the variate was less than or equal to 0.73, the driver was assigned to the field. If the variate was greater than 0.73, the driver was assigned another task, and the simulated clock time was advanced 480 min without a cost being charged to mowing.

After the first day, the probability of forecasting a clear day fluctuated from 0.78, which was the probability that, if today was clear, tomorrow would be clear, to 0.60, which was the probability that, if today was rainy, tomorrow would be clear.

The work sequence was divided into two sessions: morning and afternoon (Fig. 1). In the morning, six variates associated with each of six nonproductive activities were generated and added to the clock time in proper sequential order, as follows:

Figure 1. Flow diagram for simulation model.

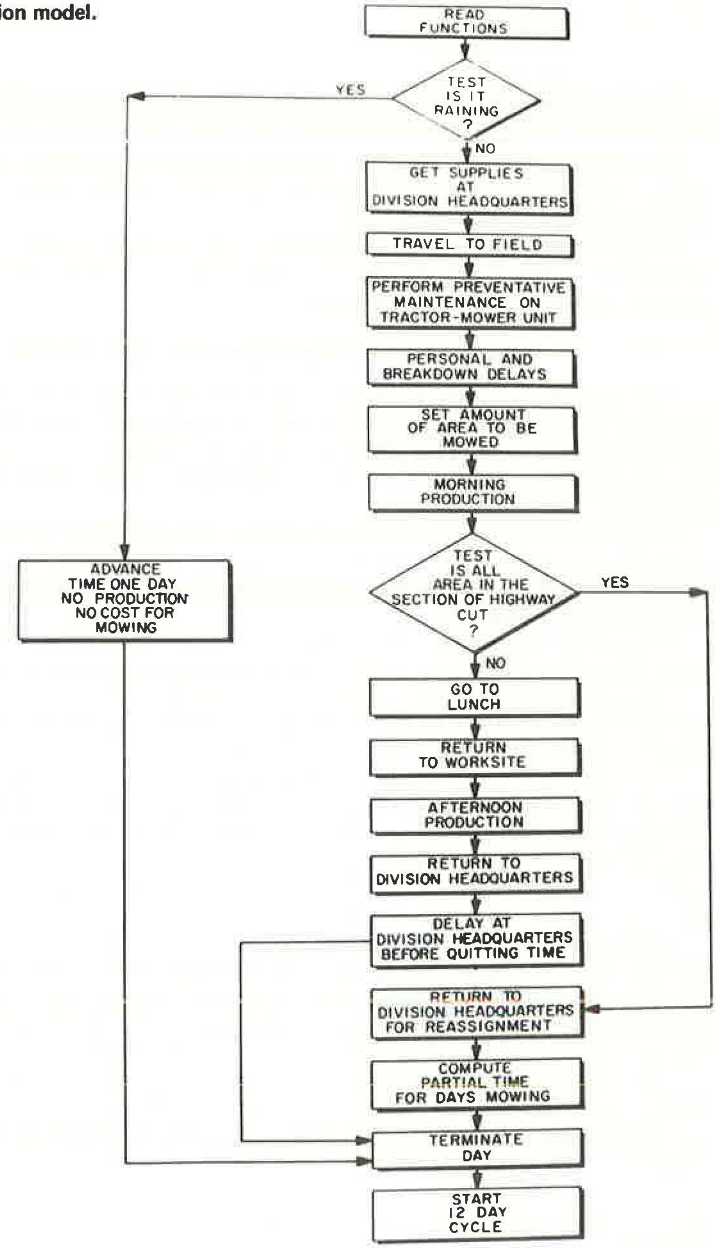


Table 1. Model functions.

Function	Description	Function	Description
1	Flail mower speeds, 0- to 8-deg side slope	17	Personal delay times in a. m.
2	Flail mower speeds, 9- to 12-deg side slope	18	Travel times from site to truck at lunch
3	Flail mower speeds, 13- to 16-deg side slope	19	Lunch times
4	Flail mower speeds, 17- to 22-deg side slope	20	Travel times from truck to site in p. m.
5	Obstacle mowing speeds	21	Number of personal delays in p. m.
6	Roading speeds	22	Personal delay times in p. m.
7	Hourly operating costs for flail mowers	23	Travel times from site to truck in p. m.
8	Hourly operating costs for tractors	24	Travel times from field to headquarters
9	Hourly operating costs for trucks	25	Turn times
10	Number of breakdowns for flail mower	26	Area, Naamans Road Interchange
11	Times per breakdown for flail mower	27	Area, Naamans Road to Harvey Road
12	Delay times at division headquarters	28	Area, Harvey Road Interchange
13	Travel times from headquarters to mower	29	Area, Harvey Road to Marsh Road
14	Preventive maintenance times	30	Area, Marsh Road Interchange
15	Travel times from truck to site in a. m.	31	Area, Marsh Road to Route 202
16	Number of personal delays in a. m.	32	Area, Route 202 Interchange

1. The delay time at the maintenance division headquarters to secure supplies, such as water, gas, and repair parts;
2. The travel time from the division headquarters to the work site;
3. Preventive maintenance and minor repairs prior to beginning work;
4. Travel time from the truck to the mowing area;
5. Personal delay times, such as getting a drink of water, picking up trash, and personal relief; and
6. Mower breakdown delay times for removing objects that had become lodged in the mower, adjusting cutting height of the blades, and so forth.

The morning production period began after the simulated clock was advanced for the six nonproductive time variates, some of which might have been zero. The production period was subdivided into 10-min work intervals.

The subsections of the highway were called sequentially, whereas the speed classifications within each subsection were called randomly. A discrete random variable was generated to select the terrain classification within a subsection. The terrain classification was designated by a 2-digit number. For example, in subsection 30 given in Table 2, if the discrete random variable 12 was selected by the random number generator, then the class B terrain classification had been designated for parameter 7. Modulo division by 10 gave a remainder of 2, which signified that a speed variate was selected from function 2 and placed in FN*7.

The amount of area mowed in a 10-min interval was given by 1 FVARIABLE = FN*7 (5,280/60)*(55/10)*10 where FN*7 is a speed variate expressed in miles per hour, 5,280/60 is a constant that changes miles per hour to feet per minute, 55/10 is the effective width of cut that was assumed as 5.5 ft for a 6-ft rear-mounted flail mower, 10 is the interval of time over which the speed was assumed constant, and 1 FVARIABLE is the total number of square feet of grass cut in 10 min in the terrain classification specified by parameter 7.

After each 10-min work interval, a series of checks was performed. First, the simulated clock was checked against the time to stop work for lunch. If the clock time was later than 11:40 a.m., the morning work period ended, and the driver went to lunch. If the clock time was earlier than 11:40 a.m., the model checked to see if all the area of the subsection had been cut. If more than 100 ft^2 of area remained, the driver returned to work for another 10-min work interval. If 100 ft^2 or less of area remained in the subsection, the area was set to zero, and a check was made to determine if the subsection was the last subsection on the highway. If all sections had been cut, the driver returned to the truck and then to the division headquarters for another assignment.

During a normal day, the driver went to lunch, and areas of uncut grass remained for the afternoon work session. When the driver went to lunch, the simulated clock was advanced five variate time intervals, each associated with a nonproductive activity. The five nonproductive activities were travel time from the work area to the truck, lunch time, travel time from the truck to the work site after eating, personal delay times, and equipment breakdown delays.

The afternoon production period began after the simulated clock was advanced for the five nonproductive time variates, some of which might have been zero. The work cycle in the afternoon session was the same as that described for the morning session.

After each 10-min work interval in the afternoon, the model performed a series of checks. First, the simulated clock was checked against the time to stop work and return to the truck for transportation to the division headquarters. If the clock time was later than 3:10 p.m., the driver returned to the division headquarters. The simulated clock was advanced two time-variate intervals, each associated with nonproductive activities. The two intervals were travel time from the work area to the truck and travel time from the job site to the division headquarters.

The last nonproductive time variate, which was the delay time at the division headquarters before going home, was developed by the model. The clock time at which the truck arrived at division headquarters was called in the program and subtracted from 4:00 p.m. to obtain the variate delay time.

If the clock time was earlier than 3:10 p.m., the model performed the same set of area completion checks that it did during the morning session. If all the area was cut before 3:10 p.m., the driver returned to the division headquarters, and a partial day's work was indicated in the program printout.

DESCRIPTION OF EXAMPLE APPLICATION

The mowing simulation model was developed with the IBM 360 computer facility at Drexel University. Data for the model were obtained from a 12-week study of the mowing operation on a 10.6-mile section of I-95 in the New Castle maintenance division.

All mowed areas on the section of I-95 from the Pennsylvania line to the intersection of I-95 and I-295 (Fig. 2) were detailed on landscape plans of the area. The detailing included the field checking of degrees of side slope, and the location of guardrails, trees, lampposts, delineation markers, and other mowing obstructions. The layout of the area and field checking the accuracy of the plans required 45 man-hours. The quantity take-off of the area required 56 man-hours. A typical detailed section is shown in Figure 3.

The terrain features associated with the mowed area were classified according to six conditions. These conditions were 0 to 8 deg (less than 5:1) side slope or class A, 9 to 12 deg (5:1) side slope or class B, 13 to 16 deg (4:1) side slope or class C, 17 to 22 deg (3:1) side slope or class D, obstacle areas of class E, and roading or class F.

Obstacle mowing included traffic islands, cutting along lines of delineation markers and lamppost standards, and cutting adjacent to guardrails and fences.

Roading was travel between grass plots where the areas become asphalt or concrete.

The simulation model required that the section of highway be divided into subsections with each subsection being divided into a set of terrain classifications. For this study, the section of I-95 was divided into seven subsections with a set of six terrain classifications per subsection as given in Table 2.

TIME STUDY OF TRACTOR-MOWER UNITS

Time studies were conducted on nine drivers and three types of tractor-mower units. Times were measured for each of the tractor-mower units to determine their speeds when cutting on slide slopes classified as 0 to 8 deg, 9 to 12 deg, 13 to 16 deg, and 17 to 22 deg.

The distances over which time intervals were measured varied according to the distances between natural and man-made obstructions that required the driver to turn the mower around. The distances ranged from 250 to 1,000 ft with the most frequent distances occurring between 450 and 550 ft. Distances were determined by pacing, referencing to guardrail post spacing, or scaling distances from the plans. All speeds were for a grass height interval of 6 to 20 in.

Typical histograms of the distribution of mower speeds and nonproduction activity times are shown in Figures 4 and 5.

COST DATA

The hourly costs for operating tractors, mowers, and trucks were obtained from monthly cost records. The data were obtained from the Oklahoma Department of Highways, the Delaware Department of Highways and Transportation, and the Pennsylvania Turnpike Commission. The data contained the hourly rates for 24 trucks, 47 tractors, and 18 flail mowers.

Histograms of the distribution of hourly cost rates for operating tractors, flail mowers, and trucks are shown in Figures 6, 7, and 8.

RAINFALL DATA

The effect of rainfall as a factor in extending the completion time of a mowing project was incorporated as a part of the simulation model.

Table 2. Lane area distribution.

Section	Class A		Class B		Class C		Class D		Class E		Class F		Total Area (ft^2)	Save-Value
	Ft^2	Per-cent	Ft^2	Per-cent	Ft^2	Per-cent	Ft^2	Per-cent	Ft^2	Per-cent	Ft^2	Per-cent		
Naamans Interchange	141,285	45	36,360	11	40,460	14	48,650	16	36,850	12	3,880	2	307,485	X30
Naamans Road to Harvey Road	139,875	28	102,180	21	116,300	24	104,000	21	—	—	27,610	6	489,965	X31
Harvey Interchange	28,150	33	10,065	12	8,200	9	15,980	18	11,620	13	12,595	15	86,610	X32
Harvey Road to Marsh Road	56,185	14	76,130	19	127,800	32	122,745	31	—	—	16,225	4	399,085	X33
Marsh Interchange	—	—	—	—	—	—	—	—	10,980	81	2,530	19	13,510	X34
Marsh Road to Route 202	229,355	46	46,380	9	112,150	23	76,770	15	—	—	32,570	7	497,215	X35
Route 202 Interchange	243,810	41	140,130	24	103,955	17	78,830	12	25,335	4	4,620	2	596,680	X36
Average	838,660	35	411,245	17	508,865	21	446,975	19	84,785	4	100,020	4	2,390,500*	

*Total area equals 54.9 acres.

Figure 2. Site location of study on I-95.

Figure 3. Typical layout of mowing areas by terrain classifications.

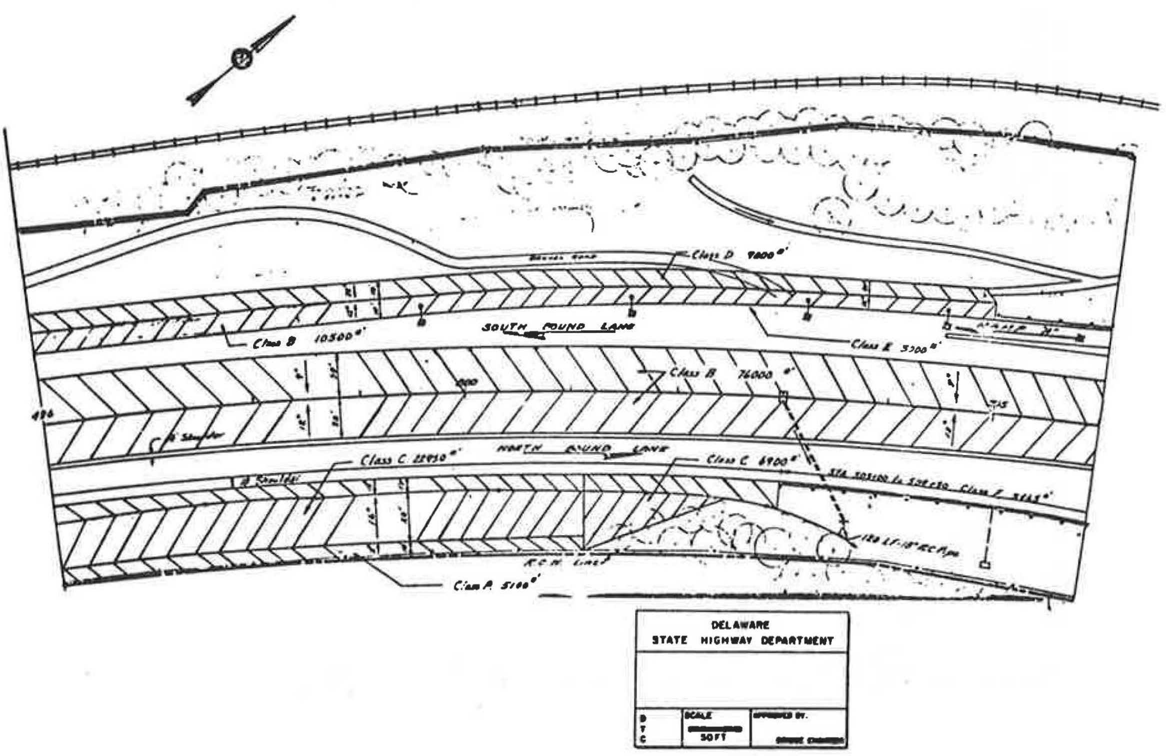


Figure 4. Speeds of flail mower, 0- to 8-deg side slope.

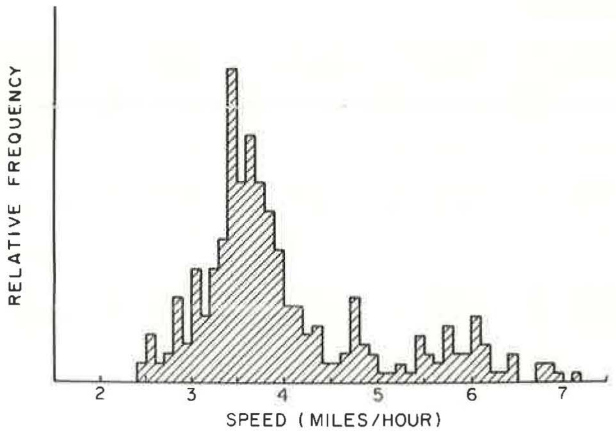


Figure 5. Times for each breakdown of flail mower.

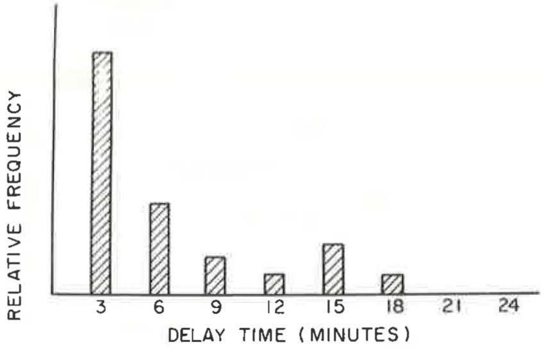
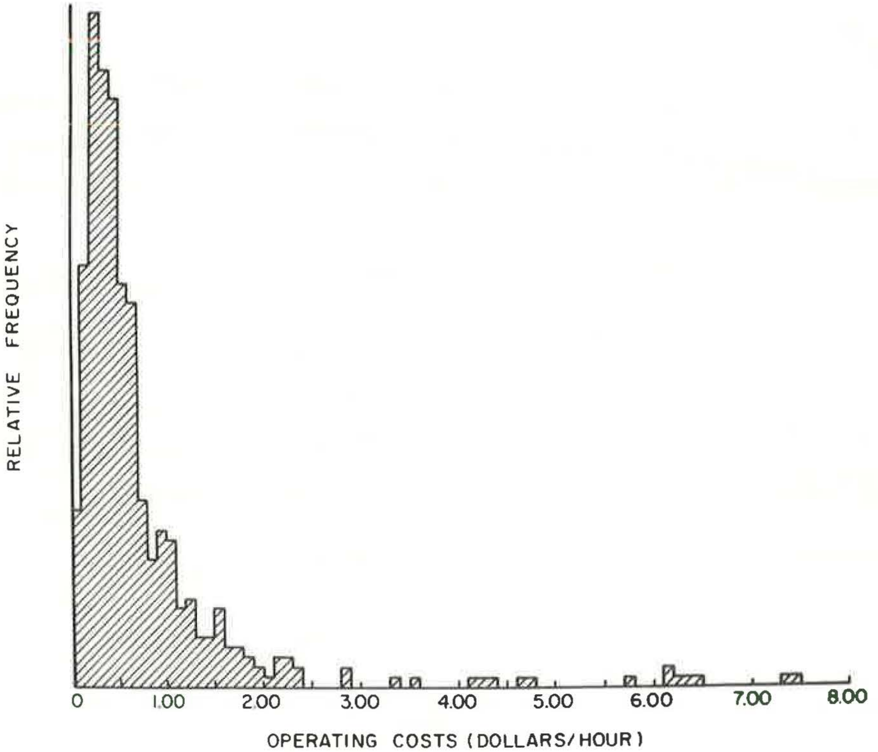


Figure 6. Hourly operating costs for tractors.



The rainfall data were obtained from the weather station at the Philadelphia International Airport, which is located 18 miles from the study area on I-95 in Delaware. Twenty years of rainfall data, dating from 1951 through 1970, were used in the forecast analysis. The data were further reduced to 5-day workweek conditions.

From the analysis of the data, the following probabilities were obtained: $P(B_1) = 0.73$ where $P(B_1)$ is the probability that a clear day will occur between May 1 and November 1; $P(B_2) = 0.27$ where $P(B_2)$ is the probability that a rainy day will occur between May 1 and November 1; $P(X_1/B_1) = 0.78$ where $P(X_1/B_1)$ is the conditional probability that, if today is clear, tomorrow will be clear; $P(X_2/B_1) = 1 - P(X_1/B_1) = 0.22$ where $P(X_2/B_1)$ is the conditional probability that, if today is clear, tomorrow will be rainy; $P(X_1/B_2) = 0.60$ where $P(X_1/B_2)$ is the conditional probability that, if today is rainy, tomorrow will be clear; and $P(X_2/B_2) = 1 - P(X_1/B_2) = 0.40$ where $P(X_2/B_2)$ is the conditional probability that, if today is rainy, tomorrow will be rainy.

Bayes' theorem for forecasting clear weather, given that a clear condition exists, is given by the following formula:

$$P(B_1/X_1) = \frac{P(B_1)P(X_1/B_1)}{P(B_1)P(X_1/B_1) + P(B_2)P(X_2/B_2)}$$

where $P(B_1X_1)$ is the posterior probability of clear weather, and $P(B_1)$, $P(X_1/B_1)$, $P(B_2)$, and $P(X_1/B_2)$ are the prior probabilities as defined previously. Therefore,

$$P(B_1/X_1) = \frac{(0.73)(0.78)}{(0.73)(0.78) + (0.27)(0.60)} = \frac{0.5694}{0.7314} = 0.779$$

Bayes' theorem for forecasting clear weather, given that a rainy condition exists, is given by the following formula:

$$P(B_1/X_2) = \frac{P(B_1)P(X_1/B_1)}{P(B_1)P(X_2/B_1) + P(B_2)P(X_2/B_2)}$$

where $P(B_1/X_2)$ is the posterior probability of clear weather, and $P(B_1)$, $P(X_2/B_1)$, $P(B_2)$, and $P(X_2/B_2)$ are prior probabilities. Therefore,

$$P(B_1/X_2) = \frac{(0.73)(0.22)}{(0.73)(0.22) + (0.27)(0.40)} = \frac{0.1606}{0.2686} = 0.598$$

APPLICATION OF THE MOWING SIMULATION MODEL

It was proposed by the author that 10.6 miles of the southbound lane from edge of roadway to right-of-way fence on I-95 be mowed with a single 6-ft flail mower. The time was estimated from a field observation to be approximately 1 workweek. Based on this knowledge, a simulated sample size of 20 observations was selected. This size sample was analogous to making field measurements of the project times for a full mowing season that extended from May 1 to November 1. It was further proposed that the model represent the recording of these measurements for five mowing seasons. Thus, the mowing model consisted of five samples, each of which included 20 observations.

All eight random number generators that are available in the GPSS simulation language were assigned sequentially to the functions to develop complete randomization within the model.

The results of the simulated project times and project costs for sample 1 are given in Tables 3 and 4. The simulated times compare favorably with the observed completion time of 1 week.

A comparison was also made in which all class D or 3:1 side slope mowing was eliminated from the cutting assignments for the southbound lane. The results of this comparison, as given in Tables 4 and 5, indicate that, on the average, the scheduled

Figure 7. Hourly operating costs for flail mower.

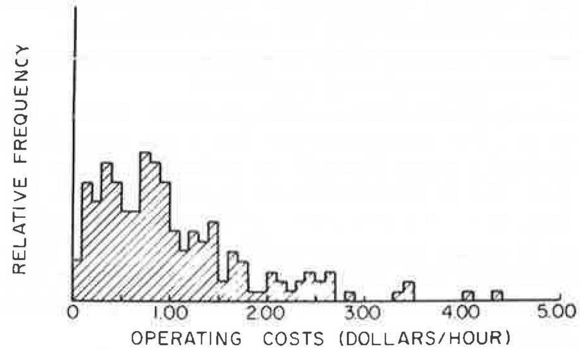


Figure 8. Hourly operating costs for trucks.

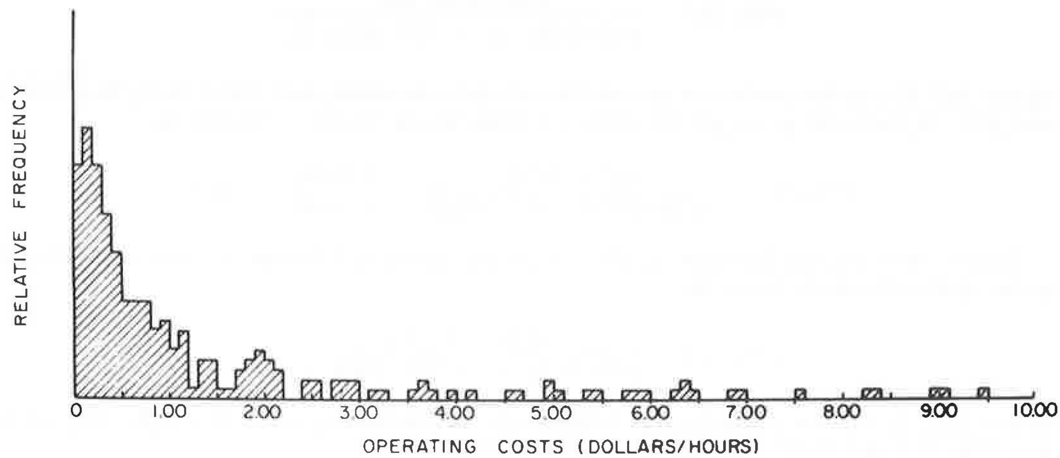


Table 3. Sample 1 project times.

Observation	Total Project Time With Rain		Total Product Time Without Rain Effect		Rain Factor[a]	Total Production Time in Project	
	Min	Hours	Min	Hours		Min	Hours
1	2,582	43.03	2,582	43.03	1.00	1,472	24.53
2	3,544	59.07	2,584	43.07	1.37	1,378	22.97
3	3,060	51.00	2,580	43.00	1.19	1,406	23.43
4	3,840	64.00	2,400	40.00	1.60	1,359	22.65
5	3,506	58.43	2,546	42.43	1.38	1,388	23.15
6	2,604	43.40	2,604	43.40	1.00	1,434	23.90
7	2,705	45.08	2,705	45.08	1.00	1,447	24.12
8	2,814	46.90	2,814	46.90	1.00	1,544	25.73
9	2,535	42.25	2,535	42.25	1.00	1,399	23.32
10	3,987	66.45	2,547	42.45	1.57	1,387	23.12
11	2,969	49.48	2,489	41.48	1.19	1,429	23.82
12	4,095	68.25	2,655	44.25	1.54	1,432	23.87
13	2,648	44.13	2,648	44.14	1.00	1,461	24.35
14	2,582	43.03	2,582	43.03	1.00	1,435	23.92
15	2,605	43.42	2,605	43.41	1.00	1,384	23.07
16	3,095	51.58	2,615	43.58	1.18	1,452	24.20
17	3,240	54.00	2,760	46.00	1.17	1,442	24.03
18	2,583	43.05	2,583	43.05	1.00	1,443	24.05
19	3,994	66.57	2,554	42.56	1.56	1,388	23.11
20	4,286	71.43	2,366	39.43	1.81	1,408	23.47
Mean	3,164	52.73	2,588	43.14	1.23	1,424	23.47
Standard deviation	603	10.05	104	1.74	0.26	42	0.70

[a]Derived from preceding two columns.

Table 4. Sample 1 project costs.

Observation	Project Cost (in dollars) With Class D	Project Cost (in dollars) Without Class D	Observation	Project Cost (in dollars) With Class D	Project Cost (in dollars) Without Class D
1	101.13	79.34	12	104.54	83.66
2	103.56	82.80	13	106.31	87.08
3	106.12	91.42	14	109.47	83.17
4	104.10	84.50	15	106.69	93.02
5	102.45	90.82	16	106.47	83.36
6	106.10	87.31	17	104.36	90.95
7	106.49	83.57	18	107.12	83.65
8	105.11	87.70	19	102.45	88.33
9	100.00	82.67	20	96.57	85.95
10	103.09	84.35	Mean	104.27	86.06
11	103.71	87.59	Standard deviation	2.86	3.57

Note: Figures represent total cost per mowing, including transportation and labor.

Table 5. Project times (without class D).

Observation	Total Project Time With Rain Min	Total Project Time With Rain Hours	Total Project Time Without Rain Effect Min	Total Project Time Without Rain Effect Hours	Rain Factor[a]	Total Production Time in Project Min	Total Production Time in Project Hours
1	2,315	38.58	1,835	30.58	1.26	1,094	18.23
2	2,352	39.20	1,872	31.20	1.26	1,103	18.38
3	3,076	51.27	2,116	35.27	1.45	1,177	19.62
4	3,068	51.13	2,108	35.13	1.46	1,101	18.35
5	2,123	35.38	2,123	35.38	1.00	1,101	18.35
6	2,764	46.07	2,284	38.07	1.21	1,130	18.83
7	3,781	63.02	1,861	31.02	2.03	1,056	17.60
8	4,480	74.67	2,080	34.67	2.15	1,111	18.52
9	2,827	47.12	1,867	31.12	1.51	1,089	18.15
10	3,549	59.15	2,109	35.15	1.68	1,099	18.32
11	2,046	34.10	2,046	34.10	1.00	1,079	17.98
12	2,540	42.33	2,060	34.33	1.23	1,059	17.65
13	3,106	51.77	2,146	35.77	1.45	1,087	18.12
14	3,980	66.33	2,060	34.33	1.93	1,091	18.18
15	2,618	43.63	2,138	35.63	1.22	1,144	19.07
16	2,045	34.08	2,045	34.08	1.00	1,086	18.10
17	3,999	66.65	2,079	34.65	1.92	1,088	18.13
18	2,534	42.23	2,054	34.23	1.23	1,085	18.08
19	3,052	50.87	2,092	34.87	1.46	1,100	18.33
20	2,558	42.63	2,078	34.63	1.23	1,090	18.17
Mean	2,941	49.01	2,053	34.21	1.43	1,099	18.31
Standard deviation	702	11.69	112	1.87	0.35	27	0.45

[a]Derived from preceding two columns.

completion time and cost per mowing of the southbound lane would be reduced 12.5 percent for the scheduled completion time and 12.1 percent for the cost per mowing. The analysis required ½ man-hour to collate the results of the computer output at a cost of $24 for computer time.

CONCLUSIONS

As demonstrated in this study, the mowing simulation model gives the highway maintenance engineer an effective tool by which he can make quantitative decisions about mowing programs for various sections of the highway system. The model is easily modified to handle any mowing situation that involves the production of a tractor-mower unit.

If the highway maintenance engineer is of the opinion that his work force performs more efficiently than the one represented in the model, he can remove the set of delay data from the data deck and replace it with a set of data that is applicable to his work force.

To apply the model to another section of highway, one needs to remove from the present program that portion of the data deck that refers to the subsections and terrain classifications and, also, the set of data in the core program that initializes the subsections and terrain classification areas. These data are replaced with data that describe the new section of highway according to its subsections and terrain classifications.

The model can be modified to handle any size or type of mower. This modification requires that the speed data in the data deck be replaced with speed data that are applicable to the performance of the new mower on the terrain classifications. If the effective width of the new mower is other than 5½ ft, the width factor in the production capacity equation must be specified in the core program.

The GPSS program developed for the mowing model is a utility program that can be extended to other highway maintenance operations such as road patching, in which the variance in the number of square feet of patching laid per day by a paver can be estimated; snowplowing, in which the number of square feet per hour of cleared road surface can be estimated for different size plows and depth of snow; or a ditching operation, in which the cubic yards of excavated material per hour can be estimated as a function of the density of the material.

With the development of the simulation model, the highway maintenance engineer now has a means by which time study data can be used effectively to make quantitative comparisons among alternatives for cost reduction decisions.

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EVALUATION OF EQUIPMENT UTILIZATION AND MANAGEMENT WITHIN THE VIRGINIA DEPARTMENT OF HIGHWAYS

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An administrative task force proposed a possible approach to evaluation of equipment utilization and management. This approach centered around providing the answers to the following questions: What should be expected of the districts in terms of equipment utilization? How could these expectations of accomplishment be achieved on a continuous basis? Why is there a variation in equipment utilization among districts? If found appropriate or desirable to do so, how could variations of equipment management and utilization accomplishments among districts be minimized or brought up to the level of the most effective district? In carrying out its research, the task force used statistical data available at the central office, field observations, interviews with central office and field personnel, and the personal judgment of its members. Implemented recommendations described and assessed in terms of their documentation included in this paper are utilization standards for most of the classes of equipment, improved management incentives and controls, a negative assessment of the possibility of utilization of hired equipment, annual estimates of equipment needs and an annual equipment budget, and increased support for the role of district equipment superintendents. Estimated savings amount to more than $450,000 annually or, in overall terms, a 13 percent improvement in equipment utilization.

IN its evaluation of the Virginia Department of Highways' equipment utilization and management, the task force made the following findings:

1. The Department had a statewide inventory of 175 classes of equipment (7,299 pieces) representing an investment of $35,920,219 on the basis of original cost.
2. This study examined in detail 25 of these classes (5,401 pieces) representing an investment of $24,233,835 on the basis of original cost or 67.5 percent of the Department's equipment in money terms and 74.7 percent of the Department's equipment in terms of number of pieces;
3. Utilizing the most conservative estimating procedures, we surmised that, through implementation of the recommendations presented in the next section of this paper, the Department on an overall basis (the degree of increased utilization achievable by class is not uniform) will utilize its existing equipment to perform 13 percent more work, perform current work at a one-time savings of $3,174,436 on the sample equipment, or by applying the sample to all equipment, save $4,669,628;
4. Viewed in terms of 10-year equipment life and 10 percent straight-line depreciation principles (again a most conservative procedure), annual equipment productivity should increase by 13 percent, thereby generating 13 percent more work with existing equipment, performing current work at an annual savings of $317,443 on the sample classes, or saving $466,962 on all classes;

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5. Savings cited in the preceding two findings in no way reduce the services performed by the Department (reduction of such services as snow removal and frequency of mowings could be used to cite further economies, but such techniques are considered to be "puffing");

6. Although geography, population, and road mileage may account for the amount of equipment assigned and how it is used, the rate of equipment utilization is primarily dependent on variations in qualities of district managements, effectiveness of services provided by the central office, and evaluation, control, and incentive techniques utilized by central office, district, and residency personnel;

7. The preceding elements of management needed to be improved in several instances, and specific recommendations have been implemented to bring about this improvement;

8. Interviews indicated that four of the eight district equipment superintendents felt that they did not have sufficient authority to carry out their responsibilities;

9. With one exception, the greater was the degree of delegation as defined by these superintendents, the more effective was the district in equipment utilization and management as defined by utilization data; and

10. Interviews with personnel in the equipment division, data processing division, maintenance division, and secondary roads division indicated that district rental rates were feasible from a developmental and procedural standpoint.

IMPLEMENTED RECOMMENDATIONS

In the spring of 1971, a committee was formed to evaluate the findings and recommendations of the reporting task force and to put into effect those recommendations deemed worthy. Results are reported in the format of recommendations made.

Utilization Standards

All 175 classes of equipment were examined by the equipment and maintenance engineers and the assistant management services officer. Standards were set approximately halfway between the district averages and the district highs for about 150 of these 175 classes. Other classes (ferry boats, for example) were exempted for specific reasons.

Management Incentives and Controls at the Central Office Level

Besides holding districts accountable for specified average hours used per unit on a class basis, the following has been or will be performed at the central office level to facilitate the districts in their efforts toward increasing effectiveness of equipment utilization and management:

1. The equipment engineer will submit an annual report to the director of operations appraising district equipment use in relation to requirements and pointing out the need for praise and corrective action that he believes is necessary;
2. The director of operations will take the action necessary to bring substandard districts up to standard;
3. The management services division will appraise the director of operations' action in terms of subsequent improvement (or lack of same) in the districts' rate of equipment utilization;
4. District rental rates were instituted effective July 1, 1972, and have provided important financial and competitive incentives for improved equipment management; and
5. The total cost purchasing formula initiated by the purchasing division and Virginia Highway Research Council on graders will be applied to dozers or loaders when requirements for replacement equipment necessitates purchase (this experiment was postponed because improved utilization practices eliminated replacement needs during 1971).

Management Incentives and Controls at the District and Residency Levels

Because the principles of management controls and incentives should flow from the central office to the districts, there will, of course, in many instances be a parallel of district-residency-area relations with central office-district relations. In order to consider field units, however, the following recommendations regarding appropriate district and residency management action are currently being implemented:

1. The district equipment engineer will report to the district engineer and evaluate residency equipment use and point out the need for praise and corrective action that he believes is necessary. Assessments of equipment utilization will take place periodically during the year, particularly with reference to requests for additional and replacement equipment.
2. The district engineer will take the action necessary to bring substandard residencies up to standard.
3. The same kind of procedures will be applied by the resident engineer to his residency maintenance supervisors and area superintendents.
4. Residency rental rates will not, however, be applied, as differential accounting because more than 40 subunits would be quite cumbersome.
5. In general, Salem district's strategy of equipment management and utilization will serve as a basis of positive equipment utilization and management. This strategy consists of, but is not limited to, an equipment school scheduled on a regular basis, with particular emphasis on preventive maintenance; appraisal of equipment utilization on a residency and class basis; forced transfer of equipment among residencies where low use rates (without sufficient justification) are occurring; replacement of equipment only where it is justified on a current hourly use basis; hiring of equipment where possible for seasonal operations (snowplows on the Interstate, for example); and very active support of the role of the district equipment superintendent on the part of the district engineer.

Utilization of Hired Equipment and Current Equipment Assignment

Besides equipment transfers from areas of surplus to areas of shortage, inventories are being reduced because districts are now requesting less equipment per lane-mile of road, so reducing unit costs.

Annual Estimates of Equipment Needs and an Annual Equipment Budget

Needs estimates are being included in the maintenance performance budgeting system instituted by the Department, and equipment budgeting is currently being studied in terms of cash flow and available funds. Substantial savings have already accrued as a result of administration action utilizing more than $2 million for road expenditures, the money of which was formerly in the form of an equipment surplus account.

Role of District Equipment Superintendents

Top management of the Department has emphasized attention to this subject and has directed the maintenance engineer to look into the problem. These directions also include a more prominent role for the assistant district engineers for maintenance not mentioned by the reporting task force.

SUMMARY DOCUMENTATION OF FINDINGS AND IMPLEMENTED RECOMMENDATIONS

Findings pertaining to total equipment inventory in terms of number of pieces and dollar investment based on original cost are as follows:

Factor	Department-Wide	Sample
Number of pieces	7,229	5,401
Investment	$35,920,219	$24,238,835

Utilization Standards

Findings and recommendations regarding savings depend on conclusive proof that rates of utilization by class are more related to management effectiveness and control than to the uncontrollable factors of geography, population, location, and road mileage. It is submitted that, although the data given in Table 1 indicate some instances of geographical relation, the preponderance of evidence shows variations to be primarily caused by differences in effectiveness of management.

This assumption is not just a guess, but is supported by interviews with district engineers who all stated that management is a most important factor in equipment utilization. This point was further emphasized by interviewer impressions of variations of knowledge, incentives, and controls encountered among the districts.

The unanimous reply of all district engineers, stating that no systematic or formal type of evaluation of their equipment utilization and management practices in the districts was carried out by the Department, provided additional converging evidence that, although variations in rates of equipment utilization by class may be to some extent accounted for by geography, they were primarily accounted for by variations in effectiveness of district management, and therefore utilization could be substantially improved.

It is noted, however, that the information given in Table 1 also offers conclusive evidence that equipment use rates varied substantially among classes. Therefore, uniform standards of utilization rates would be unwarranted. Put another way, variations in hours used were much greater among classes than among districts, and so minimum standards could be appropriately set on a Department basis for each class but not on the basis of equal utilization standards for all classes.

It was suggested that reasonable standards would be halfway between the current district average per class and the district high per class as given in Table 2. It was further suggested that this principle could and probably should be extended to all or most classes of equipment.

These proposed standards then were the task force's answer as to what should be expected of the districts in terms of equipment utilization.

Department Savings

If the proposed standards were set and achieved, then on an overall basis the Department could perform 13 percent more work with existing equipment or current work with 13 percent less equipment.

Applying this savings to current work would allow a reduction of $3,174,436 of existing equipment for the sampled classes or $4,669,628 for all classes. On an annual basis, savings would amount to $317,000 for sampled equipment and $466,000 for all equipment based on 10-year equipment life and straight-line depreciation principles.

These estimated savings did not, of course, take into account the reduction of personnel (by attrition) that could be made or the performance of more work with existing personnel.

Additionally, it was believed that, over the long run, the district highs per class could be achieved on an average basis, therefore, doubling the estimated savings figures. This was, however, not claimed as savings.

It was noted that equipment utilization performance increases called for varied by class, and the 13 percent figure represented merely an overall summation of the potential results of these improvements. Estimated savings are given in Table 3.

It was felt that, because of the Department's increasing work load, savings should probably be applied through performing more work with existing numbers of equipment and personnel. It was suggested that, if this decision was made, there would, of course,

Table 1. Equipment use.

Item	Class Code	District (hours per unit) Bristol	Salem	Lynch- burg	Rich- mond	Suffolk	Freder- icksburg	Culpeper	Staunton	Aver- age
Loaders, 3,500 lb	337	1,174[a]	939[a]	828	646[b]	698	613[b]	676	652	779
Loaders, self-propelled	328	443	347[b]	467[a]	252[b]	485[a]	379	380	412	396
Loaders, 5,000 lb	338	1,009[a]	831	789	527[b]	902[a]	630	579[b]	815	760
Distributors, 800 to 1,000 gal	156	548	688	362	309[b]	564	575	335[b]	679[a]	508
Graders, 1,000 lb	286	892	1,227[a]	1,129	1,088	1,245[a]	841[b]	823[b]	900	1,018
Graders, 20,000 to 26,000 lb	284	879	1,058[a]	920	827[b]	936	994	1,155[a]	871[b]	955
Pulverizers	476	43	37	34	109[a]	128[a]	11[b]	28[b]	40	54
Trucks, 5 tons	892	1,845[a]	1,320	552[b]	1,173	285[b]	1,175	1,608[a]	1,314	1,160
Trucks, ½ ton	828	1,806	1,738	1,686[b]	1,819[a]	1,314[b]	1,784	1,814[a]	1,731	1,712
Trucks survey	820	1,425[b]	1,612	1,522	1,573	1,413	1,704	1,754[a]	1,706[a]	1,589
Trailers	796	218	231	172	215	233[a]	106[b]	276[a]	169[b]	204
Tractors, medium angle dozers	764	676[a]	726[a]	607	312[b]	397	262[b]	406	561	532
Tractors	729	196	180[b]	194	312	507[a]	379[a]	269	112[b]	269
Mowers, tractors	724	515[a]	458	567[a]	454	472	407[b]	424	344[b]	456
Mowers, tractors, ext.	723	449	453[a]	442	382[b]	444	451[a]	329[b]	430	444
Sweepers, power action	692	262	307	327[a]	286	370[a]	208[b]	245[b]	286	287
Spreaders, strip rock	672	267[a]	232[a]	172	139	181	98	96[b]	75[b]	158
Rollers, self-propelled	573	284	328[a]	216	350[a]	204[b]	317	200[b]	262	268
Rollers, sheep's-foot	564	171	622[a]	231	254	110[b]	98[b]	330[a]	231	256
Rollers, 3 to 6 tons	540	48[b]	262[a]	106[b]	108	106[b]	135	130	203[a]	148
Tractors, 162 hp, angle dozers	761	314	851[a]	292[b]	257[b]	378	552[a]	540	467	457
Dump trucks, 2 to 3 tons	860	1,627[a]	1,461	1,538[a]	1,282[b]	1,473	1,291[b]	1,348	1,394	1,412
	864									645
Hydra-Matic drive trucks, 5 tons	893	648	949[a]	51[b]	408	118	40[b]	835[a]	755	
Truck, 6 to 8 tons	896	1,238[a]	1,233[a]	570[b]	823	728	388[b]	600	771	873
Welders, 200 to 400 amperes	960	1,119	1,669[a]	952	446	528[b]	328[b]	1,265[a]	985	912

Note: Source of data is Internal Audit Section of the Virginia Department of Highways.

[a]Two highs. [b]Two lows.

Table 2. Proposed standards of hours used by equipment class.

Item	Class Code	Hours Used, District Average	Hours Used, District High	Percent Difference Between High and Average	Total Hours	Proposed Standard Hours By Class	Percent Proposed Greater Than District Average
Distributors, 800 to 1,000 gal	156	507.8	688.1	35.4	1,195.9	597.9	17.7
Graders, 20,000 to 26,000 lb	284	955.2	1,155.4	20.8	2,110.6	1,055.3	10.4
Graders, 25,000 lb	286	1,018.3	1,245.5	22.2	2,263.8	1,131.9	11.1
Loaders, self-propelled	328	396.4	485.9	22.4	882.3	441.1	11.2
Loaders, 3,500 lb	337	779.0	1,174.0	51.0	1,953.0	977.7	25.5
Loaders, 5,000 lb	338	760.8	1,009.0	32.6	1,769.8	884.9	16.3
Pulverizers	476	54.0	128.0	137.0	182.0	91.0	68.5
Rollers, gas, 3 to 6 tons	540	147.8	262.2	77.4	410.0	205.0	38.7
Rollers, sheep's-foot	564	256.2	622.2	142.8	878.4	439.2	71.4
Rollers, self-propelled	573	267.7	350.4	30.8	618.1	309.0	15.4
Spreaders, chip rock type	672	157.9	267.0	71.4	424.9	214.4	35.7
Sweepers, power, tractor	692	286.9	370.6	29.2	657.5	328.8	14.6
Mowers, tractor, Hydra-Matic type	723	444.2	450.3	1.2	894.5	447.2	0.6
Mowers, tractor, PTO type	724	455.6	567.3	24.4	1,022.9	511.4	12.2
Tractors, 16 to 29 hp	729	269.1	507.7	88.6	776.8	388.4	44.3
Tractors, 162 hp, regular angle dozer	761	456.6	851.8	86.4	1,308.4	654.2	43.2
Tractors, medium angle dozer	764	531.7	726.4	36.4	1,258.1	629.0	18.2
Trailers, 16 tons	796	204.8	276.1	35.2	480.9	241.0	17.6
Trucks, survey, 6 to 8 passengers	820	1,589.1	1,754.3	10.2	3,343.4	1,671.7	5.1
Trucks, ½ ton	828	1,712.0	1,819.2	6.2	3,531.2	1,765.6	3.1
Trucks, ⅔ ton	860, 864	1,412.3	1,627.6	15.2	3,039.9	1,519.9	7.6
Trucks, 5 tons	892	1,159.5	1,845.9	59.0	3,005.4	1,502.7	29.5
Trucks, 5 tons, 4-wheel drive	893	645.1	949.7	47.0	1,594.8	797.4	23.6
Trucks, 6 to 8 tons, tractor	896	872.5	1,238.6	41.0	2,111.1	1,055.5	20.9
Welders, 200 to 400 amperes	960	911.9	1,669.1	83.0	2,581.0	1,290.5	41.5

Note: Source of data is Internal Auditing Section of the Virginia Department of Highways.

be no reduction in dollar costs but a 13 percent reduction in unit costs. It is further noted that these savings did not include a reduction in Department services. If such a reduction came about, astronomical figures could be used particularly if seasonal services such as snow removal or mowing were eliminated or reduced. Such reductions would not be savings but rather a trade-off between lower services and lower costs. If reduction in services were called for and the reduced costs were cited as savings, this would be "puffing" and indicate an unprofessional manipulation of figures in order to make the task force look impressive.

Management Incentives and Controls at the Central Office and District Levels

Interviews with the director of operations and the equipment engineer, and the fact that all districts stated they were not aware of any type of formal or systematic evaluation of their equipment utilization and management, were cited as evidence that this type of evaluation did not then exist. Interviews taken at the district level indicated that systematic evaluation of residency equipment and utilization management existed, but to greatly varying degrees.

The task force had taken these facts and inferred that this type of evaluation, coupled with the principles of linking authority, responsibility, accountability to positions, and the use of "reward and correction" techniques should be performed on a systematic basis.

The proposed system has been previously defined, and areas of agreement and disagreement with the affected parties were cited to top management. No additional documentation could be supplied with regard to this management system because it became a matter of judgment.

This matter of judgment applied to all recommendations regarding management incentives and controls at the district level and several affecting the central office. It may be recalled that the latter relates to the roles of the director of operations, the equipment engineer, and the then future systems and procedures or internal audit group (now lodged in the management services division).

District rental rates appeared to have many advantages and disadvantages, advantages being financial and competitive incentives and disadvantages being possible difficulties in comparing Department operations and in budgeting. The recommendation advocating district rental rates again was a judgment decision.

Expansion of efforts of evaluating total cost purchasing versus initial bid by equipment class was recommended because lowest initial price may not be the lowest total cost in all instances. Although the purchasing division and the Virginia Highway Research Council showed that the initial price method was cheaper for graders several years ago, the total cost method was at a disadvantage in relation to the advantages it may offer for dozers, loaders, and other types of equipment.

Utilization of Hired Equipment

Another item believed to be deserving of "highlighting" was the very low utilization rates exhibited by numerous classes of equipment. It was recognized that seasonal items are naturally used less, but an examination of the data given in Table 4 shows classes of equipment with utilization rates that on the surface indicate advantageous rental possibilities.

Interview data indicated district and supplier reservations regarding provision of rental equipment at economical rates even with reference to low utilization ownership. Until and unless suppliers respond affirmatively to this idea, it will not be implemented.

Interviews regarding the preceding subject included all eight district equipment superintendents and dealer representatives of the Caterpillar Tractor Company and the Galion Iron Works.

Annual Estimates of Equipment Needs and an Annual Equipment Budget

Recommendations made regarding an annual equipment needs estimate and budget are supported by various sources including documentation previously provided, manage-

Table 3. Estimated savings attainable through improvements in Department's equipment utilization and management.

Class Code	Original Cost Investment (in dollars)	Potential Reduction in Investment (percent)	Estimated Savings (in dollars)
156	340,665.45	17.7	60,298
284	4,010,319.45	10.4	417,073
286	749,870.81	11.1	83,236
328	1,677,453.53	11.2	187,875
337	1,170,689.20	25.5	298,525
228	1,266,157.67	16.3	206,384
476	202,959.67	68.5	139,027
540	286,459.14	38.7	110,898
564	52,795.98	71.4	37,696
573	199,847.87	15.4	30,778
672	50,425.06	35.7	21,572
692	204,055.46	14.6	29,792
723	939,851.31	0.6	5,639
724	587,989.70	12.2	71,734
729	94,906.01	44.3	42,043
761	489,151.91	43.2	275,244
764	1,800,812.97	18.2	327,748
796	113,108.37	17.6	19,907
820	396,340.89	5.1	20,213
828	1,963,237.66	3.1	61,170
860, 864	6,387,506.58	7.6	485,450
892	219,257.74	29.5	64,680
893	257,107.11	23.6	60,677
896	698,843.67	20.9	146,058
960	74,021.99	41.5	30,719
Total sampled classes	24,233,835	13	3,174,436
Total all classes	35,920,219	13	4,669,628

Table 4. Itemization of classes of the equipment sample.

Class Code	Statewide Inventory	Item	Percent Utilization
156	45	Distributors, 800 to 1,000 gal	24.1
328	115	Loaders, self-propelled	19.0
337	126	Loaders, R. T., 3,500 lb	37.4
338	124	Loader, R. T., 5,000 lb	36.5
476	29	Pulverizers	2.6
540	90	Rollers, gas, 3 to 6 tons	7.1
564	45	Rollers, sheep's-foot	12.3
573	37	Rollers, self-propelled	13.0
672	50	Spreaders, chip rock type	7.6
692	95	Sweepers, power, with tractor	13.8
723	28	Mowers, tractor, Hydra-Matic type	20.3
724	362	Mowers, tractor, PTO type	21.9
729	63	Tractors, 16 to 29 hp	12.9
761	17	Tractors, 162 hp with angle dozer	24.2
764	75	Tractors, medium with angle dozer	23.7
796	40	Trailers, 10 to 16 tons	9.7
893	33	Trucks, 5 tons, 4-wheel drive	22.9
896	62	Trucks, 6 to 8 ½ tons, tractor	38.0

Note: Source of data is Internal Auditing Section of the Virginia Department of Highways.

ment literature concerning needs and budget estimates, personal interviews, and judgment of the task force members. An attempt is made in subsequent paragraphs to separate some of the various elements of this documentation.

Annual estimates of inventory needs are necessary to equalize the distribution of equipment according to its rate of utilization and estimated additional work to be accomplished. These estimates and recurrent inventory adjustments would serve to optimize equipment input-output relations on a continuing basis.

In making equipment estimates, management literature, common sense, and Department precedent (estimated needs and required funding for highways) indicate that needs and dollars should be linked together. Factors that should be considered include various aspects of utilization standards, equipment costs and life, and service requirements.

Because it was recommended that needs, estimates, and budgets be provided on a continuing basis, organizational units of the Department to carry out the functions were delineated. The natural area of expertise in equipment is the equipment division and in budgets (particularly with reference to depreciation scheduling that affects the timing of any funds available for equipment replacement) is the accounting division.

Interviews with the equipment engineer indicated the availability of rather large cash balances for the purchase of equipment. Because of lack of time, this subject was not investigated in detail; but it appeared that the accounting division's participation would lead to its exercising a necessary equipment controllership function. Recent investigation by management service division personnel revealed that the department could in fact take advantage of heretofore idle funds. As a result of this analysis, the Department will, during the next 2 years, utilize more than $2 million of equipment surplus balances for road expenditures.

Role of District Equipment Superintendents

Four of the eight district equipment superintendents interviewed indicated a lack of delegation of authority for the area for which they were responsible. An examination of utilization data indicated that, in three out of the four districts involved, utilization was least effective.

These findings were discussed with top management who, without prior knowledge of task force findings, identified the districts in question. Because interviews at high levels confirmed lower level contentions and because equipment management evidence indicated a relation between little delegation and ineffective utilization, it was suggested that remedial action be taken.

It was decided that this action would be in the form of emphasis on and attention to the position of the assistant district engineer for maintenance and specific relations among the district engineers, assistant district engineers for maintenance, and district equipment superintendents. The results of the implemented recommendations have increased support of district equipment superintendents from higher levels of management.

This implemented recommendation reflects the overall reception of the task force's efforts in that top management gave serious attention to findings and recommendations and, in most cases, took affirmative action but often in a manner that I believe resulted in more effective measures than were recognized or advocated by task force members.

AN INSTRUMENT FOR DETECTING DELAMINATION IN CONCRETE BRIDGE DECKS

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Although many factors are required to characterize the extent of deterioration in a bridge deck, there are two factors that can be considered of paramount importance: delamination (a separation of the original slab into two or more approximately horizontal layers) and poor quality concrete. These two factors were singled out because it was felt that most structural damage to deteriorating bridge decks resulted from one or the other or both of these defects. Other considerations in the selection of these factors are that damage to structures caused by them is often not visible until significant deterioration is present and, also, that the known techniques for their detection are slow and tedious. Thus, the major emphasis of this research has been directed toward methods for detecting delamination and also detecting poor quality concrete. This report describes an instrument that has been developed specifically to detect delamination. It also includes an evaluation of the device, accomplished by measuring specially constructed test slabs and numerous in-service bridges. All evaluation tests that have been conducted indicate that the instrument satisfactorily detects delamination in bridge decks and that it provides a rapid and practical tool for routine use in bridge condition surveys.

•DELAMINATION is sometimes referred to as horizontal cracking. It occurs frequently at the elevation of the reinforcing steel and most often at the upper level of reinforcing steel. Delaminated areas may range in size from a few square inches to several square yards. After initial delamination occurs, additional rapid deterioration of the deck may be expected to follow, under the combined influences of weather and traffic. Figure 1 shows a delaminated bridge deck in the last stages of deterioration.

A literature search yielded relatively little information on delamination detection techniques. However, it was learned that, in actual practice, one principal technique is employed. This method relies on the subjective judgment of testing personnel regarding the sound produced by striking the bridge deck with a hammer or other solid object. This is basically the same technique employed by carpenters to locate a stud behind a rock wall. The delaminated or nonbonded area produces a distinctive "hollow" sound when it is struck.

The sound produced when the hammer strikes the concrete depends on the vibrational characteristics of the hammer itself as well as the concrete. If the hammer is highly resonant, its sound is confused with the sound from the slab. This makes the judgment by testing personnel much more difficult. Thus, claw hammers, steel rods, and the like do not make good striking objects. The best type of striking object has been found to be a steel mass tied at the end of a soft rope. This device, which is shown in Figure 2, was developed by an employee of the Texas Highway Department to facilitate bridge deck inspections. The steel mass, being essentially nonresonant, produces very little sound when hammered against a solid deck, but it causes a delaminated area to give forth a loud, distinctive hollow sound. Additionally, the mass may be dragged across

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the surface, and, unless the surface is unusually smooth, its irregularities produce a high-speed tapping effect. This dragging also produces the distinctive hollow sound on a delaminated area. A steel chain has also been used for the same purpose by dragging it across the surface.

Another device, which was developed several years ago by the research department of the State Highway Commission of Kansas to detect delamination in bridge decks, is shown in Figure 3. This device strikes the deck at regular intervals with small wooden blocks, allowing the operator to make a subjective judgment as to the type of sound produced. It was described in some detail in a report by Bertram D. Tallamy Associates (1). Although this device is capable of surveying large areas rather quickly, the wooden blocks are somewhat resonant, which in turn impairs the operator's judgment.

Another mechanism designed for the detection of delamination is shown in Figure 4. This device, invented by Nichols (2), was designed to detect the lack of bond in honeycomb metal panels. Basically, the instrument consists of a metal pegged wheel with an acoustical pickup on the handle. As the device is rolled across a metal panel, the lack of bond between the honeycomb and the metal panel is said to be indicated by the output signal from the acoustical pickup.

DEVELOPMENT OF BASIC COMPONENTS

After one considers the existing techniques for delamination detection, the device invented by Nichols appears to offer one substantial advantage—it does not require the subjective judgment of testing personnel. Thus, an instrument of this general type was tried. The attempt was not successful. The mechanism generated a large amount of signal when operated on a solid deck and, hence, gave a poor contrast between solid and delaminated areas. Nevertheless, after investigating and trying several other alternatives, the researchers concluded that the acoustic response to a tapping-type stimulus had substantial advantages over the other possible approaches.

The basic concept of an automatic device using the acoustic response to a tapping-type stimulus leads to requirements for the following three basic components: (a) a tapping device, (b) an acoustic receiver (e.g., a microphone), and (c) a signal conditioner to distinguish and produce the desired output. Many variations were tried. The most successful of the variations are described in the following subsections. They have been incorporated in the delamination detector unit discussed in the next section.

Tapping Device

The tapping device that is used is shown in Figure 5. It consists of a plunger that is oscillated vertically by a pair of solenoids. The plunger strikes a sharp blow at each end of its stroke. At one end, the blow is sufficiently violent to cause the tapping mechanism, with its rigid steel-rimmed wheels, to overcome gravity and break contact with the concrete surface. Thus, the tapping assembly chatters against the bridge deck surface and excites the characteristic vibration of any delaminated area with which it comes in contact. The magnitude of the tapping is kept to a nondestructive level. However, the wheel of the tapper leaves a visible white track consisting of fine-powdered material along the traverse. This minor crushing of surface grains is similar to that which would result from dragging the tip of a steel bar along the deck.

Acoustic Receiver

The development of a suitable acoustic receiver was unquestionably the most difficult task. Early in the research, it was found that receiving the signal through air with a conventional microphone presented a hopeless case. Ambient noises due to traffic and rolling were confused with the received signal, which made it impossible to distinguish reliably between solid and delaminated concrete.

The first successful receiver consisted of a piezoelectric crystal receiver mounted on the axle of a solid aluminum wheel. A rubber tread was glued to the aluminum wheel to minimize the noise-producing effect of deck texture. Although this receiver was able to distinguish between solid and delaminated concrete while rolling across the deck, the distinction was not as clear as desired.

Figure 1. Delaminated area of a bridge deck in the last stages of deterioration.

Figure 2. Tapping mass used for locating delaminated concrete in bridge decks.

Figure 3. Delamination detection device.

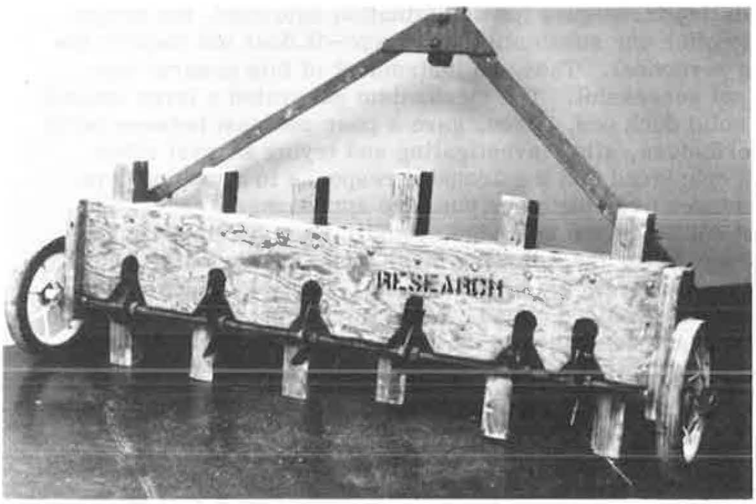


Figure 4. Hand-operated sonic testing device.

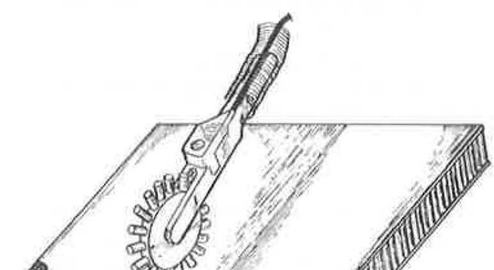
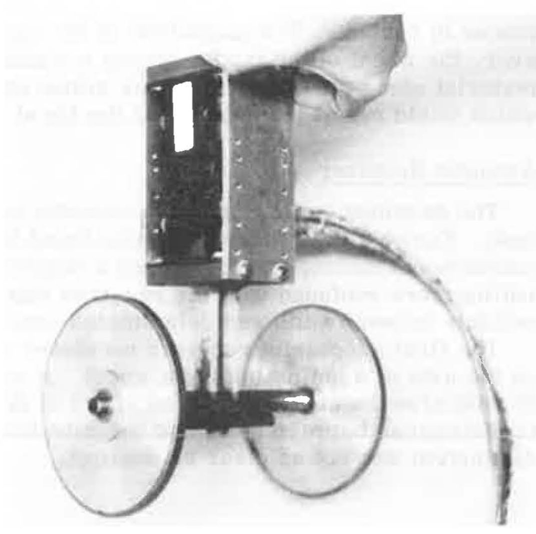


Figure 5. Tapping device for delamination detection.



The most satisfactory of the various designs tried is shown in Figure 6. It consists of an immersion-proof microphone (pressure transducer) mounted internally near the bottom of a soft rubber tire. Acoustic coupling is obtained by filling the tire with a mixture of water and ethylene-glycol. This receiver has almost no sensitivity to ambient noises or surface texture. It maintains excellent acoustic coupling while rolling, and it produces a relatively strong output signal.

Signal Conditioner

The signal conditioner that accepts the electrical signals produced by the rolling receiver and processes them for recording is shown in Figure 7. The distinction between delaminated and solid concrete is enhanced by filtering and by time-interval gating. Specifically, the distinction between delaminated and nondelaminated zones is enhanced by selecting only those frequency components of the received sound that fall between 300 and 1,200 Hz. Also, the distinction is further improved by accepting only that portion of the received signal that occurs during the first 3 msec after a tap has been made. Taps, which are produced 60 times per second, occur at intervals of 16.7 msec; thus, there is a relatively short interval during which the recording system is allowed to accept signals from the rolling receivers.

The final signal conditioning is accomplished by rectifying and integrating the signal over a period of approximately $\frac{1}{4}$ sec. This provides a rapidly responding voltage suitable for display on a pen recorder. Delaminated areas extending over 1 ft^2 or 2 ft^2 ordinarily produce responses exceeding 1 V. Smaller areas result in lesser responses that can be interpreted usefully down to about 0.05 V. Unwanted responses, resulting from rolling over rough surfaces and other disturbances, are substantially less than 0.05 V.

DELAMINATION DETECTOR UNIT

The basic components developed in this study and described in the previous section have been incorporated into the delamination detector unit shown in Figure 8. This unit, in the form of a mobile cart, is roughly the size and shape of a push-type power lawn mower. It is equipped with two rolling acoustic receivers spaced 12 in. apart and with two tapping wheels spaced 6 in. apart, centered between the receivers (Fig. 9). Because the unit detects delamination only when a receiver and a tapping wheel are simultaneously over a delaminated area, the unit surveys two 3-in. wide parallel paths that are 6 in. apart.

The unit consists of several separable components, each of suitable size and weight for one-man lifting and stowage in an automobile trunk. They are (a) a main frame that houses the tapping device and rolling receivers, (b) a two-channel pen recorder, (c) a control unit that contains two signal conditioning channels and an inverter for obtaining 120 Vac, and (d) a box that contains a 12-V storage battery. The disassembled unit is shown in Figure 10. Assembly or disassembly of the unit on site takes less than 1 min.

The two-pen recorder uses 4-in. wide chart paper divided for two-pen records. The drive for the chart paper is geared directly to one of the cart support wheels; thus, the lengthwise chart scale represents forward distance traversed. One minor chart division represents 0.5 ft of traverse. On solid concrete the pens remain at a stable small value (near zero on the transverse scale), and excursions larger than about two minor chart divisions from this low value are indicative of delamination. Although there are several control knobs on the recorder (gain, pen intensity, zero adjustment, and so forth), it is normally not necessary to adjust any of them for operation.

The operating controls consist of two on-off switches on the control unit. One is the main power switch, and the other is the tapper switch.

After charging, the storage battery will provide sufficient power to operate the detector continuously for more than 10 hours. For routine operations, it is charged each night for the next day's operation.

Figure 6. Rolling acoustic receiver.

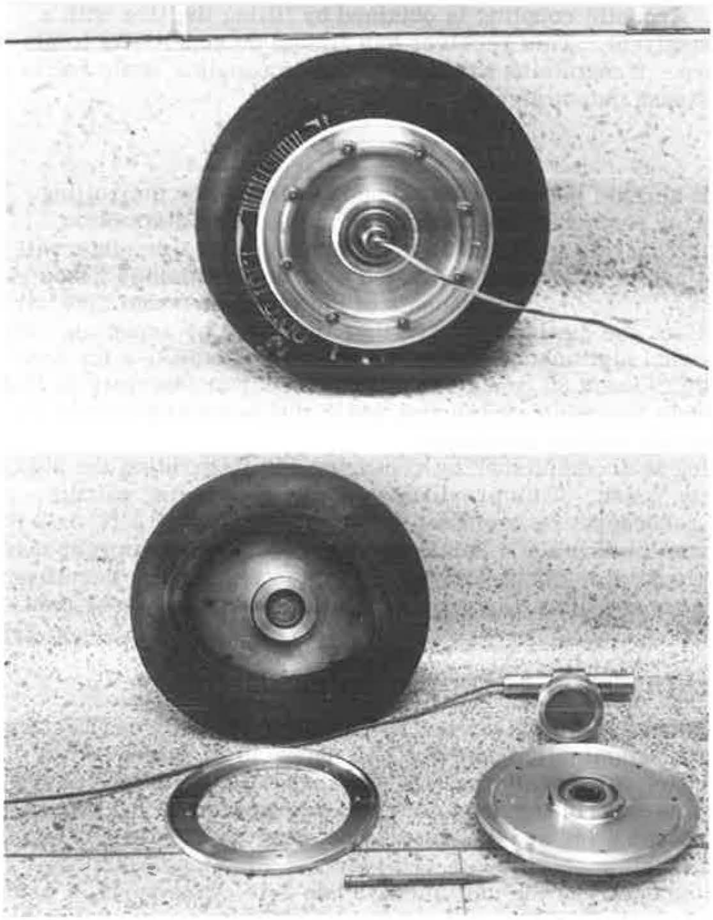


Figure 7. Block diagram of the signal conditioner.

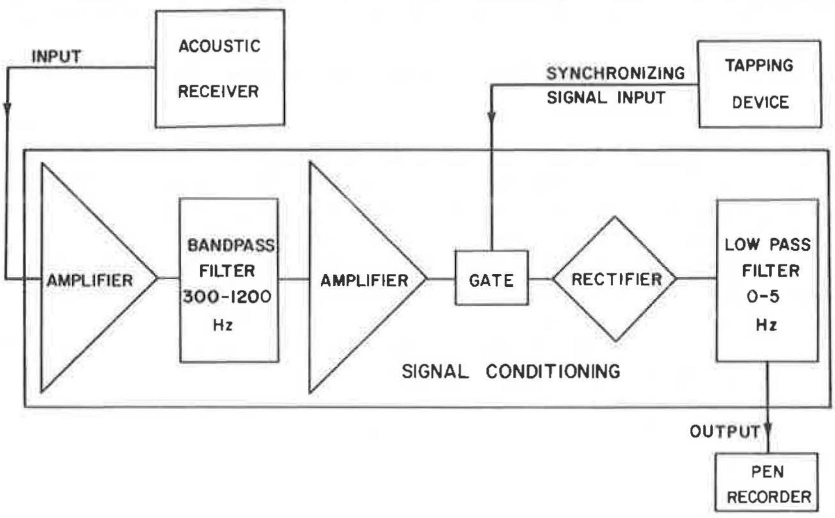


Figure 8. Delamination detector in operation.

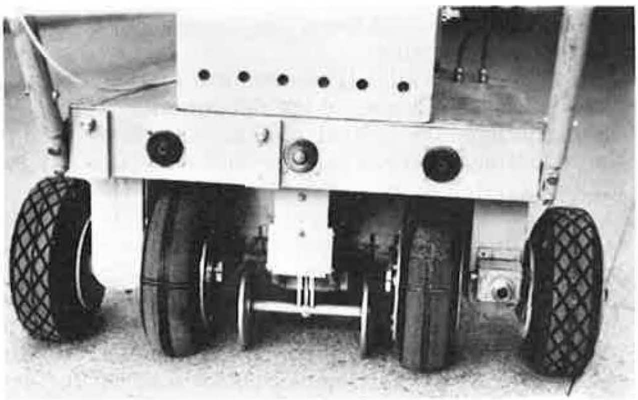


Figure 9. Rear view of delamination detector.

Figure 10. Delamination detector disassembled and stowed in an automobile trunk.

EVALUATION

In the early phase of the research, two rectangular test slabs (Fig. 11) were constructed to simulate bridge deck delamination. One of these slabs is about ½ in. thick, and the other is slightly less than 2 in. thick. Prior to placing these slabs, the foundation concrete was prepared to cause bonding to occur on half of each slab and delamination on the other half. This was accomplished by carefully cleaning the foundation concrete and allowing it to dry. Then, immediately prior to placing the fresh concrete, a neat cement paste was applied to the foundation for the bonded halves, and a fine layer of kaolinite dust was applied for the delaminated halves. The desired results of delamination and bonding were achieved, and these test slabs were used for the primary instrumentation development work.

After the delamination detector was completed, a field evaluation was initiated, consisting of surveying 30 bridge decks suspected of containing delaminations. Significant amounts of delamination were found in about half of these bridges, which were scattered over a wide area in Texas.

Results obtained from traverses about 80 ft long made on two typical bridges are shown in Figure 12. Figure 12a shows a record from a bridge in which no delaminations could be detected, and Figure 12b shows a record from another bridge that contains many delaminations (any signal larger than two minor chart divisions is an indication of delamination). Figure 12a also shows that the two channels are independent. Delaminations were encountered in the left survey path at points where they were absent in the right path. At these points, the right edge of the delaminations must lie between the two survey paths.

If several parallel traverses are made on a deck, the detector recordings can be used to prepare a map of the delaminated areas. Upon transferring the locations where delaminations are indicated on each traverse to a properly scaled plan view of the deck, the delaminated areas may be outlined. Closely spaced traverses permit drawing a highly detailed map.

The ability of the detector to distinguish delaminated from solid concrete has been verified by specially constructed test slabs (both delaminated and solid) as well as by coring 10 different bridges. On each bridge, one core was taken at a location where delamination was not indicated, and another at an apparently identical location where delamination was indicated. Agreement has been perfect. No evidence of delamination or horizontal cracking could be found on examination of the walls of the core holes at the 10 locations where delamination was not indicated. Delamination was obvious on examination of each of the other 10 holes. Six of the ten bridges had asphaltic surfacing layers that varied in thickness from ¼ to 3½ in. The delaminations found in these six bridges varied in depth from 1 to 4½ in. In one instance, the delamination was 3 in. below a 1½-in. asphaltic concrete overlay. In another it was 1 in. below a 3½-in. asphaltic concrete overlay. The delaminations found in the four unsurfaced bridges varied in depth from ½ to 2½ in. It is doubtful that conventional sounding techniques could have been used to locate the delaminated areas in most of the 10 bridges cored.

Several of the 30 bridge decks surveyed were badly spalled and, therefore, had a very rough surface texture. The instrument's operation was not impaired by the rough texture. Because the instrument performed well on these bridges and on those with overlays, it is concluded that the detector is insensitive to deck texture and to layers of asphaltic surfacing up to approximately 4 in. in thickness.

Another limited experiment was conducted during the field evaluation to determine the effect of rolling noise. Several paths on bridge decks, some on very rough textured decks, were traversed several times at various speeds. No significant differences could be detected among the records made at speeds varying from a slow walk to a fast run.

CONCLUSIONS

From the results of this study the following conclusions appear warranted:

1. The delamination detector developed in this phase of the research study provides an effective means for determining the extent of delamination in concrete bridge decks,

Figure 11. Test slabs used for development of delamination detector.

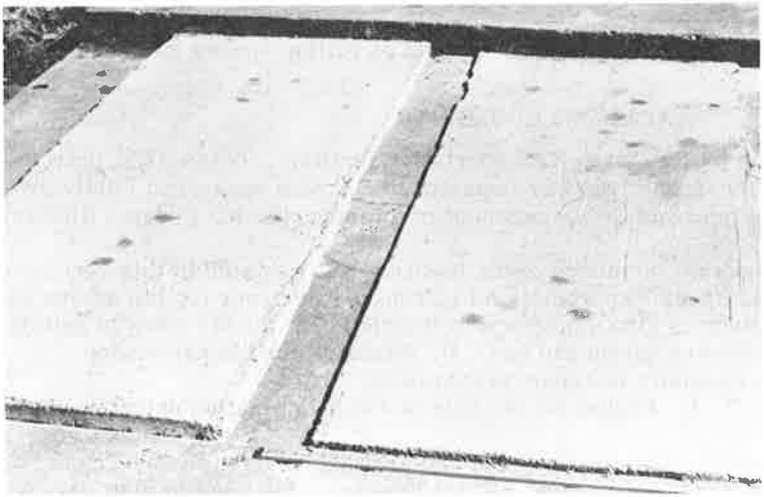
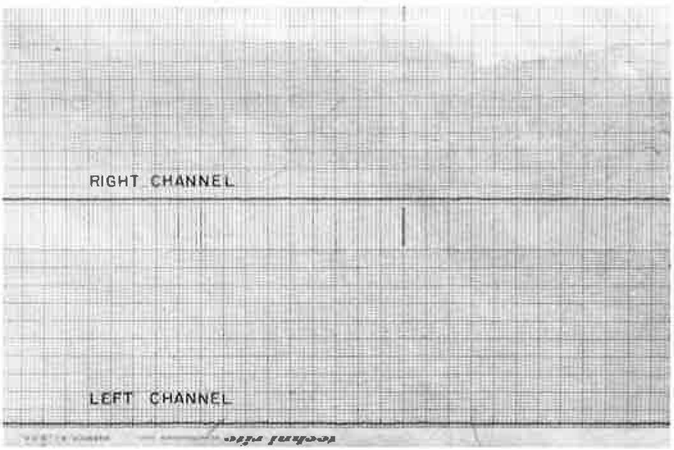
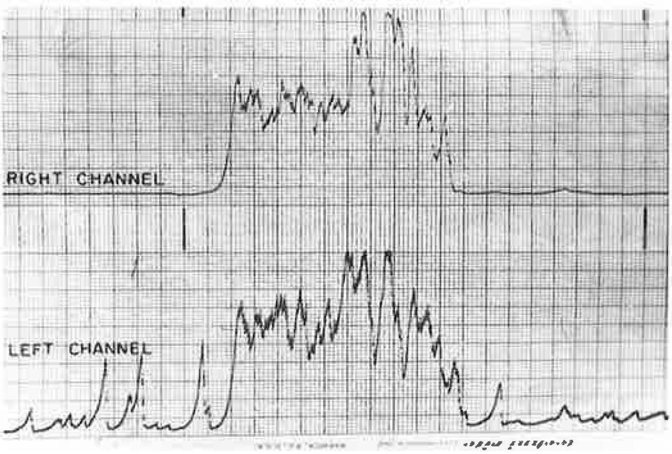


Figure 12. Typical records obtained with the delamination detector.



(a) SOLID DECK



(b) DECK CONTAINING DELAMINATIONS

2. The detector is easy to operate and practical for routine use,
3. The detector is insensitive to deck texture or to asphaltic surfacing layers up to at least 3½ in. thick, and
4. The operation of the instrument is not impaired at rolling speeds up to about 10 mph.

ACKNOWLEDGMENTS

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The authors wish to thank all members of the Institute who assisted in this research. They would like to express special appreciation to Frank H. Scrivner for his advice and assistance. Special gratitude is also expressed to Rudell Poehl for his work in setting up and carrying out the field evaluation and to C. H. Michalak for his assistance throughout the study and especially in report preparation.

Thanks are also due to R. L. Peyton for the loan of the delamination detection equipment shown in Figure 3.

The authors wish to acknowledge the guidance and assistance given by the Texas Highway Department contact representative, M. U. Ferrari. They would also like to thank the many Texas Highway Department employees who assisted during the field evaluation.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. The report does not constitute a standard, specification, or regulation.

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DETECTION OF BRIDGE DECK DETERIORATION

William M. Moore, Texas Transportation Institute, Texas A&M University

Delamination is probably the most serious form of deterioration that is commonly found in bridge decks. It ultimately results in large-scale spalling that necessitates costly repairs. This type of failure is believed to be caused chiefly from salt-induced corrosion of the reinforcing steel. An instrument designed to detect delamination and the validation tests are described. The instrument has been used by Texas Highway Department maintenance personnel and has been found to be an effective and practical tool, especially on resurfaced decks. Other bridge deck evaluation techniques that were investigated are delamination detection, corrosion potential, acoustic velocity, Windsor probe, Schmidt rebound hammer, and direct tensile strength. It appears that all of these techniques have considerable merit. It is believed that any of them can be used to search out weak spots or deterioration in bridge decks.

•TWO defects have been considered to be of paramount importance in the evaluation of concrete bridge decks: delamination (a separation of the original slab into two or more approximately horizontal layers) and poor quality concrete.

The present report describes several measurement techniques for evaluating concrete and discusses the interpretation of their results.

DELAMINATION DETECTION

Probably the most serious form of deterioration commonly found in reinforced concrete bridge decks is delamination, which ultimately results in large-scale spalling and costly repairs. This type of deterioration occurs most frequently where salt is used for winter de-icing and is believed to result chiefly from salt-induced corrosion of the reinforcing steel (1-4).

The normal maintenance procedure for repairing delaminated areas in bridges is to remove the material above the plane of delamination and replace it with a relatively fast-setting material (Fig. 1). Epoxy or fast-setting cement mixes are normally used for these repairs to minimize delay to traffic.

Delamination has been detected by maintenance personnel based on their subjective judgment of the sound produced by striking the deck with a hammer or some other object. Wooden blocks, drag chains, steel rods, and specially designed hammers have been used for such detection (Fig. 2). These techniques are very dependent on the operator's ability to judge the distinctive hollow sound produced at the location of a delamination.

An instrument for detecting delamination was developed in this study to replace the techniques that involve subjective judgment (Figs. 3 and 4). The basic design of the instrument and the results of preliminary field evaluations were described in an earlier report (5). The ability of the detector to distinguish delaminated concrete from solid concrete has been verified by using specially constructed test slabs (both delaminated and solid) and by coring 10 different bridges. On each bridge, one core was taken at a location where delamination was not indicated and another at an apparently identical location where delamination was indicated (Fig. 5). Agreement has been perfect. No evidence of delamination or horizontal cracking could be found on examination of the

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Figure 1. Delamination repair.

Figure 2. Locating shallow delaminations in nonresurfaced bridge decks.

Figure 3. Instrument developed to detect delamination on bridge decks.

Figure 4. Typical record produced by delamination detector.

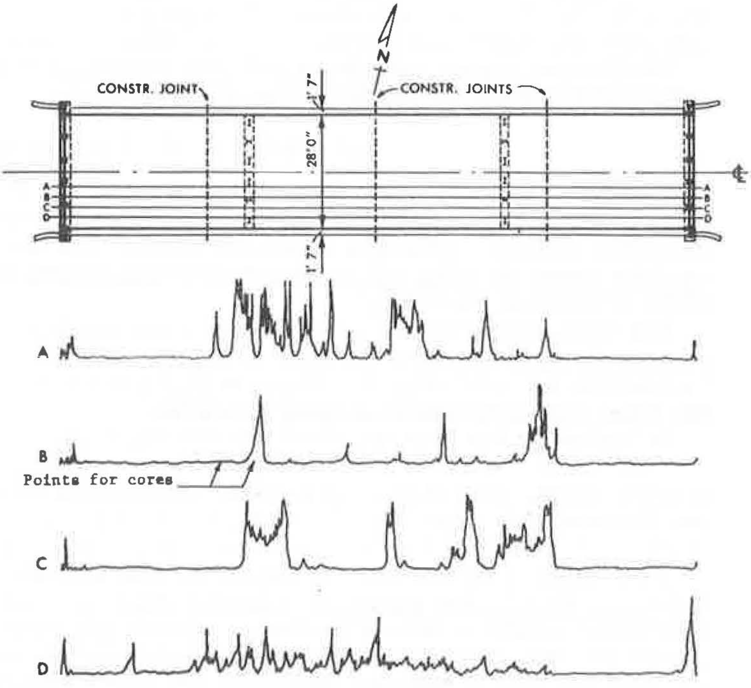

Figure 5. Verification of detector's accuracy.

walls of the core holes at the 10 locations where delamination was not indicated, whereas delamination was visible in each of the other 10 core holes. Six of the ten bridges had asphaltic surfacing layers that varied in thickness from 1/4 to 3½ in. The delaminations found in these six bridges varied in depth from 1 to 4½ in. In one instance the delamination was 3 in. below a 1½-in. asphaltic concrete overlay. In another it was 1 in. below a 3½-in. asphaltic concrete overlay. These findings were felt to be particularly significant because the characteristic hollow sound produced by conventional techniques is greatly diminished by asphaltic surfacing layers. The delaminations found in the four unsurfaced bridges varied in depth from ½ to 2½ in. It is doubtful that conventional sounding techniques could have been used to locate the delaminated areas in most of the 10 bridges cored.

Since the earlier report (5), the instrument has been used by maintenance personnel in several Texas Highway Department districts. Through this use, several design problems in the instrument were found, but they were eliminated by subsequent modifications. The major modifications consisted of the following:

1. Modification of the electrical power pack to permit more than 8 hours of continuous use,
2. Modification of the acoustic receivers to eliminate transducer deterioration, and
3. Development of a calibrator to standardize and equalize the sensitivity of the acoustic receivers.

Probably the most extensive use of the instrument was by maintenance personnel in the El Paso district, who surveyed about 130 bridges. Most of these bridges contained asphaltic concrete or epoxy overlays. El Paso maintenance personnel report that conventional sounding techniques were not effective on most of these decks because of the overlays.

CORROSION POTENTIAL

As mentioned previously, bridge deck delamination is believed to result chiefly from salt-induced corrosion of the reinforcing steel. If this corrosion can be detected before it causes delamination, it may be possible to arrest the corrosion prior to its damaging effects on a deck. Currently, cathodic protection is being investigated as a possible means of arresting corrosion.

The California Division of Highways has reported that electrical potential measurements, indicative of active corrosion of reinforcing steel (2, 6, 7), can be made on the surface of a concrete bridge deck. These measurements are obtained by making an electrical connection to the reinforcing steel and an electrolytic connection between a saturated copper-copper-sulfate half-cell and the upper surface of the deck (Fig. 6). The latter connection is made with a sponge saturated with copper-sulfate solution. The electrical potentials are measured using a high input impedance voltmeter.

Typical results of an electrical potential survey using the California technique are shown in Figure 7. These measurements were made by a Federal Highway Administration demonstration team under the Region 15 Research and Development Demonstration Projects program. In this survey, a core was taken in the area of the highest potential indicated, and rust was found on the reinforcing steel at that location.

Under this Federal Highway Administration program, the demonstration team has made measurements on bridges in 48 states and the District of Columbia. Results to date indicate that the system gives reasonably accurate indications of the degree of corrosion in bridges. Measurements have been confirmed with actual on-site inspections. Because a complete survey required measurements to be made at numerous points on a deck, considerations are being given by the Federal Highway Administration research team to automate the device.

ACOUSTIC VELOCITY

From the literature, acoustic pulse velocity measurements appeared to offer a promising method for determining the quality of concrete in bridge decks (8-15). Thus, as a first step, the relation of acoustic wave velocity to other properties of concrete was explored. Laboratory measurements were made on a wide variety of concrete specimens, and the relations among measurements of acoustic compressional wave velocity, unit weight, elastic modulus, and strength were examined. The results of this investigation, as well as a description of an instrument designed for field measurements, have been reported previously (16).

Two measuring techniques for determining acoustic velocity were investigated in the laboratory. The simplest technique, referred to as "timing through," is based on the time required for an acoustic wave train to travel the distance between a pulsed transducer and a receiving transducer that are coupled to opposite sides of a specimen. The other technique, which is applicable to making measurements on the accessible upper surface of bridge decks, is referred to as the "timing along" technique. This method is based on determining the travel time of the wave train between two points on the same surface as the pulsed transducer. Using either technique, attainment of accuracy requires consideration of the effects of time delay in the transducers and their couplings. Comparison measurements indicated a satisfactory agreement between the two techniques. Upon comparison of the measurements, substantial agreement was found between the dynamic elastic modulus as determined by ASTM C215 and an estimate based on velocity and unit weight. Similar agreement was found for the chord modulus as determined by ASTM C469. The estimating equations found are as follows:

$$\hat{E}_r = \frac{V_c^2 W}{5,670} \tag{1}$$

$$\hat{E}_c = \frac{V_c^2 W}{6,630} \tag{2}$$

where

E_r = estimated dynamic modulus in pounds per square inch,
E_c = estimated chord modulus in pounds per square inch,
V_c = compressional wave velocity in feet per second, and
W = unit weight in pounds per cubic foot.

The coefficients of variation for Eqs. 1 and 2 were found to be 9.5 and 12.0 percent respectively.

No single consistent relation to velocity was found among the compressive strength measurements made on all the cylindrical specimens; however, separate trends were found for velocity to increase with strength within each group of cast cylinders containing a specific type of coarse aggregate. These comparisons of laboratory measurements indicate that velocity measurements used with discretion are generally indicative of the concrete quality.

As mentioned previously, a portable type of field velocity measuring instrument was developed in this study for use on the accessible upper surfaces of bridge decks (Fig. 8). It employs a probe that places an array of four acoustic transducers into contact with the concrete. Velocity is measured, using the "timing along" technique, by observing the time of travel of the acoustic waves between two identical receiving transducers. Waves are produced and propagated successively in opposite directions, and the two time intervals are measured and averaged to cancel coupling delay errors. Other design features include a precise digital timer used in combination with a novel timing method in the oscilloscope display and low power consumption that permits the instrument to be operated from a vehicle battery.

Since the previous report, the field instrument has been used to make measurements on 25 different bridge slabs and 12 specially constructed laboratory slabs. Normally, the average of three velocity measurements was determined for each slab. It was found that, on many of the bridges that have been in service for several years, it is difficult to measure the acoustic velocity because of the attenuation introduced by numerous small surface cracks. Often these surface cracks were visible only after the surface had been moistened. This problem was not encountered on the new slabs.

The compressive strengths of air-dried cores taken from the slabs were found to be slightly correlated with the average acoustic velocities of the slabs. In a linear

Figure 6. Measuring electrical potentials between a copper-copper-sulfate half-cell and the steel reinforcement.

Figure 7. Typical results of an electrical potential survey.

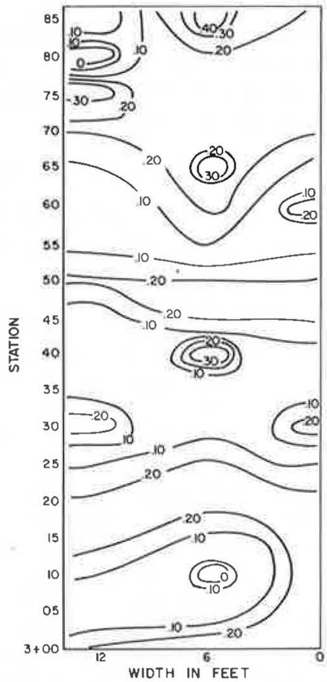

Figure 8. Control unit of the field-type velocity measuring instrument.

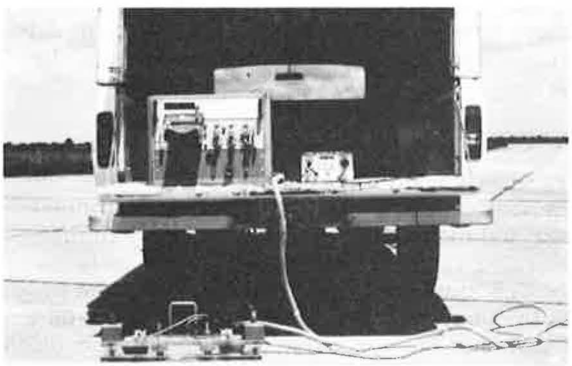

Figure 9. Use of the Windsor probe test system to determine concrete quality.

regression analysis, to estimate slab core strength from its average acoustic velocity, the coefficient of variation was found to be 19.9 percent.

The instrument is believed to be practical for use in research studies when it is desirable to nondestructively estimate the modulus of elasticity (Eqs. 1 and 2). It is not believed to be practical for routine bridge deck measurements because on too many in-service bridges the measurement process is difficult and time-consuming even for a highly trained operator. A single measurement requires about 3 min on a new slab but may require up to 30 min on an older slab that contains surface cracks.

WINDSOR PROBE

The Windsor probe test system has been used in field investigations to estimate the in situ strength of concrete in pavements, bridges, walls, and pipes (17, 18, 19). The device is easy to use and seldom requires surface preparation prior to testing. Basically, the tests consist of shooting a standard probe into the concrete with a standard cartridge. The depth of penetration is determined by measuring the height of the exposed probe. A special gun or driver unit is provided for shooting the probes (Fig. 9). Gauge plates are also provided to measure the average height of the exposed probes in a standard group of three shots. The higher the probes are (i.e., the more resistant they are to penetration) the stronger the concrete is.

Windsor Probe Test Systems, Inc., provided for temporary use at no charge in this study a complete measurement system and a set of minerals for performing scratch tests to determine Mohs' hardness. Probes and cartridges were furnished for a nominal charge. Measurements were made with this instrument on 38 different portland cement concrete slabs that contained many different kinds of aggregates.

From the average of three probe penetration values and the Mohs' hardness of the coarse aggregate, estimates of the compressive strengths were made using tables furnished by the manufacturer. These estimates were generally higher than the measured compressive strengths of air-dried cores taken from the slabs. The measured core strengths were found to be slightly correlated with the probe values. In a linear regression to estimate core strengths directly from probe values without any correction for aggregate hardness, the coefficient of variation was found to be 20.3 percent.

This test system is believed to be practical for bridge deck survey measurements to locate weak spots. The test is slightly destructive. In addition to the small hole made by the probe penetration, a spall about 6 in. in diameter and up to ¾ in. in depth at the center is often produced by the test. A standard group of three probes can be shot and measured in about 5 to 7 min.

SCHMIDT REBOUND HAMMER

The Schmidt rebound hammer is a very widely used instrument for estimating the quality of in situ concrete. Basically, the test consists of striking a rod, in contact with the concrete, with a standard hammer and measuring the height of the hammer rebound. The higher the rebound is, the stiffer (and better quality) the concrete is.

Several authors have suggested that the Schmidt rebound hammer can be used to estimate the compressive strength of in situ concrete (20, 21, 22). They agree that the type of coarse aggregate, surface condition of the concrete, its moisture condition, etc. have a pronounced effect on the relation between rebound reading and strength. Also, there is common agreement that the instrument can be used to determine the uniformity of concrete and thus is an effective tool for locating weak spots.

A Soiltest Model CT200 rebound hammer was used for this study (Fig. 10). Measurements have been made with it on 38 different portland cement concrete slabs that contained many different kinds of aggregate. From the average of 15 rebound readings at each site, estimates of the compressive strength were made using curves furnished by the manufacturer. These estimates were generally much higher than the measured compressive strengths of air-dried cores taken from the slabs. The measured core strengths were found to be slightly correlated with the rebound values. In a linear regression to estimate core strengths from rebound values, the coefficient of variation was found to be 21.2 percent.

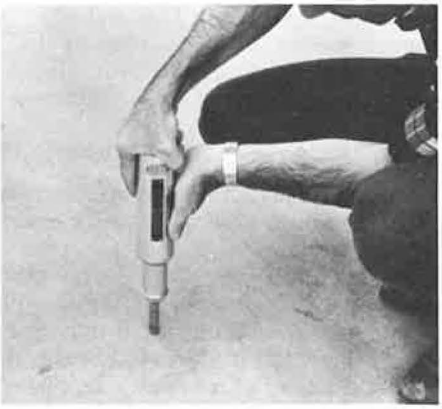

Figure 10. Soiltest Model CT200 rebound hammer.

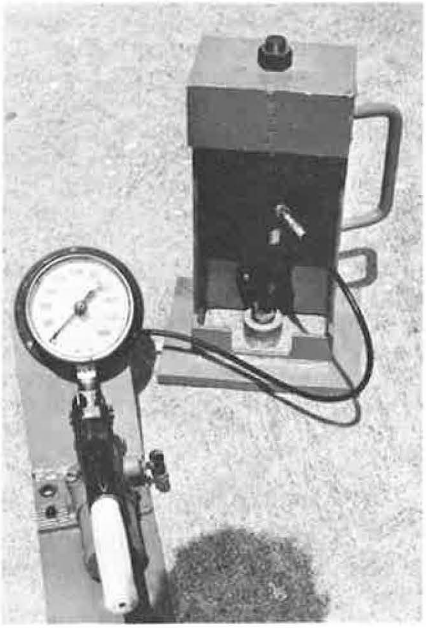

Figure 11. Device used to evaluate the tensile strength of concrete slabs.

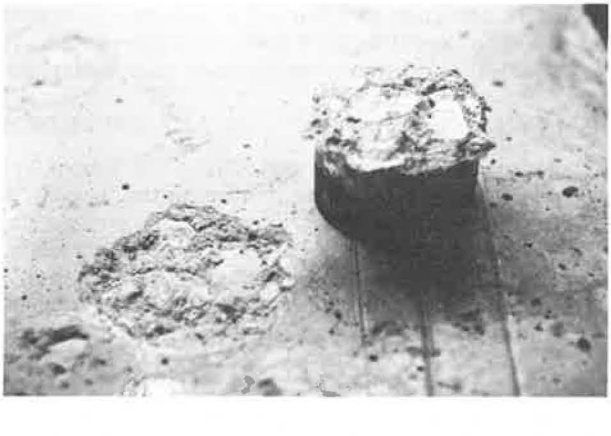

Figure 12. Two-in. diameter aluminum cylinders epoxied to a smooth, clean concrete surface.

The rebound hammer is fast and easy to use and is believed to be practical for bridge deck measurements to locate weak spots. Prior to measurements, the surface of the deck should be ground smooth with a hand grinder. The smoothing operation and 15 tests can be made in about 3 to 5 min.

DIRECT TENSILE TEST

An important characteristic of concrete, which is seldom considered in field evaluations, is its tensile strength. This characteristic is highly significant in quality bridge deck construction.

In 1956, the Shell Chemical Corporation introduced a Highway Tensile Tester. This tester was developed for evaluating the quality of resinous cement overlays and to preevaluate the surfaces upon which they were to be applied. A device similar to the Shell tester was fabricated in this study (Fig. 11). The chief modification was that a hydraulic cylinder, instead of a screw, was used to apply tension to eliminate the possibility of horizontal forces on the screw handle being converted into unwanted tension.

Another tensile tester, quite similar to the Shell device, is described in Test Method California 420-A. The procedure used to measure tensile strength in this study is the same as that described in Part II of the California test method, Evaluation of Soundness of Portland Cement Concrete Surfaces.

Using this device, direct tensile strengths were measured on 30 different portland cement concrete slabs (Fig. 12). Normally, the average of three tensile tests was determined for each slab. These tensile strength measurements were found to be slightly better correlated with the compressive strengths of air-dried core samples taken from the same slabs than any of the other measurement techniques investigated. In a linear regression analysis to estimate core strengths from the average tensile strengths, the coefficient of variation was found to be 17.7 percent.

The test is somewhat time-consuming because it requires a period of about 1½ hours for the epoxy to harden prior to testing. On a warm day about 40 tests could be made in an 8-hour day. Values obtained using this test would probably be more indicative of the general quality of the concrete slabs than any of the other tests investigated, and the test is believed to be practical for bridge deck measurements.

CONCLUSIONS

The study substantiates the following conclusions:

1. The technique utilizing the delamination detector developed in this study has been found to be practical and effective for determining the extent of delamination in bridge decks;
2. It appears that all of the six measurement techniques investigated have merit and can be used to locate weak spots or deterioration in bridge decks, although each technique is designed to measure a different characteristic property; and
3. The direct tensile test, velocity meter, Windsor probe, and the rebound hammer can each be used to estimate core compressive strength within about 20 percent.

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