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CONCRETE PAVEMENT DESIGN AND REHABILITATION, REPORT I STATE OF THE ART OF PCCP EVALUATION TECHNIQUES

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16. ABSTRACT

The state of the art of Portland cement concrete pavement evaluation is reviewed with emphasis on the methods applicable to the urban freeway environment. Methods are recommended for texture evaluation, void detection and condition surveys. Data analysis methods useful for the development of pavement performance models are presented. The overall framework for life cycle cost (LCC) analysis is described with recommendations for the development of a LCC method for the Arizona Department of Transportation.

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INTRODUCTION

Arizona DOT has a world renowned pavement management system. This system has provided tremendous benefits to the department in many areas. However, the system is not perfect and it cannot be expected to fulfill all of the needs of the department with respect to pavement condition evaluation needs. One area of particular concern is the urban freeway network. For several reasons, the urban freeways cannot readily be treated within the framework of the department's current pavement management system. The primary reasons for treating urban freeways in a unique manner are the use of portland cement concrete pavements and the high traffic volumes in urban areas.

Stated bluntly, ADOT's pavement management system primarily addresses the bulk of the rural network consisting of predominately asphalt pavements with low traffic volumes relative to the urban conditions. The pavement condition survey procedure, performance models and life cycle analysis methods are not appropriate for the evaluation of urban PCC freeways.

Due to these considerations, research is required to fulfill the needs of urban freeway evaluation and modeling. The high concentration of traffic on the urban freeway facilities make this an important task even though the mileage of the urban freeway system is relatively limited. Complete development of an urban freeway evaluation, modeling and life cycle cost analysis procedures is a lengthy process. Texas has an ongoing project which was initiated in the early 1970's. The purpose of this project was to get the process started by providing background information on the current state-of-the-art for rigid pavement evaluation and life cycle cost analysis.

The final product of the project was to be an executive summary type report for administrative personnel. Yet as the project unfolded, too much valuable information was uncovered to be adequately treated in such a short report. Therefore, a unique approach was taken for the structure of this report. The summary, recommendations and conclusions of the project have been pulled forward for the convenience of the administrative reviewers. The facts and literature citations which support these conclusions are presented in the subsequent chapters. The state-of-the-art in pavement condition evaluation equipment is presented in Chapter 2. Specific procedures for rigid pavement condition evaluation and data analysis for the development of both a composite pavement condition index and rigid pavement performance models are described in Chapter 3. Life cycle costs analysis methodologies are presented in Chapter 4. The format selected for this report necessitates some redundancies in the presentation of information between Chapter 1 and the subsequent, more detailed chapters. In addition, material in Chapter 1 is presented without references. The appropriate references as well as support for the conclusions and recommendations are presented in Chapters 2, 3, and 4.

SUMMARY AND RECOMMENDATIONS

Pavement condition evaluation, performance modeling and life cycle cost analysis have been important topics for many years and there is a wealth of information. Yet constantly changing technology is providing new tools for pavement evaluation and modeling at a rapid pace. Unfortunately, pavement condition evaluation is an extremely complex task requiring specialized equipment, yet the market for pavement evaluation equipment is very limited. Manufacturers of pavement condition evaluation equipment must amortize equipment development costs over very few units. The primary example of pavement evaluation equipment which appears to be over-priced relative to comparable technology in other industries is the K. J. Law Profilometer. This device has been on the market since 1968 yet only seven units have been purchased. While the Law Profilometer is an extreme example, even the most widely used pavement evaluation equipment such as the Mays meter and the Falling Weight Deflectometer are generally custom manufactured after being ordered.

The net result of the complexity of the required measurements and the relatively low demand is that pavement evaluation equipment is generally expensive, and the user may wind up having a larger than anticipated role in the final development and field testing of the equipment. As a result, many pavement condition measurements which can conceptually be automated are still being performed by technicians using relatively simple methods.

Pavement Evaluation Equipment

There are a wide variety of devices used for pavement evaluation equipment. This project was limited to the evaluation of:

1. Surface texture
2. Pavement layer thickness
3. Pavement distress and joint condition
4. Void detection

Devices for roughness, pavement profile, friction, deflection, etc., were not reviewed during this project.

Surface Texture. There is increasing interest in the use of pavement surface texture as an indicator of the ability of the pavement to provide adequate friction at the tire-pavement interface. There are many methods for measuring texture and ASTM standards are available for several of these. The drawback to these measures is the need to close the facility for the measurement.

The Federal Highway Administration recently sponsored the development of an optical device for pavement texture measurements. The device can reportedly measure both micro and macro-texture from a vehicle moving at 40 mph. Pennsylvania State University had the contract for the design and assembly of a prototype device. The device is currently being evaluated by state highway agencies. The results of the evaluation are not available at this time. Thus, use of this equipment is not recommended at this time.

The Swedish RST equipment uses high speed lasers to measure in great detail the profile of the pavement. The services of this equipment are marketed by Infrastructure Management Systems, formerly Novac Dempsey. In my opinion, the manufacturer and his representative are not releasing enough information about the device for independent evaluation. In addition, the equipment cannot be purchased. Hence, routine pavement condition evaluation requires a commitment to continually use the services of IMS. For these reasons, the use of the RST is rejected.

At this time the only standardized method which may be recommended is one of the volumetric methods such as the silly putty, sand patch or the grease smear. The volumetric methods have several shortcomings which should be recognized. First, they are only applied to a very limited area of the pavement. The contact area of the measurement material is measured in square inches. A test is generally assumed to be representative of several thousand square yards of pavement surface. One must question if this is an adequate sample for obtaining a meaningful measurement. Second, the volumetric tests require closure of the pavement to traffic which may be difficult to justify in an urban environment.

The alternative to measuring surface texture is to use the Department's Mu-meter to obtain friction measurements. The availability of the equipment and standard test methods in the department, as well as the ability to test at high speeds are all factors which weigh heavily in favor of using the Mu-meter to obtain friction measures rather than surface texture measurements.

Pavement Thickness. The traditional method for determination of pavement layer thickness is by obtaining a core of the pavement. This is slow and expensive. Unfortunately, there is no proven technology for rapidly determining pavement layer thicknesses at this time. There are two devices which will determine pavement layer thickness, the RODAR unit and the Spectral Analysis of Surface Waves, SASW. The RODAR device is proprietary. The services are available through Gulf Technologies. The services have been evaluated by several highway agencies with mixed results. The operating speed is five to ten mph so lane closure is required for urban freeway operation. The SASW technique is currently being developed at the University of Texas for the Texas State Department of Highways and Public Transportation and the U.S. Air Force. The advantage of the system is the closed form solution for determining both modulus and layer thickness. Unfortunately, the method requires sensors in contact with the pavement surface. Thus, it is a static test. Currently, each test requires about one half hour although the researchers are attempting to speed up the test.

Thus, there is not a viable option at this time for rapidly determining pavement thicknesses. Coring is still the only viable method of reliably determining pavement thicknesses.

Surface Distress and Joint Condition. Of all the areas of pavement condition measurements, surface distress is generating the greatest attention by equipment manufacturers. Unfortunately, this area has not produced proven commercially available equipment at this time. The Swedish RST is not acceptable for reasons given earlier. There are several devices for capturing pavement condition images for manual analysis in the laboratory. This appears to be the best method for obtaining the data without interfering with traffic. Other systems for onboard and real time processing of the data have not been successful at this time.

The only proven method for pavement distress surveys at this time is with human observers. For the time being the observers will have to be in the field, although the economics of hiring a photologging van should be further evaluated.

Joints are the critical element in the performance of rigid pavements. Distress at the joints will be determined during the condition survey. The structural adequacy of the joint is generally evaluated as the ability of the joint to transfer deflection from one side of the joint to the other. The ratio of deflection from one side of the joint to the other is termed the joint efficiency. Both the Dynaflect and Falling Weight Deflectometer may be used for measuring joint efficiency.

Void Detection. Voids are a major problem with rigid pavements. Two technologies are available for detecting voids, ground penetrating radar and deflection measurements. Ground penetrating radar services are available from Gulf Technologies and Donahue Associates. Demonstration projects in several states have not been particularly successful. Deflection measurements is the method of choice for evaluating void presence. The key to using deflection devices for detecting voids is the location of the measurements. Schemes have been developed in Illinois, Indiana and Texas for void detection with deflection equipment.

Rigid Pavement Distress Surveys

There are a wide variety of pavement condition survey manuals available. Many of these manuals are based on the distress identification photos first published by Smith, Danter and Herrin for the Federal Highway Administration. In general, when starting out in pavement evaluation, the pavement distress survey should be as complete as possible. After experience is gained with the evaluation system, the intensity of the data collection may be reduced. The FHWA recently published a pavement condition rating guide for all highways based on the state-of-the-art in pavement condition evaluation.

The survey requires observers to walk on the shoulder of the pavement and observe the distress. The observer must record data on two forms, pannel condition and joint condition. The sample size, i.e. the portion of the pavement observed, recommendations in the FHWA report were developed for rural conditions. The sample size requirements for urban freeways in Arizona should be determined in a follow-up research project.

The recommended procedure for determining the minimum required sample size for reliably defining the condition of the pavement is:

1. The distress survey method should be applied to obtain a 100 percent sample of the pavement condition for several miles of highway. The exact mileage requirement would be determined during the research, but I suspect 20 to 30 miles of data are required.
2. The data are divided into one-mile sections and a pavement condition index is computed for each section. This value is accepted as the true pavement distress value for the section.
3. Each mile is divided into sample units of 25 feet (a somewhat different length may be used depending on joint spacing, etc.)

4. The data for the sample units can now be combined to obtain various lengths of pavement condition observations. For example, two sample units can be combined to define a 50 foot long section which corresponds to approximately a one percent sample (50 ft per 5,280 ft). A pavement condition rating score is computed for each of the composite lengths and compared to the pavement condition score for the entire mile. Since this analysis may be completely automated, it is possible to analyze a wide variety of combinations.
5. The results of the process will be a definition of the minimum amount of data required to obtain reliable measures of the distress of the entire pavement.

The pavement condition evaluation is an extremely important activity for the development of pavement performance models and subsequently life cycle cost models. Therefore, until the procedures recommended in this report are field tested in Arizona, they cannot be expected to be the perfect answer. For example, the photos used for distress identification have been widely accepted by the highway community. However, there could be distresses in Arizona not adequately covered in the manual. Also, the original negatives for the FHWA pavement distress identification photographs have been misplaced; thus, there has been a loss of clarity in the photos. Therefore, it may be necessary to obtain some new photographs of the distress types of particular concern in Arizona.

The procedures described in this document are for the measurement and evaluation of pavement distress. Pavement condition determination requires the evaluation of all aspects of pavement performance including roughness, structural capacity and friction. These parameters may be combined to develop a composite pavement condition index. The composite index is useful for defining the condition of the process, but it is not sufficient for the decision process. Decisions concerning pavement strategies should be tempered by factors such as the traffic volume, highway classification, reliability requirements, etc. While these factors must eventually be analyzed, further discussion of them is outside the scope of this report.

Life Cycle Cost Analysis

The ultimate goal of a project on urban freeway evaluation is the development of analysis tools for determining the least cost of providing the facilities. Least cost must be determined over the life of the facility rather than just using the first cost. Life cycle cost, LCC, analysis requires determining both the cost of providing the facility and the user cost. The costs of providing the facility are administered by the state highway agency and are thus called agency costs.

Agency costs are generally separated into the initial construction cost and the maintenance and rehabilitation costs. In general, the initial cost is much easier to determine than the maintenance costs. Initial costs may be estimated from detailed bid documents of contractors. Maintenance costs are more difficult to estimate because they are dependent on the performance of the pavement and the cost for performing each maintenance activity. Data bases are now being established which will allow the development of reasonable estimates of these parameters.

User costs have always been difficult to quantify. However, there has been a considerable amount of research developed in the past ten years for estimating user costs in life cycle cost analysis of pavements. There are computer models available for estimating user costs directly in the life cycle cost analysis.

Once the costs have been estimated, the economic analysis to place all of the costs on an equivalent basis is relatively straightforward. The net present value method is successfully being applied by other agencies.

There are several computer programs available for performing life cycle cost analysis for projects. The models used in Alaska, Texas, and Pennsylvania should be obtained and examined for suitability in Arizona. Criteria for use in LCC model evaluation are:

1. modular construction to permit easy updating and modification
2. applicability of the pavement performance models

3. sensitivity of the models to environmental, traffic and pavement design variables
4. input data requirements

While there is a considerable amount of research and practical applications available for the urban freeway pavement evaluation, the problem has not been solved. Local conditions must be examined and incorporated into the pavement condition evaluation, the performance models and the life cycle cost analysis. The process will require years of effort, but as with the success of the ADOT pavement management system, the payoffs are great, particularly in light of the freeway construction program the department is facing.

CHAPTER 2 STATE OF THE ART

INTRODUCTION

The purpose of this chapter is to document the state-of-the-art in pavement evaluation equipment that will potentially be useful for determining the condition of the urban freeways in Arizona. The contents of this chapter were derived from the engineering literature on the topic, research reports and interviews with equipment manufacturers. There are several pavement condition variables that can provide an estimate of the need to maintain or repair a pavement. The pavement condition variables of interest during this project are:

1. Surface texture
2. In-place pavement thickness
3. Surface distress
4. Voids under the pavement surface
5. Joint condition

The other measures of pavement condition, such as structural capacity, roughness, friction number, etc. were not considered in this project.

SURFACE TEXTURE EVALUATION

Historically, the safety aspects of the tire-pavement interaction were measured with a locked wheel friction (skid) tester. In Arizona, the Mu meter is used in place of the locked wheel skid tester. In general, the problem with friction measurement is the sensitivity to both the friction of the tire-pavement interaction and the technique used to obtain the measurement. Hence the need for the calibration of the friction testers at the national centers. While the tire-pavement friction is truly the important parameter when it comes to stopping a vehicle, friction is not a pavement condition parameter. This fact may contribute to the poor correlation between pavement friction and accident rates. Research in Pennsylvania has demonstrated both the seasonal and short term variations of the pavement friction measurements (Ref 1, 2).

The main pavement characteristic which influences the tire pavement interaction is the three dimensional texture of the pavement surface. Highly textured pavements have better friction characteristics in wet weather and are therefore safer than pavements with little texture. Since pavement surface texture is a physical characteristic of the surface that can be expected to correlate with overall safety and wet weather accidents, there has been considerable attention focused on trying to measure pavement texture. Tables 1, 2, and 3 were developed by Wambold et al. in a recent study for the Federal Highway Administration (Ref 3).

Pavement texture is defined by the American Society of Testing and Materials as two levels of deviations in the pavement surface:

> Pavement Microtexture - The deviations of a pavement surface from a true planar surface with characteristic dimensions of wavelength and amplitude of less than 0.5 mm.
>
> Pavement Macrotexture - The deviations of a pavement surface from a true planar surface with the characteristic dimensions of wavelength and amplitude from 0.5 mm up to those that no longer affect tire-pavement interaction.

Traditionally pavement texture measurements required performing a static measurement on the pavement surface. Recent research is demonstrating the feasibility of measuring pavement texture from a moving vehicle (Ref 3).

Static Texture Measurements

There are several relatively simple measurements of pavement texture if the pavement can be closed to traffic while the measurements are being performed. Table 1 is a summary of the direct texture measurement techniques. The descriptive names of the measurements provide some insight into the principle used for the measurement.

For the silicone casting method, a casting of the pavement surface is made that can be taken back to the laboratory for inspection and measurement.

Table 1. Direct micro-profile (texture) measurement methods (Ref. 3).

1. Silicone Casting

2. Macrotexture Profile Tracing

   a. Profilograph or Profilometer
   b. Modified Versions of the Profilograph
   c. University of New South Wales Unit
   d. Linear Traverse Device
   e. Texturemeter/Rainhart Text-Ur-Meter

3. Microtexture Profile Tracing

   a. Profilograph or Profilometer
   b. Gould Surfanalyzer
   c. Surfindicator

4. Stereophoto-Interpretation Mapping

5. Non-Laser Light Stylus

   a. Vertically Projected Narrow Light Beam
   b. Zero-Slope Detector

6. Laser Light Stylus

   a. TRRL Contactless Sensor
   b. Modified TRRL Contactless Sensor
   c. Autech Laser Dimension Gage Models 2DSLT6 and .5DSLT3

7. Line of Light (Goodman) Method

   a. Maryland Vidicon System
   b. KLD Optical Rail Wear Inspection System
   c. Ensco Photographic Line of Light System

8. Shadow Interpretation

   a. Ontario Highway Department System
   b. Photoestimation

Table 2. Direct measurement methods producing averaged texture values (Ref. 3).

1. Sand-Patch Methods
   a. Simple Sand Patch
   b. Modified Sand Patch
   c. Vibrating Sand Patch
2. Sand Track
3. Grease Patch
4. Putty Impression
   a. Simple Putty Impression
   b. Modified Putty Impression
5. Schonfeld Method
6. Laser Light Stylus
   a. TRRL Contactless Sensor
   b. Autech Laser Dimension Gage Model 2DSLT6

Table 3. Indirect texture measurement methods (Ref. 3).

1. Outflow Meter

   a. Static Drainage Method
   b. Pressurized Drainage Method

2. Tire Noise

   a. Microphone Mounted on a Moving Vehicle (near-field measurement)

   b. Stationary Microphone Located by Roadside (far-field measurement)

3. Ribbed versus Blank Tire Skid Test

4. Light Depolarization

5. British Pendulum Tester

6. Penn State University Drag Tester

7. White Light Speckle

There are several mechanical devices for the direct measurement of macrotexture. These generally consist of a mechanical probe, or stylus, that is dragged across the pavement surface. The stylus is wired to produce an electrical current that is proportional to the deviations in the pavement profile. The signal is input to either an analog or paper trace recorder. The output can then be analyzed to obtain a direct measure of the pavement macrotexture.

The Rainhart device consists of a series of closely spaced pins standing vertically in a frame. The frame is placed on the pavement and the pins are allowed to drop vertically onto the pavement surface. The deviations in the height of the top of the pins is recorded as the measure of the pavement texture.

Stereophoto interpretation requires capturing a detailed stereophoto of the pavement surface. The photos are then interpreted using standard stereophoto data reduction methods. At least conceptually the stereophotos could be taken with a high speed camera in a vehicle traveling at normal highway speeds.

Dynamic Measurements of Pavement Texture

The mechanical stylus of the profilograph may be replaced by a noncontact probe to obtain the measurements of the pavement profile. Penn State University has recently developed an optical probe for capturing an image of the pavement profile on a research project of the Federal Highway Administration. The prototype device is currently being evaluated by several states.

The Penn State optical texture measuring device uses a strobe to project a well defined band of light onto the pavement surface from a vertical position. A high speed video camera captures the image from an oblique angle as shown on Figures 1 and 2. The components of the texture measuring device are:

Strobe system - EG&G FX-201 bulb type neon tube with PS-302 power supply and filter to improve contrast in the near infrared range and a duration of ten microseconds.

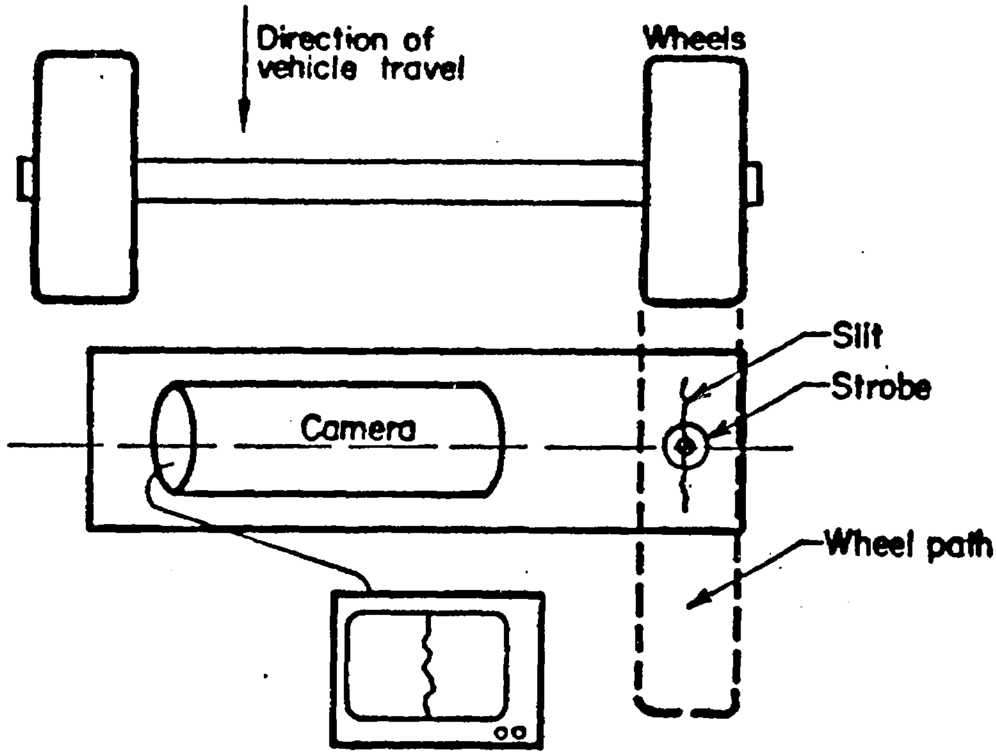


Figure 1. Orientation of texture measuring instrument in the Penn State test vehicle.

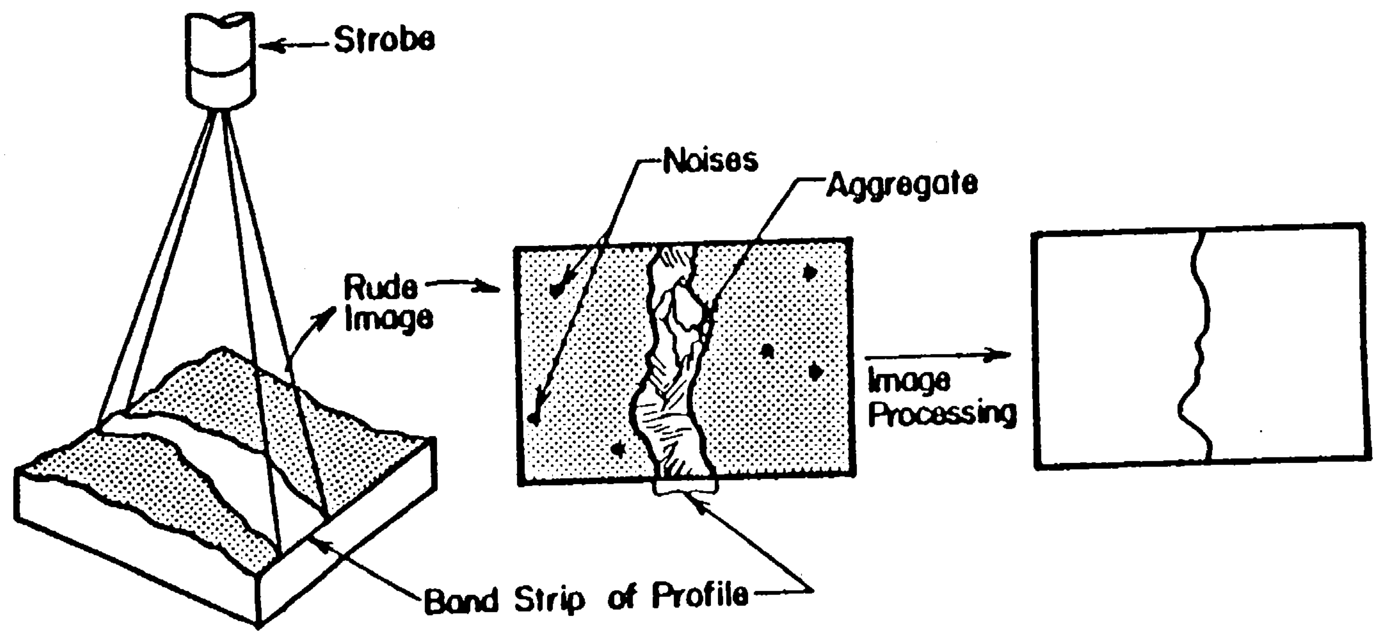


Figure 2. Overview of the projection on the road, TV scan, and the processed profile for the Penn State texture measurement device.

the need to provide traffic control and the time required to obtain the data.

There are two devices that at least have potential for determining the thicknesses of the pavement layers although the devices were designed for determining much more than the pavement thickness. Ground penetrating radar has been proposed as a tool for evaluating the subsurface condition of pavements. The primary use of these devices is for the location of voids under the pavements as is subsequently discussed.

Dr. Stokoe at the University of Texas has been working on a device for the measurement of both the thicknesses and modulus of pavement layers. The technique is based on measuring the velocity of wave-propagation through a pavement structure. Dr. Stokoe claims this method is the most direct method for measuring the elastic moduli of the layers in a pavement system since each layer is uniquely identified by the wave-propagation velocity of the material in the layer (Ref 4). The fact that the system also determines the thicknesses of the pavement layers is an added bonus that is all but ignored by the authors.

The theory behind the measurement method is relatively straightforward, but mathematically complicated. An impulse load is transmitted to the pavement using a hammer. Velocity transducers measure the time from the impact of the impulse load to the movement of the wave past the transducer. The data are collected for multiple distances of the transducer from the load. A computer specifically constructed to perform Fast Fourier Transforms is used to reduce the data to a series of modulus versus depth measurements. The locations where there is a large change in the modulus identifies the boundary of the layers and thereby defines the depth of the layers' interfaces.

The theory supporting this pavement evaluation method is well established and documented. Dr. Stokoe is currently working on equipment to automate the process. Due to the need to conduct measurements of the wave-velocities at multiple locations, the process is time consuming. The measurements at each location can take 45 minutes. While improvements to the equipment may significantly reduce the time required, the process will always require a contact sensor and will therefore require more time for performing the measurements than is desirable for urban freeway evaluation.

SURFACE DISTRESS AND JOINT CONDITION

There are two issues that must be addressed for determination of surface distress. The first is to define the types of distress that are of concern to the agency. The second is to define a method for measuring the distress.

Types of Distress

There are many pavement condition evaluation manuals available in the literature. Zaniewski et al. (Ref 5) recently reviewed pavement condition rating manuals from 25 states. None of the states use a procedure that is common with another state. In 1979 the Federal Highway Administration published the Highway Pavement Distress Identification Manual for Highway Condition and Quality of Highway Construction Survey (Ref 6). This is an excellent reference for the definition of the various pavement distress types for both flexible and rigid pavements. There are three types of rigid pavements:

1. jointed plain concrete
2. jointed reinforced concrete
3. continuously reinforced concrete

The types of distress identified for the plain and reinforced jointed pavements are the same although different example photographs of the distress were demonstrated in the manual. A total of 21 types of distress are identified for jointed pavements. Since there are very limited CRC pavements in the current urban freeway network, distresses for these pavements will not be discussed further. The Highway Distress Identification Manual was evaluated extensively by Zaniewski et al. for a Federal Highway Administration project for the development of a Pavement Condition Rating Guide (Ref 5). In this rating manual, the concrete pavement distresses are divided into four categories:

1. joint condition
2. cracking
3. surface defects
4. patches

Within each of the categories, several types of distresses are defined for ease of recognition and rating by the observer.

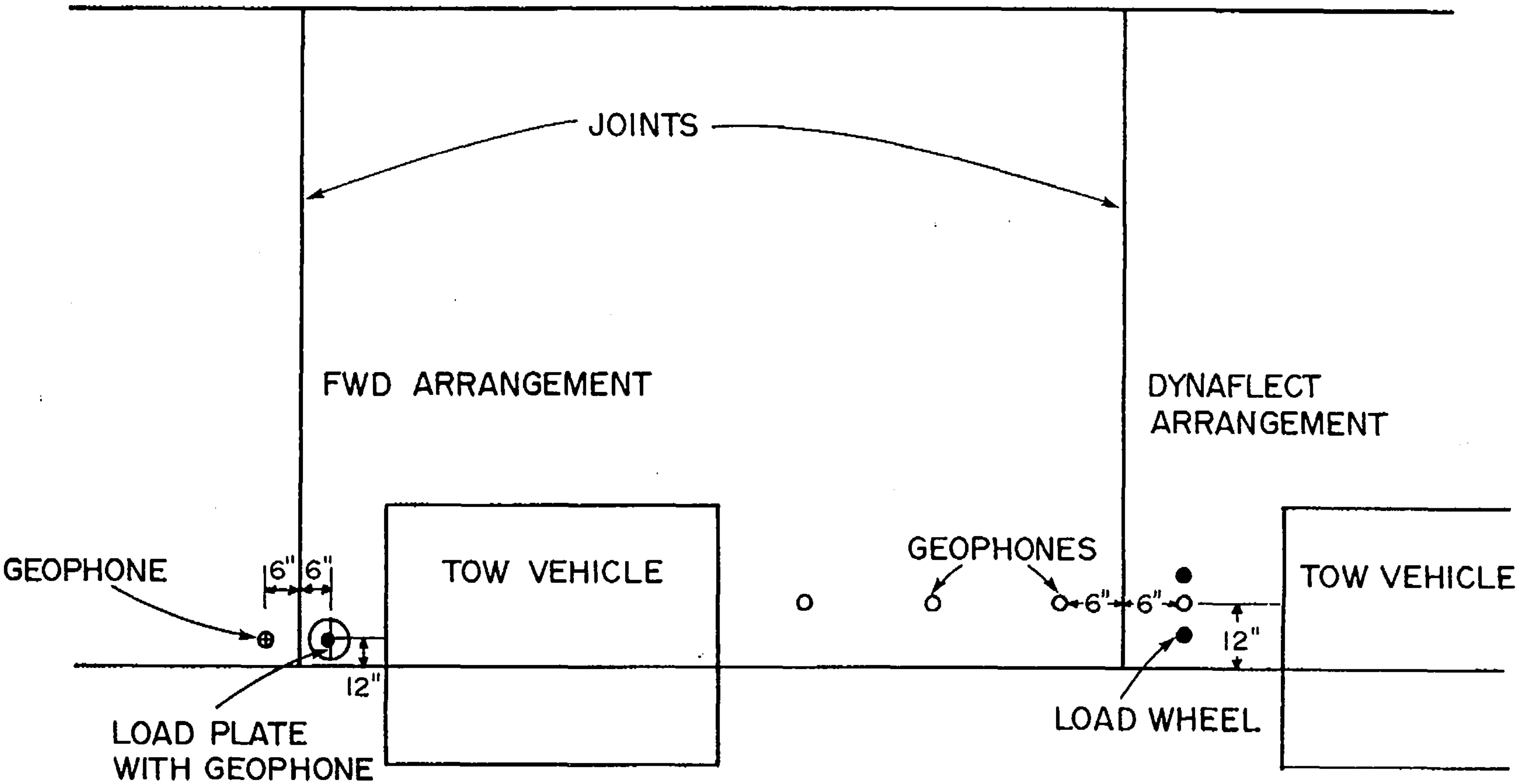
Joint Condition - The joint is the weakest part of rigid pavements. Frequently the condition of the entire pavement can be determined from the condition of the joints. The distresses that occur at the joints are:

1. seal damage
2. corner breaks
3. spalling
4. faulting
5. "D" or durability cracking
6. load transfer problems
7. blowups

For the most part, the names of the distresses is descriptive of the appearance or cause of the distress. Detail definitions of the distresses are contained in both references 5 and 6.

The structural adequacy of the joint is generally evaluated as the ability to transfer loads from one side of the joint to the other. Generally the load transfer ability of the joint is measured using deflection equipment setup as shown in Figure 3. The ratio of the deflection on the unloaded side of the pavement to the deflection on the loaded side of the pavement is defined as the load transfer factor. A load transfer factor of 1.0 indicates perfect load transfer. Using the test set up shown in Figure 3, one would not expect the deflections on each side of the joint to be equal due to the distance of the sensors to the load points.

Cracking - There is a tendency to define multiple types of cracking based upon the perceived cause for the distress. In reality, little information is gained by these attempts to classify the type of



$$\text{LOAD TRANSFER} = \frac{\Delta \text{ UNLOADED SLAB}}{\Delta \text{ LOADED SLAB}}$$

Figure 3. Layout of deflection testors for measuring load transfer at the Joints.

cracking. For rigid pavement condition evaluation, cracking may be classified as either longitudinal or transverse.

Surface Defects - There are several types of defects that can occur on the pavement surface. Frequently, these are related to some form of local materials problem and are not indicators of widespread problems with the functional characteristics of the pavement. The types of surface distress are:

1. scaling, map cracking, and crazing
2. pop outs
3. bumps
4. potholes
5. polishing

Patches - The extent of patching in a rigid pavement is important for evaluating the overall condition of the pavement. An excessive number of patches indicates the surface of the pavement is wearing out and may need to be replaced or renewed. Evaluation of the condition of the pavement with respect to patching required identification of the type of patch, either asphalt or concrete, and the condition of the patch and the area around the patch.

Methods for Measuring Distress

Evaluation of pavement condition is an extremely complex task. There have been several attempts to automate the process, but the current state-of-the-art in pavement distress measurement requires human observers to recognize and quantify the extent and severity of the distress. Since this is a state-of-the-art report, research into the automated collection of pavement condition data are reviewed. There are two devices that can capture images of the pavement from a vehicle traveling at near highway speeds, but these images must be manually reduced to pavement condition data.

There have been six studies for the application of machine vision to the measurement of pavement condition. ADOT sponsored a study by

Novak, Dempsey and Associates to evaluate the feasibility of an automated pavement cracking inventory (Ref 7). Although there have been significant enhancements to video technology since the Novak study, the cost of equipment has not been significantly reduced and the key finding of the study was that automated data collection methods were not cost competitive with the manual pavement condition survey method that is used by ADOT for the Pavement Management System data base. The survey for the pavement management system is limited to observation of 1,000 square feet of pavement condition per mile. The adequacy of this intensity of data collection should be evaluated for rigid pavements in urban environments. There was a HPR study by McCullough et al. in Texas that indicates the condition of concrete pavements cannot be determined form a small sample of the pavement surface. Thus, there is a need to determine the sample rate that is required for accurately capturing the condition of the pavement. If the sampling rate is as high as McCullough indicates, then there is a need to evaluate the automatic methods for evaluating the condition of the pavement.

There have been several research studies for the development of equipment for automatically capturing pavement condition data. The Federal Highway Administration sponsored a pilot study by KLD Associates Inc. for the design of an automated crack survey device (Ref 8). A prototype device was developed under this contract; however, there will not be any further developments toward a practical working system.

Dr. Ralph Haas of the University of Waterloo in Canada has been investigating the application of machine vision for pavement condition evaluation (Ref 9, 10). Video cameras were used to capture several images of pavement condition which were digitized in the laboratory. The researchers have been developing algorithms for identifying the types and extent of the pavements distress. While these developments are promising and demonstrate the conceptual feasibility of performing automatic distress identification, they lack field implementation.

The Federal Highway Administration has an ongoing project with Eikonix for the development of equipment for Automatic Recordation and Analysis of Pavement Condition (Ref 11). A feasibility study has been completed and the contractor is now in the process of assembling the hardware for the demonstration of the technical feasibility of capturing and processing images of pavement distress. The equipment will be for demonstration purposes only and the contractor will not be required to deliver the equipment at the end of the project. The project will produce a set of plans that may be used by interested parties for assembling their own equipment.

At the 1986 Transportation Research Board meeting a presentation was made to the committee for pavement monitoring and evaluation on a pavement distress survey performed for the Idaho Transportation Department using video equipment. The preliminary findings of the project were very positive concerning the feasibility of using video equipment to capture pavement condition images (Ref 12):

> Acquiring pavement condition data at highway speeds (even in heavy traffic) is relatively simple.
>
> Visual data acquired is of a quality that allows surface images (including cracking) to be well defined and stable.
>
> Time and costs involved in gathering data appear to be quite reasonable.
>
> All of the prototype equipment used in the project is available for over-the-counter purchase. A special trailer and some specialized, self-contained lighting were required, but both of those items are also readily available. The mobile equipment used to gather the data proved to be very sturdy, dependable and tolerant of a wide variety of environmental conditions (varying temperatures, dust, and so on).
>
> It is apparent that the technology exists that will allow for cost-effective, objective and consistent collection of highway pavement condition data.
>
> Data collected during the project will soon serve as an input source for software programs being developed by VideoComp that will employ computer analysis techniques in analyzing the type, extent and severity of cracking.

While this report was very positive and indicated a strong conceptual feasibility of automatic data collection, there was no hard evidence presented by the authors to support their claims. If the problem is as easy to solve as Idaho authors are reporting, why are the federally sponsored research projects having such great difficulty?

The Connecticut Department of Highways also had a demonstration of a video camera data collection system at the Transportation Research Board annual meeting. This equipment was for photologging of highway features but due to the data storage method of using video disks, it appeared this system had potential for the collection of pavement condition data. The system uses a camera focused through the windshield of the vehicle. The photographic images are transferred to a video disk. During the transfer process, the quality of the photographs can be significantly enhanced such that the recorded images are significantly clearer than the images are originally recorded by the camera. The concepts of capturing the image and using computer enhancement and storage on computer disk demonstrate some interesting data processing methods, but the implementation by the Connecticut DOH is not suitable for pavement condition surveys due to the angle of the camera.

There are two automated cameras that capture continuous high resolution images of the pavement surface, the Pasco from Japan and the GERPHO of France. The photographic capabilities of these devices are very similar. A high quality 35 mm camera is mounted on a boom in front of the vehicle as shown in Figure 4. The shutter of the camera is controlled by a distance measuring instrument to obtain the continuous coverage. Due to the need to carefully control the lighting to obtain the highest quality image, the device can only be operated at night. The maximum operating speed is approximately 40 mph. Perhaps the greatest single drawback to the device, in addition to the cost for both the initial purchase and the data collection, is the need to manually reduce the data to a pavement condition score. The advantage is the ability to perform the condition rating in the safety of the office and the ability to review ratings without the need of returning to the field. The FHWA is currently evaluating these devices as the leading candidates for pavement distress surveys for SHRP.

The National Science Foundation sponsored a project for "Pavement Management Using Video Imaging Techniques" with AMI Consultants (Ref 13, 14). This project examined the feasibility of using video imaging and onboard processing of the data for collecting pavement distress data. Based on the feasibility study performed by AMI, The Earth Technology

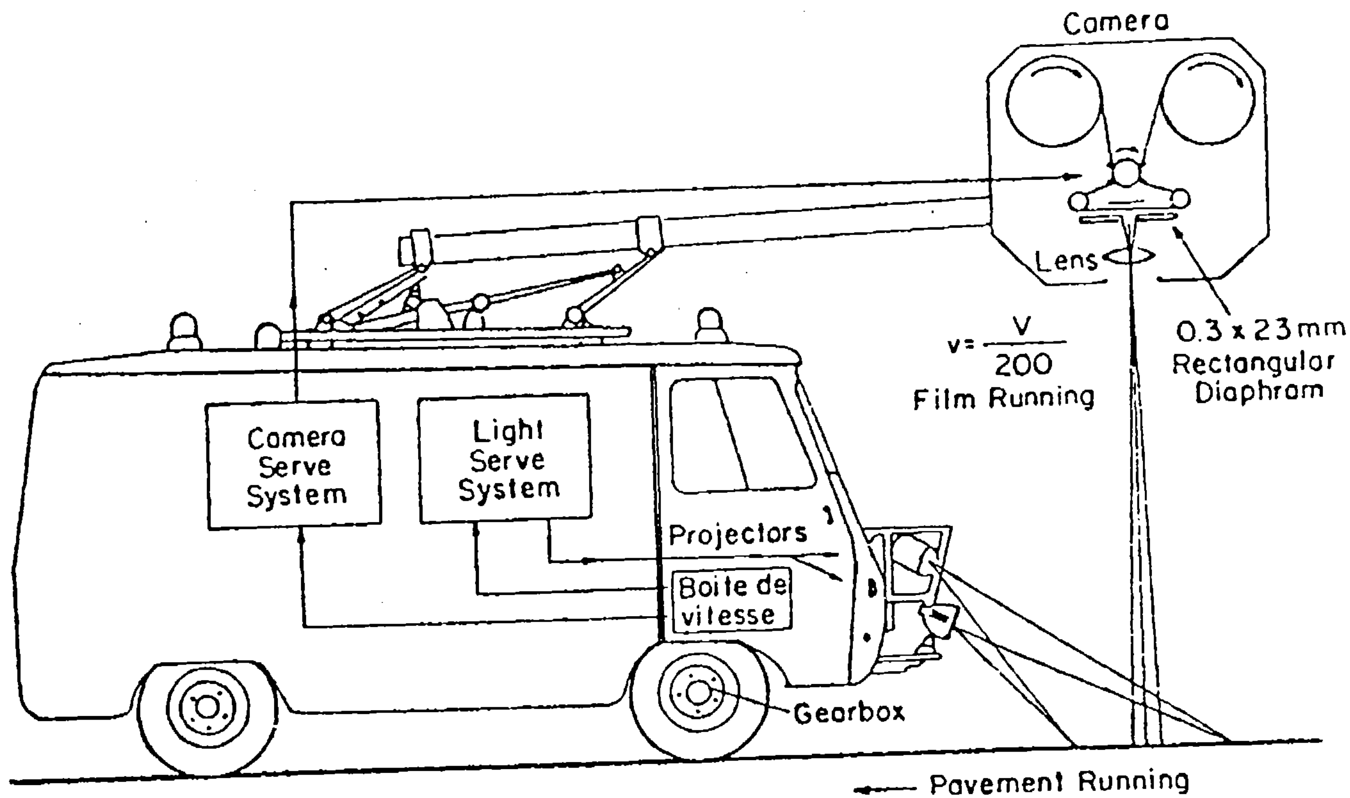


Figure 4. Elements of the GERPHO System.

Corp. is investing venture capital into the development of a complete system. Earth Technology anticipates complete development of the prototype device by the end of 1986. The data collection method uses a slit sensor to gather an image of the pavement system. The data processing system then starts manipulation of the data. The authors claim to have an algorithm that can recognize various types of pavement distress. The current challenge is the development of a system for processing the data in real time. By the author's calculations, this will require the processing of 100 million instructions per second.

When the development is complete, the Earth Technology machine should be able to collect and process at real time pavement condition data. The machine was originally being developed to automate the pavement rating process used in Nevada. However, the researchers claim they will be able to readily adapt the system to any of the distress ranking methods currently in use by state highway agencies.

The last system for pavement distress data collection described is the Swedish Road Surface Tester, RST. The services for this device are currently being marketed by Infrastructure Management Services, formerly Novak, Dempsey, and Associates. The machine is not for sale in this country so a decision to use this device carries with it a commitment to continue using the services of Infrastructure Management. The data collection serviced cost approximately $30 per mile.

The reported capabilities of the machine are very impressive:

1. Time stable roughness measurements
2. Transverse crack counting and classification by the width and depth of the cracks
3. Rut depth measurements
4. Surface texture

The primary instrument on the RST are 11 lasers mounted across the front of the vehicle. These lasers are used as noncontact distance measuring probes. An accelerometer is used in the vehicle to establish a datum and for roughness measurements. The machine has been demonstrated extensively throughout the United States. It does appear to produce data when operated over a pavement, but there are very limited independent data to verify the accuracy or validity of the measurements. The RST did participate in a profilometer comparison at the University of Michigan but the data were not submitted to the researchers after the road testing, so there is no basis for comparison to the other devices in the study.

VOID DETECTION

The loss of support under the pavement due to voids leads directly to increased stresses from loads and consequently a reduced pavement life. Proper detection of voids is very important yet under the current technology, is time consuming and there is a high degree of uncertainty. Means for detecting voids include visual inspection, deflection based methods, and ground penetrating radar. Visual inspection requires the observer to identify the clues that a void exists:

1. Staining or deposits of material on the pavement or shoulder surfaces.
2. Ejection of water and fine material as a truck passes over a saturated pavement.
3. Faulting is a general indicator of the presence of voids at the joints.
4. Corner cracking indicates a loss of support as a contributing factor to the distress.

While the visual inspection gives a clue as to the presence of voids, more direct evidence is desired.

Use of Deflection Surveys

Due to the impact of the voids on the support of the pavement, deflection measurements have been proposed and applied as indicators of the presence of voids. Several types of deflection measuring devices have been used for detecting a sudden change in the subgrade support as an indicator of the presence of a void. Benkleman Beams, Road Raters, Dynaflects, and Falling Weight Deflectometers have been used for void detection. In Texas, a method based on Dynaflect measurements and supported by theoretical investigations on the effect of void size, has been used to establish a systematic method for void detection (Ref 13, 14, and 15). The method has been extended for evaluating the effectiveness of undersealing operations. The methodology relies on:

1. Measure deflections one foot from the pavement outside edge.
2. Measure deflections at the centerline of the outside pavement lane.
3. Correct the measurements for any temperature differential.
4. Plot the deflection profiles for the two lines of measurements.
5. Mark on the plots the areas suspected of having voids.

This method is crude and has several limitations. For example, the detection of a void depends upon obtaining the deflection measurement at the location of the void. Since the location is unknown, there is uncertainty as to the thoroughness of the method. In addition, there are several factors that can influence the deflection measurements in addition to the voids. For example, the Proposed AASHTO Interim Guides (Ref 17) recommends collection of deflection data during morning hours only to avoid joint lockup and slab curl.

Use of Radar Technology

Conceptually, ground penetrating radar is a very promising method of detection of void detection. This method has been used widely in geotechnical investigations to locate underground utilities, pipelines and tunnels. When applied to pavement evaluation, the method can conceptually be used to determine pavement thickness, locate voids, identify delaminations, and locate steel reinforcement. Unfortunately, there appears to be a large difference between what the equipment can conceptually do and what the equipment is actually capable of performing.

Under the current state-of-the-art, the equipment has a very complex output that must be evaluated by a trained technician. This effectively limits the use of the equipment to the developer of the machine, hence only the services of the radar testing are available. As with the RST, it is difficult to assess the capability of the device when there is no independent evaluation. At least two states have contracted for radar pavement evaluation services on a trial basis. In Iowa, the radar was able to detect the presence of reinforcing steel, but did a less than satisfactory job at determining the pavement thickness and void detection. In Alabama, the trials were unsatisfactory due to the lack of repeatability and the influence of environmental conditions. For example, void presence, size, and location were sensitive to the direction of travel of the survey vehicle.

SUMMARY AND RECOMMENDATIONS

With the rapid development of electronics, it is natural to expect a broad availability of equipment for measuring pavement condition. Unfortunately, that is not the case. Due to the limited market for pavement evaluation equipment, and the reluctance of highway agencies to take on the development of equipment or the testing of prototype equipment, private industry has not invested extensively in the development of pavement evaluation equipment.

In order to implement a program of urban freeway evaluation in the near future, ADOT will have to depend on tried and proven methods. Pavement thickness should be determined by coring the pavement. The resulting thickness should be compared to the as built plans on file to determine if the plans are satisfactory for generally acceptable use in the urban freeway pavement data base. For the time being, the only feasible method for performing a pavement distress survey is with human observers. If ADOT wishes to avoid using observers on the shoulder of the freeways for safety reasons, consideration should be given to hiring the services of a photologing van that is specifically designed to photograph the pavement. Normal photologing equipment, such as the Techwest, are not suitable for pavement condition evaluation. The pavement distress survey method should be tailored to the conditions on urban freeways. The method currently used by ADOT for the pavement management data base is not acceptable for rigid pavement evaluation.

Load transfer at the joints may be evaluated using the deflection based method. Deflection measurements should also be used for evaluating pavements for the location of voids. The scheme of deflection testing developed in Texas for void determination should be field tested in Arizona.

The methods recommended in this document are slow and will be expensive due to the need to provide traffic control during the testing. The impact of the traffic control can be minimized through proper planning. However, it would defeat the purposes of the data base to restrict the testing to times when the conditions are unsuitable. For example, the pavement distress survey cannot be conducted at night. Also due considerations of the temperature in the slab, the deflection testing time must be carefully considered.

This chapter presents the state-of-the-art of equipment for the evaluation of pavement condition. The next chapter describes a recommended pavement condition rating method.

CHAPTER 3 RIGID PAVEMENT CONDITION SURVEY METHOD

INTRODUCTION

Based on the state-of-the-art review, manual pavement distress evaluation surveys are required due to the lack of suitable equipment for this task. The purpose of this chapter is to establish suitable pavement condition rating scheme. Before presenting the recommendations, the need for the measurements is reviewed and the state-of-the-art with respect to visual surveys of rigid pavement distress is presented in greater detail than presented in the previous chapter.

Although there are no automated equipment for collecting and analyzing the distress information, there are devices capable of capturing an image of the pavement surface with adequate resolution for viewing in an office. the condition procedures described in this memo are for visual condition surveys on site. They could be readily modified if photographic records of the pavement surface were obtained.

PURPOSES OF PAVEMENT CONDITION SURVEYS

There are several reasons for performing pavement distress surveys. The type of pavement condition data collected should be dictated by the intended use of the data. Pavement condition data are generally required for one of three purposes:

1. Research on the performance of one specific aspect of pavement performance.
2. Data required for the evaluation and design of a specific pavement project.
3. Data required for network pavement management.

In the 1985 North American Pavement Management Conference (Ref 18), Lee and Hudson introduced the concept of an additional level of data requirements. As shown in Figure 5, there is a definite correlation

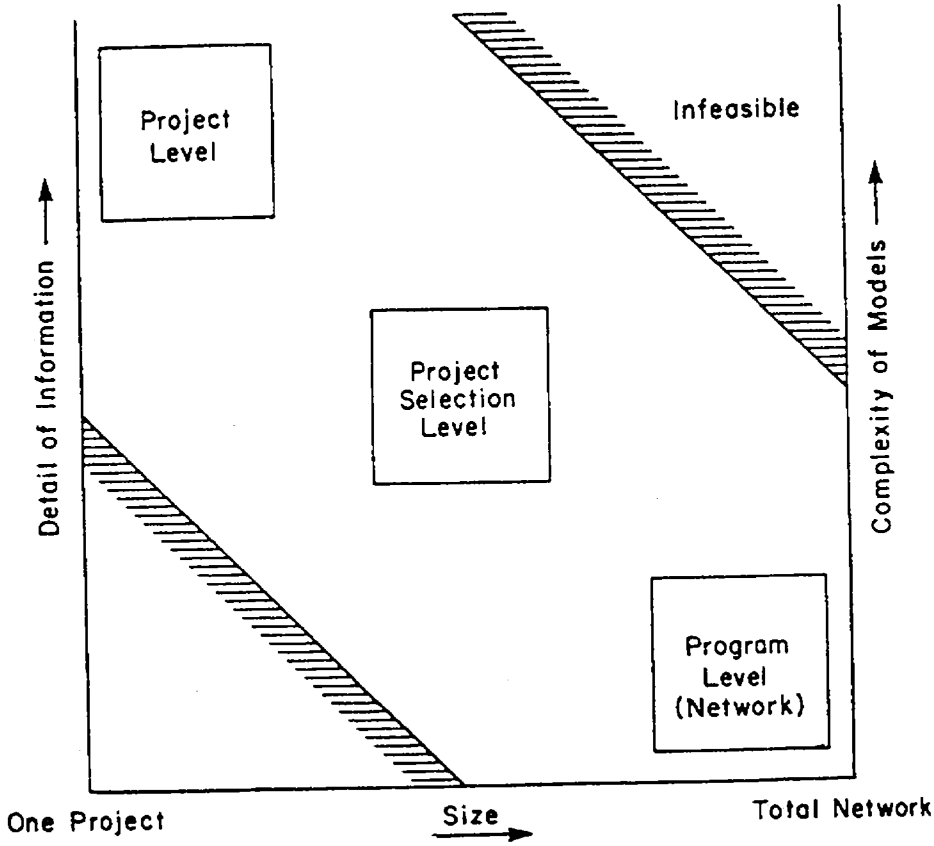


Figure 5 PMS models and data requirements at three decision levels of PMS.

between the size of the system or network in the data base, the amount of detail required in the data base and the level of complexity of the pavement analysis models. The level of data required for research is not shown on this graph but it will also be sensitive to the size of the network being studied.

The underlying concept behind Figure 5 is data are expensive to collect, maintain and analyze; the data requirements should be tailored to the needs of the decision making process. ADOT currently collects a very limited amount of information for the pavement management program. The system was developed for the predominantly flexible pavement rural network. One of the eventual products of the research into data collection requirements for the urban freeways must be a definition of the minimum data requirements for the decision making process at the network level. Since the rigid pavements have different types and severities of distress than flexible pavements, the pavement distress surveys must be tailored to each pavement type. In general, rigid pavement distress is more complicated than flexible pavement distress which leads to the conclusion that rigid pavement distress survey procedures will be more complicated than flexible pavement distress survey procedures.

The other factor that should be considered when developing a scheme for rigid pavement distress surveys is the fact that rigid pavements are predominantly used in areas of high traffic volumes. The consequences of closing a high volume road for repair or maintenance are much greater than a similar action on a low volume road. Thus, the data used to make decisions concerning high volume roads should reflect the need for greater reliability in the decision making process.

OBJECTIVE OF THE PAVEMENT CONDITION SURVEY

The stated objective of the project for the evaluation of Arizona's Urban Freeways is, "to establish a data base that will show the changes in pavement condition over time so that performance models can be developed." The term "performance models" can be construed in several ways.

Definitions of Performance Measures

The term "pavement performance" as coined by Carey and Iric (Ref 19) strictly means the serviceability-time (or traffic) relationship. Under this definition, the development of the performance model will use the serviceability index as the dependent variable. The independent variables will be the objective measures of pavement condition that correlate to pavement condition. At the AASHO Road Test the independent variables that correlated with the Present Serviceability Index were the slope variance as measured by the CHLOE profilometer and the cracking plus patching. Subsequently, highway agencies have attempted to use the serviceability equation to compute the dependent variable for pavement performance model development. However, the CHLOE profilometer is not being used as a primary data collection tool for pavement roughness at this time by any highway agency. Thus, a degree of error is entering into the calculations when alternative deflection measuring devices are substituted for the CHLOE.

Strictly speaking, serviceability is a measure of the ability of the pavement to serve the users of the road. The variable that demonstrates the highest correlation with user surveys of road quality is the roughness of the road. At the AASHO Road Test other measures of pavement condition were included in the statistical regression analysis in order to obtain the best possible statistical predictions of the present serviceability index. Inclusion of the cracking and patching term in the AASHO equation only improved the predicative capability of the equation by approximately 5 percent. The distress measures were not added to the performance equations for any engineering reason. The inclusion of the surface distress terms has resulted in a great deal of confusion in the application of these equations. Practical application of the serviceability concept in recent years has shown it is better to separate a distress index from the serviceability considerations (Ref 20). In fact the current philosophy of pavement evaluation is to separate out each of the four measures of pavement condition into separate indices of pavement condition which may subsequently be aggregated into a single overall measure of pavement condition as shown in Figure 6.

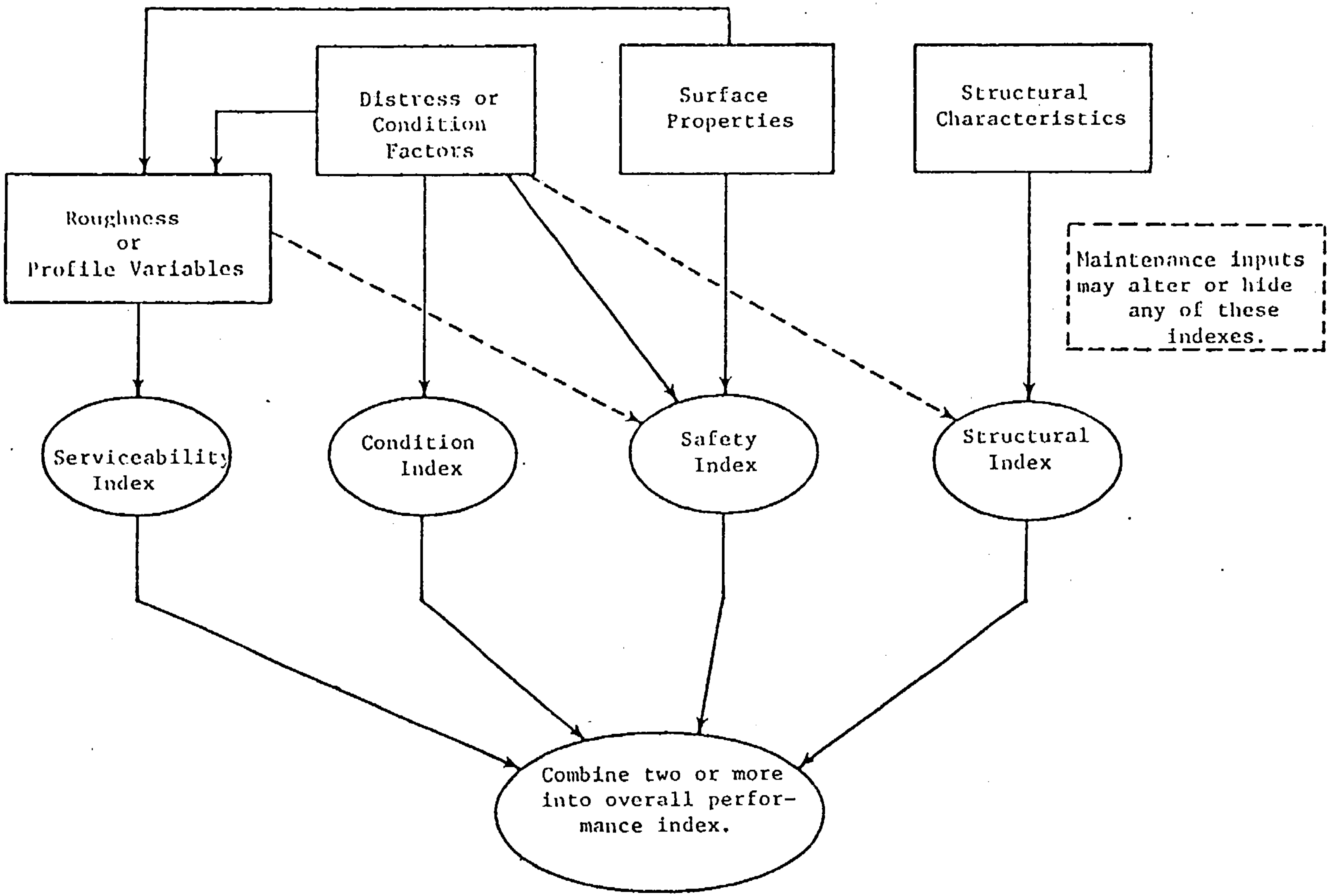


Figure 6. Interrelationships of pavement characteristics and pavement fitness measures (indexes).

These considerations lead to several interesting and pragmatic conclusions:

1. Serviceability-time curves are the generally accepted measure of pavement performance. The serviceability should be related to ride quality only.
2. Pavement distress is an important measure of the condition of the pavement with respect to pavement management and should therefore be included in an evaluation of the overall quality of the pavement.
3. Separate indices should be generated for each of the four measures of pavement condition. These indices may subsequently be combined into an overall index of pavement performance.

Definitions of Pavement Distress Measures

With respect to the needs of Arizona for urban freeway evaluation, distress is an important factor for pavement management. Distress affects the life and maintenance requirements for the pavement. Definition of a pavement distress measure is difficult because of the number of the different factors that must be taken into consideration.

First, there are a wide variety of distresses that must be taken into consideration when evaluating rigid pavements. The relative importance of each of the different distress types must be established in the formulation of the distress index. Second, the extent of the different distress types has to be evaluated. This requires development of a scale that ranks the distresses by both severity and extent. Finally, the interaction between the different distress types and their level of severity.

The broad objective of the ADOT research into this area is to establish a pavement performance data base that may be used to develop performance models. This requires a more intensive data collection process than is required for monitoring the condition of a network for a pavement management system. Development of performance models will require collecting data at a greater level of detail than is required for pavement management. Thus, the pavement condition index for distress should incorporate the elements of type, extent, and severity of the distresses as they influence the need to maintain, repair, reconstruct, and rehabilitate the pavement. The level of detail captured should be sufficient to allow an evaluation of the performance of the various design features of rigid pavements.

ELEMENTS OF A PAVEMENT CONDITION RATING GUIDE

Although the development of a pavement condition rating guide is beyond the scope of this project, it will be necessary for ADOT to develop such a guide for the evaluation of the urban freeway network. Eventually the work presented in this memo should be included into the guide. Therefore, it is worthwhile to describe the requirements for a pavement condition rating guide.

A pavement condition rating guide is composed of four basic components:

1. identification of the pavement sections
2. identification and description of the pavement condition elements, the type, extent and severity of the distress
3. procedures for the collection of the data in the field
4. procedures for the treatment of the data, including storage, sorting and analysis.

Selection and Identification of Sections

Normally, the first decision that must be considered for the development of a pavement condition data base is the method used for establishing the pavement sections. However, since the ADOT has a well established system for pavement management, the procedure currently used by the pavement management systems group should continue to be used. This method will provide the basic foundation for the development of the data base. As I understand the pavement management data base, the sections are defined as beginning and ending at each milepost.

For the purposes of urban freeway evaluation, I strongly recommend establishing a method for identifying subsections within the current section structure. It is very important that the subsections are used to identify areas of homogeneous conditions with respect to design, construction, traffic, and maintenance. Generally, project limits are convenient and necessary data collection points in a pavement database. Unless the sections are homogeneous with respect to each of the independent variables that need to be studied, the influence of some of the variables on pavement performance will be confounded and therefore the data will not support the development of the required performance models.

There are several schemes that may be used for identifying subsections. Since the milepost system is already established, the most straightforward method for identifying the subsections will be the use of fractional mileposts. The purpose for identifying subsections is for accurate identification of the data location.

The other considerations for the identification of subsections is related to the sampling method used to reduce the data collection from the entire roadway to a smaller, but representative sample of the pavement. Due to the cost of manual data collection, it is necessary to make a compromise between the amount of data required by the system and the amount of data that can be collected within the budget of the agency. Generally the compromise consists of either making the survey from a moving vehicle to improve the production rate, or reducing the amount of data required by limiting the observations to only a limited portion of the pavement. Techniques for performing each of these types of surveys have been reviewed with the conclusion that data observations from a moving vehicle, even at low speeds are undesirable. Thus, a sampling procedure is required.

Definition of a sampling procedure requires determining the size of the sample required, the size of the sampling units and the location of the sampling units. There has been some research into the size of the sample unit required to accurately define the condition of the pavement. The current method in Arizona requires observation of 1,000 ft^2 per mile of pavement.

Other researchers have indicated the sample requirements are much higher than 1,000 square feet per mile to obtain a reasonable representation of the pavement. While the data from other studies indicate the need for high sample rates, the exact level of sampling required should be determined by an analysis of the local conditions and for the specific condition survey technique being used by the agency. The exact sample size requirement can be accurately determined using statistical methods. First, a continuous survey of several miles of pavement is required. A pavement condition score is computed for each homogenous section. The data from each section are then separated into short sample units. The pavement condition index is computed for various combinations of the sample units. The objective is to determine the minimum number of sample units which provides the same pavement condition score as when the entire data set is used.

The final consideration with respect to the definition of the pavement sections is the interfacing of the pavement condition data with other sources of information. Eventually the pavement condition data will need to be interfaced with data for traffic, construction and maintenance. This aspect of the data base design will not be discussed further in this memo, but it should be kept in mind as the actual format of the pavement condition data base is being developed.

Definition of Distresses

The second major element of the pavement condition rating guide is the definition of the type, severity and extent of the pavement distresses that will be surveyed. There are several pavement condition survey manuals in use by the various highway agencies. Several of these were reviewed by Zaniewski et al. in a research project for the Federal Highway Administration (Ref 21). Table 4 summarizes distress types considered by different state highway agencies. The most frequently observed distresses are:

CONCRETE	Alabama	Arkansas	California	Connecticut	Florida	Illinois	Iowa	Kansas	Kentucky	Louisiana	Minnesota	New Mexico	New York	Ohio	Oklahoma	Oregon	Pennsylvania	Texas	Utah	Washington	Total
Blow Ups						✓														✓	2
Cracking						✓		✓					✓		✓	✓			✓	✓	7
Crack Spall			✓								✓										2
Corner Breaks		✓			✓	✓								✓							4
"D" Cracking						✓															1
Depression		✓		✓				✓													3
Displacement					✓								✓								2
Divided Slab																					0
Drainage										✓		✓			✓		✓				4
Faulting	✓	✓	✓		✓	✓	✓				✓		✓	✓			✓	✓		✓	12
Joint Seal Damage					✓			✓						✓			✓				4
Lane/Outer Shoulder Joint Displacement			✓																		1
Lane/Outer Shoulder Joint Separation			✓																		1
Lane/Shoulder Drop Off			✓			✓									✓		✓				4
Linear Cracking	✓	✓		✓	✓	✓	✓				✓		✓	✓				✓			10
Patching, Large Utility Cuts	✓	✓	✓		✓	✓	✓				✓			✓			✓	✓		✓	11
Patching, Small	✓	✓	✓		✓	✓	✓				✓			✓			✓	✓		✓	11
Polished Aggregate				✓																	1
Popout														✓					✓		2
Pumping		✓			✓								✓	✓				✓		✓	6
Punchouts		✓																			1
Railroad Crossings										✓											1
Rupture													✓								1
Scaling/Map Cracking				✓		✓					✓									✓	4
Settlement														✓							1
Shattered Slab																	✓				1
Shrinkage Cracks				✓																	1
Spalling at Corners		✓		✓	✓	✓	✓		✓							✓		✓			8
Spalling at Joints		✓		✓	✓	✓	✓	✓	✓		✓			✓		✓	✓	✓		✓	13
Surface Deterioration					✓	✓								✓	✓		✓	✓	✓	✓	8
Swell		✓																			1
Transverse Cracking		✓			✓	✓	✓				✓										5
Number of Variables Observed	4	8	7	7	12	14	6	4	2	2	8	1	6	11	4	3	9	8	3	9	

Table 4 Summary of state pavement condition rating guides for rigid pavements.

Distress	Frequency
Spalling at the joints	13
Faulting	12
Patching	11
Linear cracking	10
Spalling at the corners	8
Surface deterioration	7
Pumping	6
Transverse Cracking	5

Figure 7 summarizes the geographical distribution of the three most commonly observed distress types. The two states closest to Arizona which had published condition survey manuals for rigid pavements at the time of the survey were Texas and California. Both of these states observe faulting and spalling of the joints. Texas observes linear cracking and California does not.

Table 4 shows there are 32 different distress types defined by the various state agencies. This is obviously too many types of distress for inclusion in any pavement condition rating guide. Zaniewski et al. (Ref 5) have developed a pavement condition rating guide for the Federal Highway Administration which uses a grouping of the distress types to reduce difficulty in training the survey personnel. Table 5 shows the recommended grouping of the rigid pavement distresses.

For each of these distresses, the pavement condition rating guide should define extent and severity. Severity is generally rated in terms of low, medium and severe. Extent is usually rated on a percentage basis. For jointed rigid pavements extent may be rated as the percent of the panels that are affected.

Data Collection Procedures

The key operational issue that must be resolved in a pavement condition rating guide is the physical procedure used for the collection of the data. Visual condition surveys involve one or more persons observing the pavement from either a moving vehicle, walking or a combination of both, and recording the existing distress. The problem of collecting pavement condition data requires a compromise between the quality of the data and the cost of data collection and analysis. Survey procedures range from high speed surveys to detailed data

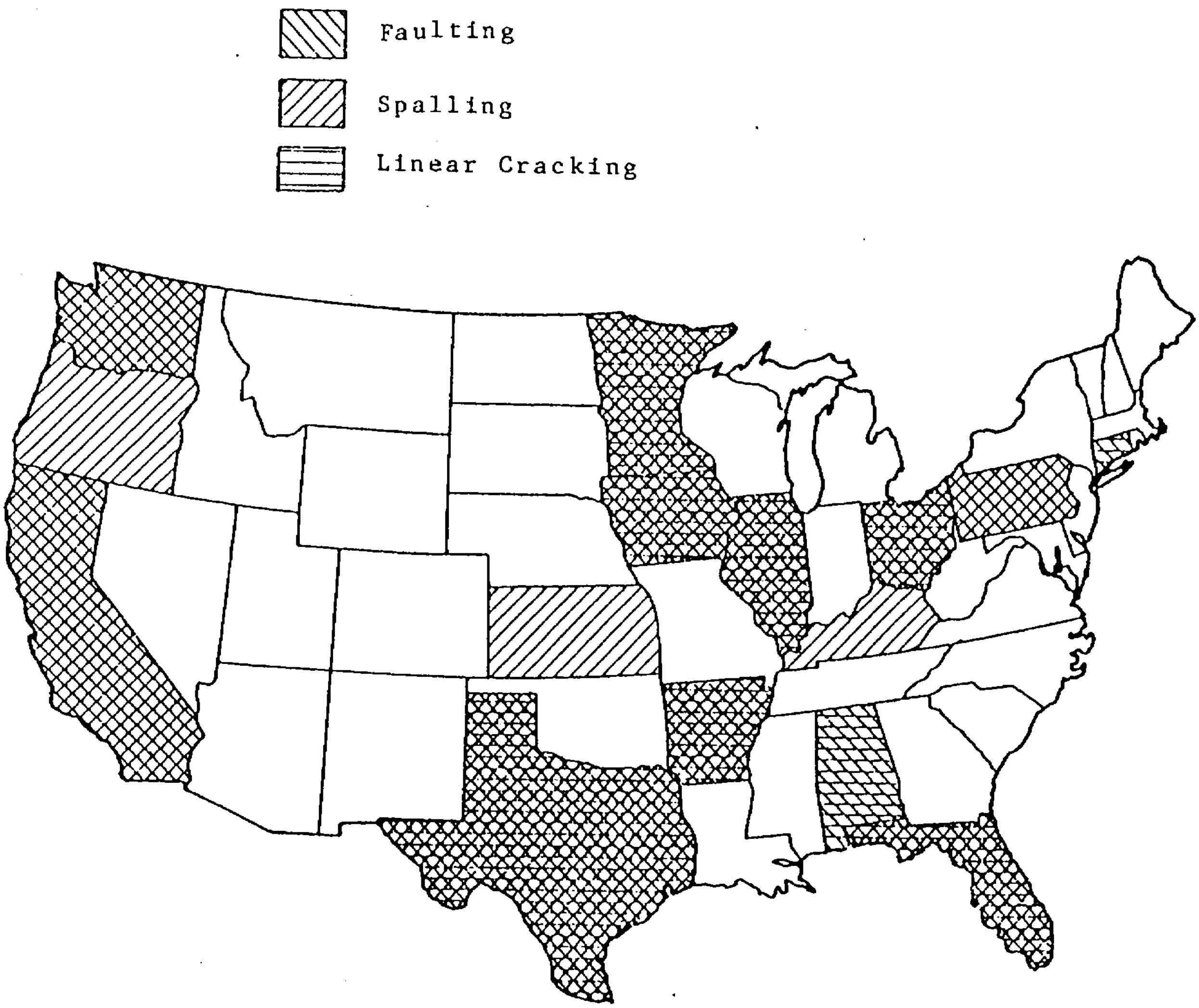


Figure 7. Distribution of rigid pavement distress identified by state pavement condition rating guides.

JOINT CONDITION

- Seal Damage
- Corner Break
- Spalling
- Faulting
- "D" (durability) Cracking
- Load Transfer Problems
- Blowup
- (Only punchouts are rated on CRCP since no joints exist)

CRACKING

- Longitudinal
- Transverse

SURFACE DEFECTS

- Scaling, Map Cracking and Crazing
- Popouts
- Bumps
- Potholes
- Polishing

PATCHES

- Asphalt Concrete Patch
- Portland Cement Concrete Patch
- Patch Deterioration
- Patch Adjacent Slab Deterioration

Table 5 Categorization of distress types into rated categories for rigid pavements.

collection which requires walking on the pavement. The various methods of collecting the data are compared in Table 6.

While driving at high speeds allows maximum coverage of the pavements in a given time period, there is a serious concern that data can be reliably collected at high speeds. The ability of the observer to recognize the pavement varies with the speed, the position in the vehicle, the angle of the sun, etc. Under the best of conditions, the reliability of data collected from a high speed vehicle is questionable. Operating on an urban freeway is a very difficult condition and therefore in my opinion, high speed observations is unacceptable.

Operating at low speed on a freeway cannot be tolerated due to the safety problems. Operation on the pavement shoulder is a viable option and is being used by several agencies. The problem with driving on the shoulder is that some sections of road lack adequate shoulders, and there may still be some safety considerations. However, the success of other agencies in making pavement observations from the shoulder prevents discarding this option at this time. Frequently, observations from a slow moving vehicle are augmented by allowing the observer to stop and walk along part of the section. This is a bad practice due the fact that it allows a differential means of collecting the data. The observer should not have any discretion in the method of data collection.

The last alternative is to have the surveyor walk the pavement while making observations. This is the most time consuming and expensive method of data collection. However, it also produces the most reliable data. Safety while walking on the shoulder of the urban freeway may be a problem; however, it may be less of a problem than having a vehicle traveling on the shoulder. Observations should be made while walking along the shoulder at least in the early stages of the data collection.

As a final note with respect to the collection of the data in the field, there are several tools that may be used to facilitate the data collection process. The simplest is the use of preprinted forms which are easy for the surveyor to record the data on and can be designed for direct key punching. There are several small (lap top) computers that may be programmed to present the surveyor with a data input screen. ARE

Survey Type	Advantages	Disadvantages
high speed survey	low cost	poor ability to identify and distinguish between distress types
low speed survey	relatively low cost, can be used with photographs to distinguish extent and severity of distress	only practical on roads with shoulders or extremely low ADT
high speed survey with walking supplement	increase precision over high speed survey	accuracy of survey frequently depends on raters ability to identify "representative" sections
low speed survey with walking supplement	improved precision	higher cost than above with same drawback on selection of sections
walking survey with detailed measurements	high precision	expense, selection of representative section, obtaining adequate coverage

Table 6 Advantages and disadvantages of various approaches to pavement condition surveys.

Inc. has successfully programmed the Epson lap top computer for data collection surveys. The computer used by ARE Inc. has both a microcassette and a printer for recording the data. The printer proved to be very valuable as a backup for the automatic data transfer process. There are now several brands of computers that may be used for this function. Minnesota has gone one step further by using an optical sensor to read preprinted code bars correspond to the different distress types. The operator merely needs to point to a bar code to record the type of distress that is being observed. The data can then be automatically transferred to the main data base.

Treatment of the Data

By proper planning and equipping the data collection process, the treatment of the data in the office can be significantly reduced, particularly if an automated data transfer process can be established using either the lap top computers or the bar code reader like that used in Minnesota. The main concern is to ensure the compatibility of the data base between the data collected in the field and the data put on the computer from the department's historical records.

Concern for Accuracy

The final point for consideration in the pavement condition rating guide is the need for accuracy in the data collection. There are several opportunities for variances in the data collection and recording process to enter into the pavement condition survey. First, there is the ability of each individual to record data in a consistent manner. The ability of an observer to record data will vary depending the attitude of the observer and environmental conditions. There can be significant variations from one day to the next and from the morning to the evening. There are even larger variations when the data are being collected by more than one observer. When a team is used to collect the data, there is a strong probability for large variations between the observers.

The amount of variability in the data can be minimized by carefully designing the survey method to limit the amount of decisions the surveyor is required to make and by thorough training of the field surveyors. Without exception, the data are more reliable when the surveyor is required to measure a parameter rather than being allowed to make an estimate. A good pavement condition rating manual should include a section on training of the crew. Training sessions frequently require two days of classroom instructions and a day of field practice.

DISTRESS SURVEY

As pointed out in Table 5 rigid pavement distress types may be placed in four categories. There are several types of distress that must be rated within each category of distress. The best method for the identification of the distress is with a photo of the distress and a verbal description of the distress. There are several manuals for pavement condition surveys that present adequate descriptions. Several of these are based on the pavement condition rating guide developed for the FHWA and NCHRP by Smith, Darter, and Herrin (Ref 6). The most recent pavement condition rating manual based on these distress definitions was prepared by Zaniewski, Hudson and Hudson for the Federal Highway Administration (Ref 5). This manual should serve as a good starting point for a rigid pavement condition survey manual for ADOT. In particular, Appendix B presents the distress identification photos. The photos presented in the Pavement Condition Rating guide have been reprinted several times and are losing some clarity. It may be desirable to take a new set of photos for a pavement condition manual for ADOT.

The method recommended in Ref. 5 was developed for network surveys so some modifications are required for the survey of the urban freeways in Arizona. The condition survey requires filling out two forms as shown in Figures 8 and 9 at each sample location. A sample location is 100 ft of pavement that is rated for the nonjoint related distresses and ten consecutive joints.

At each sample location, the 100 ft rated for cracking, patching and surface defects is divided into four subsections corresponding to the columns A, B, C, and D, on Figure 8. Each subsection is rated for the severity of the cracking, surface defects and patches according to

Rigid Pavement Distress Survey Data Form

Date:____________ Rater:____________________ District:____________________
Route No:__________ No. of Lanes:_____________ Section No:_______________
Link ID: Node No.________________ to Node No.____________________________
Section ID: Beginning Station________________ Ending Station___________

	DISTRESS CATEGORY												
Severity Level	Joint Problems or Punchout	Cracks				Surface Defects				Patches			
		A	B	C	D	A	B	C	D	A	B	C	D
0													
1													
2													
3													
4						X	X	X	X				

COMMENTS:

Figure 8 Form for rating rigid pavement distress.

Transverse Joint Rating Worksheet

			Joint Number									
		Distress	1	2	3	4	5	6	7	8	9	10
		None										
Joint Distress Level	A	Seal Damage										
	B	Corner Break										
		Spalling										
		Faulting $\geq$ 1/2"										
		D Crack										
	C	Load Transfer Problems										
		Blowups										

Severity Level Assignments

0 - No checks
1 - Any checks in distress level A
2 - $\leq$ 9 checks in distress level B
3 - 10 - 30 checks in distress level B
4 - > 30 checks in distress level B or any checks in distress level C

Figure 9. Transverse joint rating worksheet.

the criteria in Figure 10 by placing a check mark in the column of the subsection column for the distress being observed and in the row corresponding to the severity. During the data reduction, the extent of the distress is determined based on the number of times the distress was observed.

Joint condition needs to be evaluated separately from the other elements of pavement condition due to the discrete nature of the joints and the fact that the majority of rigid pavement distress occurs at the joints. Figure 9 is used to record the data for the condition of the joints. The observer places a check mark in the block corresponding to the types of distress for each joint observed. The overall ranking of the joint condition is determined as shown at the bottom of the figure and transferred to the appropriate column in Figure 4. There is no attempt to rate the extent of the distress at each joint as each of the distresses indicated are assumed to affect the entire joint.

There are several approaches for the collection of distress data for rigid pavements. The method recommended here has been tested by the author and seems to capture the most important information in a way that is easy for the survey personnel to understand. That is not to say that this is the perfect system and that it should be implemented verbatim at this time. Prior to routine use the method should be critiqued by ADOT engineers, revised, field tested and revised, etc. until a working system is established. Specifically, the data should be analyzed to determine the number of 100 ft. sections that are required to accurately define the condition of each homogeneous pavement section. Also, the types of distresses and their categorization should be evaluated to determine if the level of detail is adequate. For example, it may be desirable to record the type of material used in patches as an indicator of potential maintenance problems.

DATA REDUCTION FOR DETERMINATION OF A PAVEMENT CONDITION RATING

Until a method is developed to reduce information from the distress survey into a statistic that represents the overall condition of the pavement structure, there will be little use for the data. The distress data represent individual data points about the condition of the

Cracking - Longitudinal and Transverse

Severity Level	Guidelines
0	None
1	Crack widths < 1/2" and no other distress at the crack.
2	Crack widths ≥ 1/2" and no other distress at the crack.
3	Cracks < 1/2" wide which have any of the following: Faulting ≥ 1/2", 'D' cracks, or spalling.
4	Cracks ≥ 1/2" wide with any of the following: Faulting ≥ 1/2", 'D' cracks, or spalling.

Edge Punchouts

Severity Levels	Guidelines
0	None
1	One occurence per 100'
2	Two occurences per 100'
3	Three occurences per 100'
4	Four occurences per 100'

Patches - AC, PCC, Adjacent Deterioration

Severity Level	Guidelines
0	None
1	PCC patch in good condition.
2	AC patch in good condition.
3	Any patch in poor condition.
4	Any significant occurance of adjacent slab damage.

Surface Defects - Scaling, Popouts, Bumps, Potholes, and Polishing.

Severity Level	Guidelines
0	None
1	Slight or moderate severity raveling, popouts, scaling, map cracking or crazing.
2	Occurence of bumps or severe occurences of the distresses mentioned above (severity level 1).
3	Occurence of any potholes or aggregate polishing.

Figure 10. Guidelines for severity rating of rigid pavements.

pavement structure at discrete points in time. The distress information must be analyzed in a manner that will allow the development of a statistic that can be monitored over time to define the performance of the pavement. There are several approaches to the development of a pavement condition rating statistic but in essence, the approach is the definition of an algorithm for computing the pavement condition score and then the development of a method for interpreting the meaning of the pavement condition score. The actual development of a pavement condition rating method is beyond the scope of this project; however, the state-of-the-art does provide several approaches to the problem that are described herein.

In the simplest sense, all of the available pavement condition rating scores are a summation of the individual distress scores multiplied by a weighting function. The development of the pavement condition rating score requires determining appropriate weighting values for each distress type such that the composite rating value has a meaning. Once the composite rating value has been determined, decision criteria need to be developed for interpretation of the data.

There are several analytical methods that may be used for the data analysis:

1. Multiple regression analysis
2. Bayesian analysis
3. Utility Theory
4. Markov processes
5. Discriminant analysis
6. Time series analysis

Each of these analysis methods have an application depending on the type of data available and the results required from the analysis.

Multiple Regression Analysis

Regression analysis is one of the most common of the statistical tools available for developing models from data bases. Finn et al. used regression analysis for the development of the performance models for the ADOT pavement management system where the change in serviceability with time is related to the environment, traffic and structural variables (Ref 22). Multiple regression analysis is used as either a descriptive tool, where the linear dependence of one variable on another is summarized or decomposed, or as an inferential tool by which the relationships in the population are determined by an examination of a sample of the population.

The linear regression method of analyzing pavement condition data was recently used in a study for the Alabama Highway Department (AHD) to develop pavement rating scale for determining pavement maintenance or replacement priorities based on the measured pavement distress (Ref 23). In the Alabama model, the level of roughness, cracking and patching, and raveling is used to determine the overall pavement rating index. There are actually several terms to capture the effects of the different types of cracking. In order to establish the data base for the development of the regression model engineers form throughout the department were ask to rate 30,000 pavement sections throughout the state. The Delphi procedure was used to design the rating scale for the field evaluation of the test sites.

While the work performed by AHD was for flexible pavements, it did demonstrate the feasibility of capturing expert opinions of the relationship between pavement distress the need for an action by the highway department.

Bayesian Analysis

The Bayesian analysis approach was formulated to assist decision making when there are insufficient data for a deterministic solution. The data usually represent past experience in similar situations and may be of any degree of complexity ranging from simple guesses on the part of the decision maker to detailed numerical results of a large experiment. The data must be expressed as the probability that various consequences will result from a specific decision.

The Bayes principle then tells the decision maker to choose the decision which minimizes the expected loss or maximizes the expected gain. The Bayesian approach is typically used when there are repetitive experiments on identical systems, or when a decision is required for maximizing or minimizing a utility function when deterministic data are not available.

Figure 11 shows how the Bayesian approach may be applied to the development of a relationship between pavement distress data and pavement performance (Ref 24). The analysis begins in the upper left quadrant of the figure where the current data on the pavement structure, local environment, and projected traffic are employed to determine the prior distribution. This distribution provides the first estimate of future performance. For the evaluation of an existing pavement, the data on the levels of distress, serviceability and maintenance histories are used to establish the prior distribution. The prior distribution is used to predict the dependent variable. After the initial prediction, a new set of data can be analyzed; the prior distribution is upgraded to a posterior distribution, which allows the estimation of an updated distribution of the dependent variable.

The advanatage of the Bayesian approach over standard regression analysis is the built-in mechanism for updating the models as more data are made available. With standard regression, one must completely redefine the model and repeat the analysis when new data are added to the data base.

The major weakness of this approach is the need to define the data in probabilistic terms. This is difficult to accomplish in many situations. The Bayesian approach is frequently used in combination with other statistical analysis methods such as the Markovian method.

Utility Theory

Utility theory is a method of summarizing or combining multiple attributes into a single parameter by the use of utility functions. These functions can be used directly to obtain weighting values, or subjective preferences of experienced engineers in assessing the relative importance of a variety of factors. Utility theory was used by Finn et al. for the development of the ADOT pavement management system (Ref 22) and was used by Nobles and McCullough (Ref 25) for the evaluation of Continuously Reinforced Concrete Pavements in Texas.

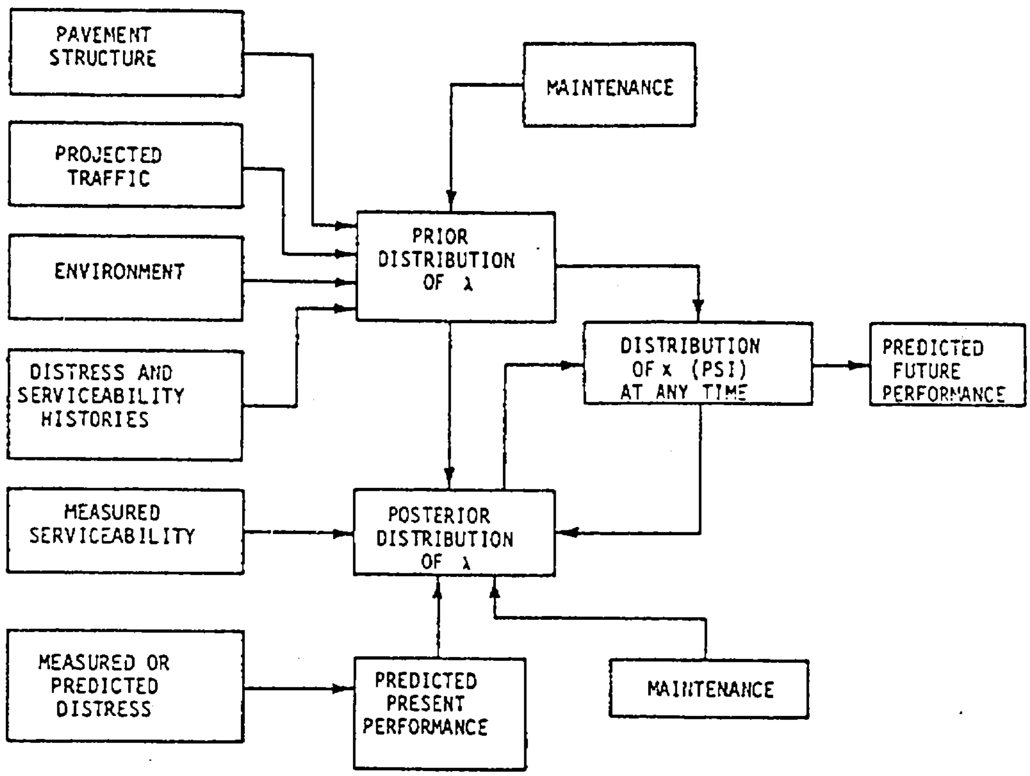


Figure 11. Flow Diagram of a Bayesian approach for pavement condition modeling.

The utility theory relies on the subjective opinion of experienced personnel to define the levels of the dependent variables.

Markov Process

The Markov process is used in the ADOT pavement management system for the prediction of change in pavement condition over time. Any system that can exist in a series of possible states or conditions is a candidate for description in Markovian terms. Consider a system with a finite number of states, labeled 1, 2, 3 . . . N and assume the systems always in one of these states. At discrete times, let the system make a transition from one of these states to another condition state with a fixed probability. An entire set of probabilities for transition from one condition state to any of the other condition states defines the transition probabilities. These transition probabilities are stored in a N N matrix, the (i,j) element represents the probability the system will undergo a transition from state i to state j. The current state of the system described in a row vector of length N, the elements in the vector are the probability distribution over the set of all possible states. The state of the system after one transition is determined by multiplying the state vector by the transition matrix to define a new state vector.

The Markov process is a very powerful tool for the analysis of pavement condition. The main difficulty in developing and using the system is the development and revision of the transition matrices. A separate transition matrix is required for each variable that requires a performance prediction. The initial development of the transition matrix may be established with engineering judgment, but eventually one would desire to revise the matrices to reflect the experience demonstrated in the pavement data base.

Discriminant Analysis

Discriminant analysis was developed specifically for combining a number of variables into a composite index and locating the critical values or boundary values that define distinct classifications or groups within the data. This is accomplished by selection of composite variables on the basis of maximum differences among the means of composite scores coupled with minimum overlap of the distribution of these scores. Noble and McCullough have used this analysis method for the development of pavement rehabilitation criteria for continuously reinforced pavements in Texas (Ref 26).

In the Texas study, the data base was large enough so that the data could be divided into two groups of data, pavements that had been overlaid, and pavements which had not been overlaid. For each group there was a complete data set for pavement distress. The discriminant analysis was then performed to determine the distress factors, along with severity and extent, which existed predominantly in either the overlaid or nonoverlaid pavements.

Time Series Analysis

Time series analysis is an extremely powerful tool for the treatment of time dependent data. It offers a method of iteratively analyzing the data to maximize the quality of the models. However, due to the formulation of the method, it requires data that are exactly evenly spaced in time. The only set of pavement condition data that meets this requirement are the results of the AASHO Road Test. It is unlikely that the data collected on the urban freeways in Arizona will meet the uniformity of time requirement so time series analysis will not be considered further.

Summary and Recommendations for an Analysis Method and a Pavement Rating Statistic

There are a wide variety of analysis methodologies available for the treatment of pavement condition data. Some are suitable for the development of weighting functions for combining the individual measures of pavement distress into a meaningful composite index of pavement condition. I have worked with the discriminant analysis and found it to be very powerful and useful for the analysis of these type of data. Of the methods discussed in this memo, the discriminant analysis method is the best method for both establishing the composite rating scale and for identifying criteria for interpreting the scale in a meaningful way.

Other methods of analysis are useful for the development of performance models. The Markov process is very powerful and has the advantage of being familiar to the pavement management group. The main drawback to the Markov process is the need to establish multiple transition matrices. While the development of multiple matrices is cumbersome, it is not technologically difficult. I recommend the Markovian process as the primary analysis method for the development of performance models for the urban freeways in Arizona.

In the meantime, a method is needed for the reduction of the distress data that will be collected during the condition survey. Since the primary data base will remain intact for subsequent analysis, the method used for the preliminary analysis may be relatively unsophisticated and simple.

I propose the use of the pavement distress index, PDI, developed for the Federal Highway Administration Pavement Condition Rating Guide (Ref 5). This data reduction method is compatible with the recommended data collection procedure. The PDI is a deduct value method of computing the condition score. that is the PDI is on a scale of 0 to 100 with 100 being a perfect pavement. The number of deduct points is computed as a function of the type, extent and severity of the distress. That is:

$$PDI_i = 100 - \sum_{j=1}^{nd} DP_j$$

where

PDI_i = Pavement Distress Index sample location i

$\ldots\sum_{j=1}^{nd} DP_j$ = Sum of mean deduct points for each distress category j for sample unit i

nd = the number of distress categories

The sum of the deduct points is computed as shown on Figure 12. The observed severity level for each of the types of distress is transcribed onto Figure 12. The sum of the level of severity is computed and multiplied by the weighting factors. The sum of the weighted distress levels is divided by 4 to determine the sum of the mean deduct points for each sample location. At this time I do not recommend combining the data across sample units.

Rigid Pavement Distress Survey Data Analysis Worksheet

(HEADER INFORMATION)

		Joint Condition Severity	Cracking Severity	Surface Defect Severity	Patch Severity	
Sub Section	A		____	____	____	
	B		____	____	____	
	C	____	____	____	____	
	D		____	____	____	
Sum						
Weighting Factor		X(40)	X(6)	X(8)	X(3)	Total of Weighted Sums (TWS)=
Weighted Sum (Product)						

$\Sigma DP = TWS \div 4 =$ ____________

$PDI = 100 - \Sigma DP$

$PDI = 100 -$ ____ $=$ [ ]

Figure 12 Data analysis worksheet for rigid pavements.

CHAPTER 4 LIFE CYCLE COST ANALYSIS

As roads deteriorate, vehicle operating costs increase, absorbing spendable user resources. These cost components are best analyzed by a life-cycle costing (LCC) program which makes an economic assessment of competing design or rehabilitation alternatives. Life cycle costs have been studied extensively by several highway agencies. There are two recent reports summarizing the state of the art with respect to life cycle costs of pavements. In 1985, Texas Research and Development Foundation, TRDF, prepared a state of the art report for the Pennsylvania Department of Transportation (Ref 27). This report provides very practical information for the development of a life cycle cost analysis methodology. The second report is a synthesis of life cycle cost analysis practices prepared by Dale Peterson for the National Cooperative Highway Research Program (Ref 28). The TRDF report deals directly with the development of a LCC methodology whereas the NCHRP report presents more general background information. Much of the following information was obtained directly from the TRDF report.

LCC analyses allow highway administrators to explore several feasible economic alternatives to select the best design/maintenance/rehabilitation strategy. On a broad scale such analyses can form the basis for budgetary request. Administrators can use it to demonstrate to those controlling resources the consequences to future agency costs and to the economy of not meeting identified budgetary needs. Life-cycle cost analysis provides an invaluable tool for highway administrators.

HISTORICAL ASPECTS OF LIFE-CYCLE COST ANALYSIS

Although life-cycle costing for pavements is not a new concept, it has not been uniformly applied by state highway agencies. Figure 13 shows the pavement selection procedures used by the states (Ref 28). The problems most often cited for not using LCC analysis are: the lack of certain input information particularly related to user costs, such as unknown interest rates, the time value of money, and the effect of inflation. Others question the appropriate methodology for incorporating these factors into the life-cycle cost analysis. A number of project level life-cycle cost techniques have been developed and applied in the United States. Among these are Systems Analysis Method for Pavements (SAMP) developed by Hudson, et al. (Ref 29), and the Flexible Pavement System (FPS) developed in 1969 by Hudson, McCullough, Scrivner and Brown (Ref 30).

Subsequent development work was done in Texas to produce a Rigid Pavement Design System (RPS) in 1969 by Kher, Hudson and McCullough as part of the Texas Cooperative Pavement Research Program (Ref 31, 32). Dr. Kher subsequently developed the OPAC (Ontario Pavement Analysis of Costs), a comprehensive life-cycle costing method in the Canadian province of Ontario (Ref 33, 34). Total pavement costs are predicted throughout the life of the pavement including initial capital expenditure, resurfacing and maintenance expenditure, road user costs, and salvage value. In 1972, an optimization system was developed for the U.S. Forest Service at the University of Texas (Ref 35, 36).

The common basis of these methods is the application of a systems approach to pavement analysis and design (Ref 29, 30, 37, and 38). Computerized models of these methods generate an array of alternative design strategies, compute costs associated with each feasible strategy over its analysis life, and select candidate strategies based on an appropriate economic analysis. A conceptual framework of life-cycle cost analysis used in the systems approach to pavement design is illustrated in Figure 14.

Other computer programs for pavement analysis and design which consider LCC methodology are LIFE2, HDM, RPRDS1 and PRDS1. The Construction Engineering Research Laboratory (CERL) has developed the LIFE2 program (Ref 39) for life-cycle analysis of both flexible and rigid pavements. The program HDM (Highway Design Model) is a cost model for flexible pavements (Ref 40) developed and used primarily by the World Bank as a guideline for investing money in the development of roads in third world countries. RPRDS1 was developed at the University of Texas at Austin specifically for rehabilitation design of existing

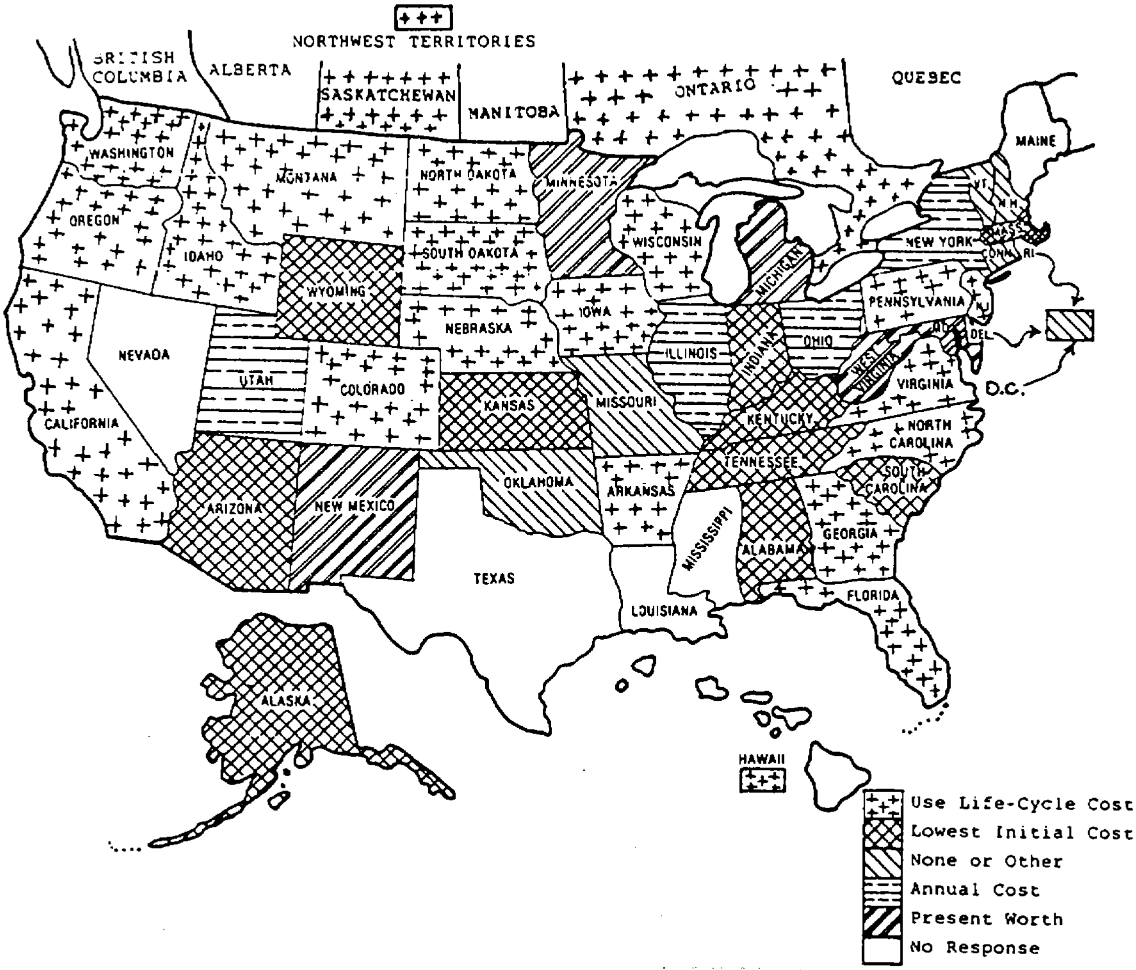


Figure 13 Pavement selection procedures used by various agencies in 1984 (Ref 28).

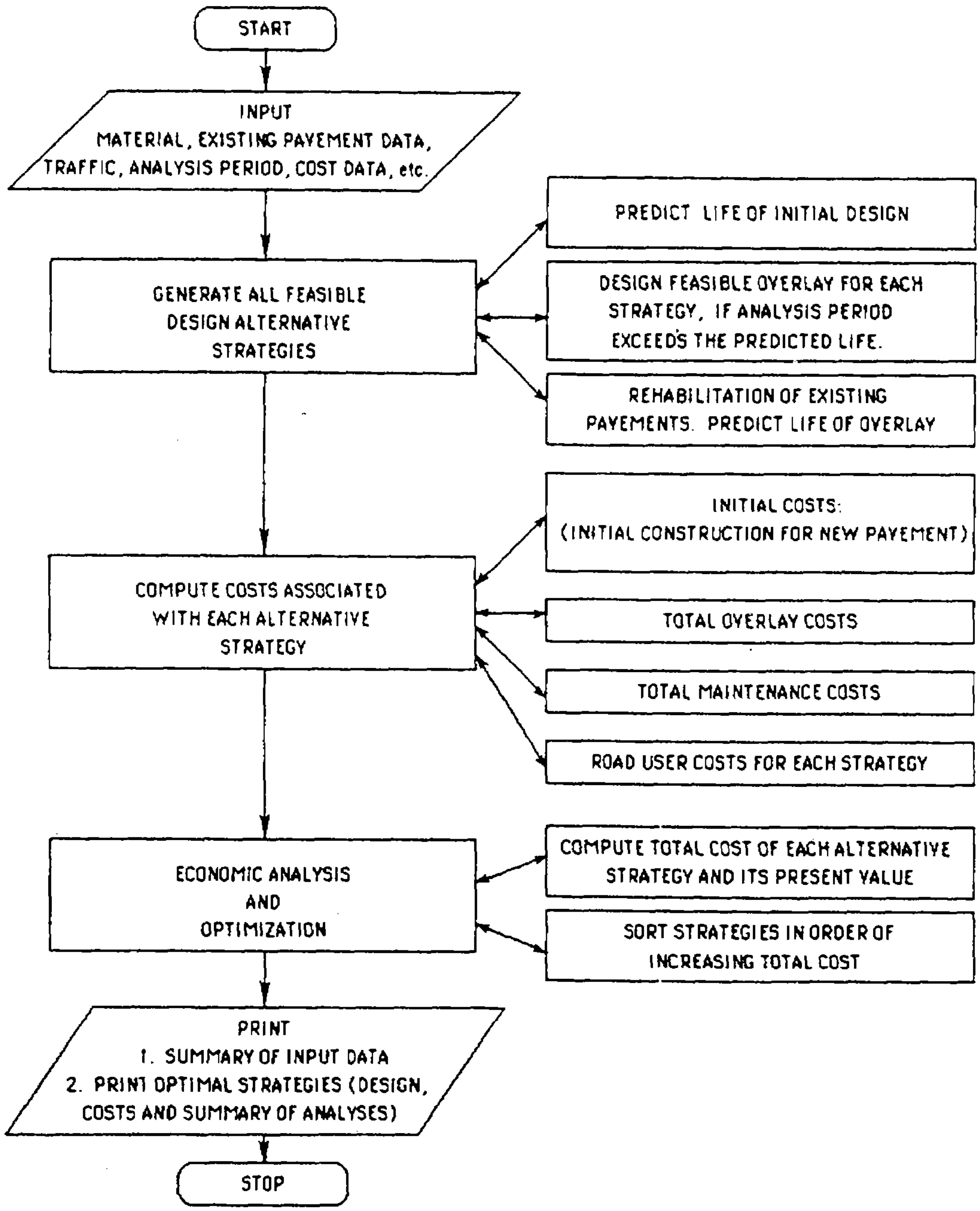


Figure 14. A conceptual framework of a comprehensive LCC methodology (Ref 27).

rigid pavements for use by the SDHPT (Ref 41). The PRDS1 program is a modified version of RPRDS1 (Ref 42) and is capable of performing life-cycle analysis of both flexible and rigid pavements for rehabilitation design.

In the simplest case, LCC analysis evaluates inputs and costs associated with a particular strategy through the analysis period, discounts the cost to the base year and generates an output report that can be used in management decision-making. The computer programs cited above offer immense advantages as these have the additional capability of examining a multiple number of strategies, maintenance treatments, and traffic scenarios in different combinations.

PURPOSE OF LCC ANALYSIS

A life-cycle cost analysis involves modeling the performance of a given structural pavement segment for several years (a pavement's life-cycle) exposed to a given set of conditions:

1) expected environment
2) forecast traffic loadings
3) select maintenance treatments
4) alternative rehabilitation strategies

For each design strategy, total agency costs and user impacts are quantified. The analysis is used to evaluate different pavement design, rehabilitation and/or maintenance treatments. The modeling process depends on a number of different cause and effect relationships defined by mathematical equations. These equations do two things. First, they predict the future condition of a specified pavement. Second, they quantify the user impacts of using the pavement in each condition. Costs are then computed over the analysis period and discounted to a base year.

A comprehensive pavement life-cycle analysis can quantify agency and user costs for any design, maintenance or rehabilitation policy. This means alternative strategies or options can be analyzed to determine their relative costs.

The basic structure of a comprehensive LCC methodology is illustrated in Figure 14. The initial cost of each particular design for a specific pavement project is computed and compared against available funds. If the costs are excessive, the design is discarded and the model moves to the next alternative. If the costs are within feasible levels, the design is checked against a total structural constraints and is discarded if the criteria are not met. Those designs meeting both the initial cost and structural constraints are retained, and the expected design life is calculated using performance models, environmental parameter, and anticipated traffic. If the specified minimum time to the first overlay exceeds the initially calculated design life, the design is discarded and the program continues to other alternatives. The program considers each design in turn and continues until all designs have been analyzed. The cost of construction, maintenance, overlays, major maintenance, and user costs are then combined to yield the total predicted costs for each alternative. The alternatives are then ranked by minimum cost.

PAVEMENT ANALYSIS AND PERFORMANCE COMPONENT

Past practices of pavement design and rehabilitation have been concerned primarily with layer thickness selection based on a structural analysis. Pavement analysis and a performance prediction are extremely important in the formulation of a LCC methodology. The major elements of the pavement analysis and performance models are:

1. Structural analysis for new pavements or rehabilitation design.
2. Pavement distress and performance prediction models.
3. Generation of rehabilitation alternatives.
4. Traffic models.

Structural Analysis

Structural design for pavements is a function of traffic, material properties, and environmental input as shown in Figure 14. In the case of rehabilitation design, the thickness and condition of the existing pavement are also influencing variables. A thickness design is assumed to be adequate if the predicted response of the trial pavement structure is below critical or limiting values. The response variable can be deflection, distress, or strain. The limiting values are based on empirical studies, experience and traffic levels. A majority of rehabilitation design methods use the limiting deflection criteria which is an empirical approach.

The mechanistic-empirical approach of structural design is becoming increasingly popular. In this approach, the pavement is modeled as a multi-layered linear elastic system, and each layer is characterized by a modulus of elasticity and Poisson's ratio. For a new pavement design, the materials are characterized in the laboratory. For existing pavements, in situ material properties can be determined from the mechanistic interpretation of deflection basins measured by a nondestructive testing device. The critical response is then computed by a program based on layered theory for the assumed pavement structure and design load. Empirically response versus performance relationships are used to predict the structural capacity and strengthening requirements.

Distress and Performance Prediction Models

For life-cycle analysis of pavements, mathematical models are needed to estimate the rate of pavement deterioration associated with each design alternative or rehabilitation strategy. Performance of a given strategy can then be predicted under future traffic conditions for a specific environment. These mathematical models define the damage function which are different for different pavement types and performance variables.

Distress prediction models are used for evaluation of pavement structural condition, and serviceability prediction models are associated with functional performance of pavements. These damaged functions are of significant importance in developing life-cycle analysis methodology because these are used to predict future pavement conditions. Table 7 presents a list of performance variables for rigid pavements which have been modeled empirically.

It is not feasible to consider all these performance models. Commonly used performance variables are roughness, some form of distress such as fatigue cracking, serviceability index, or a composite condition rating. These models make it possible to quantify the performance curves and service life of different design strategies by computing the time to reach a limiting value.

Multiple regression analysis techniques are historically used to develop performance/distress models in which rate of deterioration in terms of a specific variable is related to explanatory variables such as traffic, age, deflection, regional, and environmental factors for a particular pavement type. Other types of analysis such as the Markovian process or discriminant analysis may be more appropriate at this time.

Generation of Design Alternatives

Application of the systems approach to pavement design (Ref 38) enables the user to analyze and evaluate a large number of alternative design strategies. Figure 15 illustrates the general order involved in generating alternatives to be considered in any particular design situation. A true life-cycle analysis for pavements is incomplete without contemplating feasible alternative strategies in a specific case.

The model to generate rehabilitation alternatives should have the capability to generate multiple options based on (at the very least) type of rehabilitation, timing, and extent of rehabilitation (e.g. overlay thickness). Since it may not be possible to consider all of these combinations (for a given project), it will be necessary to suggest a method to screen out most of the infeasible alternatives. On rigid pavements, for example, a project oriented design system, PRDS1 permits an economic analysis of numerous alternatives, such as flexible overlay, rigid overlay, concrete shoulders, and/or continued routine maintenance to be used over an analysis period. A sensitivity analysis of the program revealed that under low traffic volumes, for example, the only viable alternatives are flexible overlays or continued routine

Table 7. List of performance variables to be considered in developing damage functions.

RIGID PAVEMENTS

Present Serviceability Index
Faulting
Cracking
Pumping
Defects (punch out)
Depression
Skid Number
Spalling
Blow ups
Roughness

OVERLAID RIGID PAVEMENTS

Cracking
- Transverse
- Longitudinal
- Multiple
- Reflection

Patching
Serviceability Loss

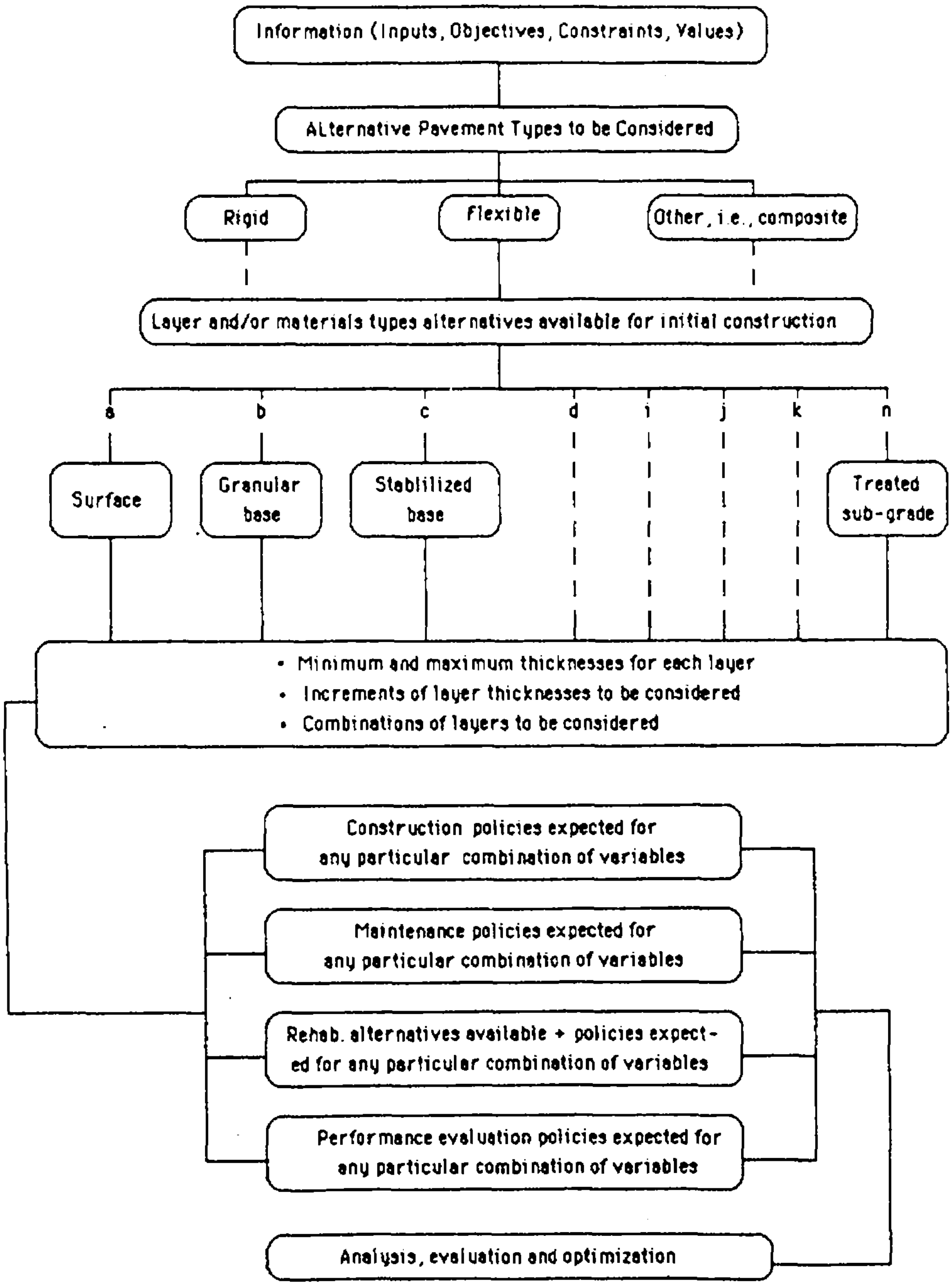


Figure 15. Key components of generating alternative pavement design strategies (Ref 27).

maintenance. Therefore it is desirable to limit the number of combinations for design alternatives in some situations to minimize computer time and file storage requirements. In the PRDS1 program the screening is handled by user-specified options related to rehabilitation type combinations.

Traffic Models

Traffic models are needed to determine pavement loading, vehicle behavior, fatigue life prediction, and user time costs. An adequate model to predict future traffic generation throughout the analysis period is an important component of a LCC methodology. Since the life-cycle cost model will include user costs, the results produced will be extremely sensitive to traffic characteristics. This will include not only traffic growth, but estimates of the vehicle population by class and fundamental vehicle design parameters.

COST ANALYSIS

Selection of a feasible pavement design based on a life-cycle analysis considers not only the initial construction costs but also other costs incurred during a life-cycle period which include maintenance and rehabilitation costs, user costs and salvage value, as illustrated in Figure 14. Interest rates and inflation factors should also be examined with relation to these costs. The cost component can be broken into two broad categories, i.e., agency costs expenditures and user cost expenditure.

Agency Expenditures

The direct agency cost expenditures required in any life-cycle analysis include:

1. construction
2. restoration, rehabilitation, resurfacing, and reconstruction
3. periodic maintenance
4. routine maintenance
5. pavement salvage value

Additionally, funds are expended in surveying the pavements to determine their condition and thorough testing to characterize materials to establish designs for resurfacing, restoration, rehabilitation and maintenance programs. Finally, the highway agency must administer each of the above activities and, therefore, have various facilities and personnel expenses making up an overhead burden that should be included in each of the costs activities.

Collecting information on rehabilitation falls into two categories:

1. Prepare pavement for rehabilitation
2. Rehabilitate pavement

When a pavement requires rehabilitation, the same corrective measures can vary considerably in costs due to the extent of deterioration present at the time the pavement is rehabilitated. Initial construction and rehabilitation cost data could be collected from contractor's payments. Maintenance costs should be extracted from the experience of the agency, preferably through an analysis of the agency's maintenance management system data base.

The residual value of the pavement structure at the end of the analysis period needs to be recognized in the economic analysis. Conceptually, the salvage value is equivalent to how much the pavement structure is "worth" at the end of its design life. However, since different life-cycle rehabilitation strategies can produce different pavement performances, the remaining structures may be at different serviceability levels at the end of the analysis periods. Since pavements are rarely discarded, the differential serviceability levels at the end of the analysis period should be recognized in determining the salvage value.

User Expenditure

The user expenditures for highway transportation costs is generally much greater than the agency expenditures. However, highway agencies are sometimes reluctant to give adequate weight to user costs when making a LCC analysis. Anything done by the agency to reduce the user costs will generally reduce total transportation costs, even though agency expenditures may increase. Figure 16 demonstrates the sensitivity of vehicle operating cost to pavement performance.

The user costs which need to be quantified for a pavement life-cycle costs analysis include:

1. vehicle operating costs,
2. travel time costs,
3. accident costs, and
4. discomfort costs.

Since speed and vehicle operating mode have a direct and strong influence on user costs, it is necessary to examine the impact of roadway parameters and pavement condition on operating speeds. In addition to the direct relationship between pavement condition and vehicle operating costs, there is a subtle indirect relationship in the interaction between pavement condition, operating speed and vehicle operating costs, which may be more important than the direct relationship. The Federal Highway Administration has a research project with Texas Research and Development Foundation for the development of a user-costs computer program.

LIFE-CYCLE COSTING AND OPTIMIZATION

In a life cycle cost analysis, several alternatives to providing a pavement for the design period must be analyzed. A method must be selected for placing all alternatives on a comparable basis. Figure 17 illustrates a straight forward method computing the life-cycle cost of a design alternative over the analysis period.

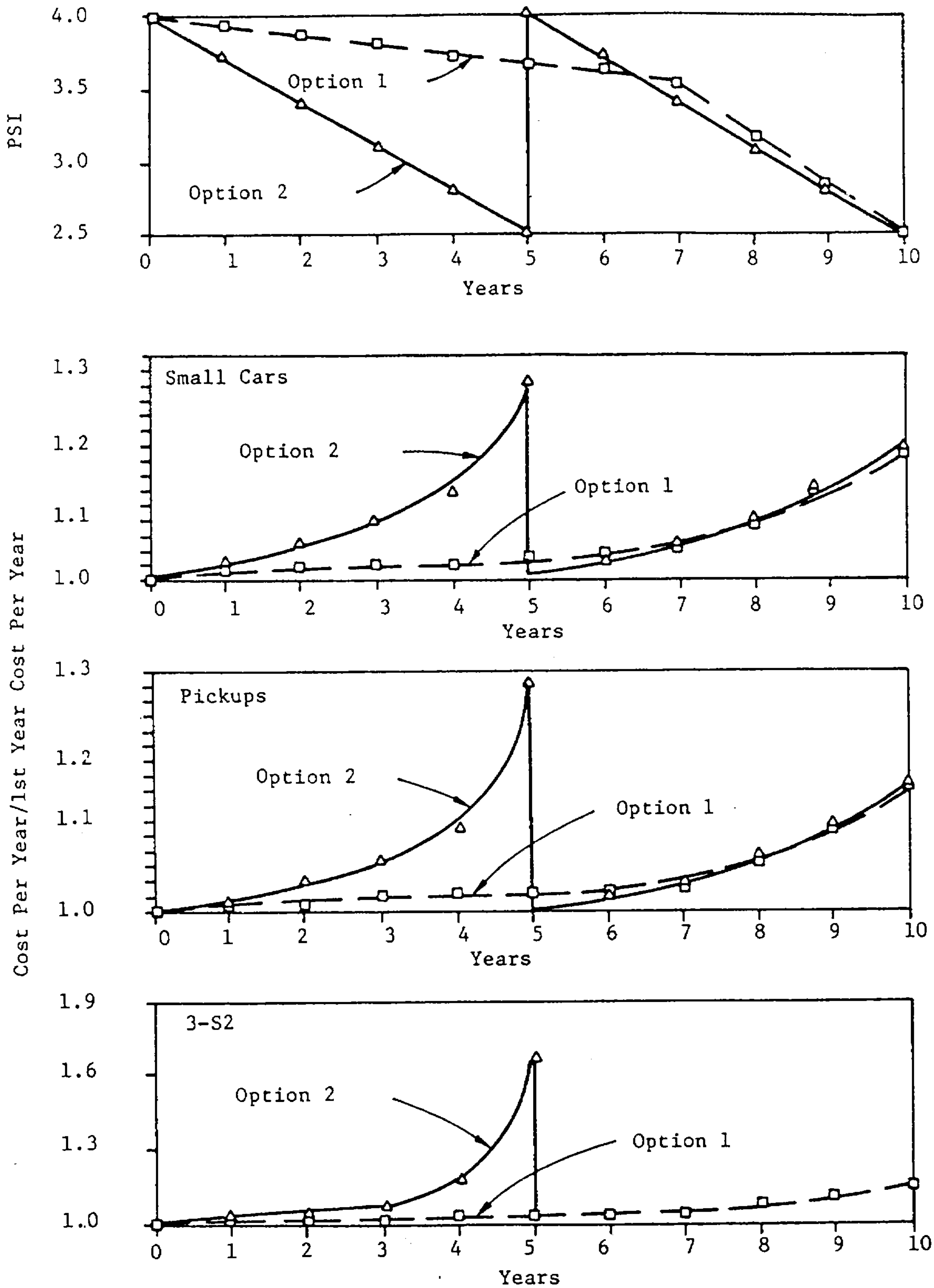


Figure 16. Influence of roughness of operating cost (Ref 27).

ECONOMIC EVALUATION PROCEDURES

An economic analysis procedure provides the basis for selecting the best alternative, but it does not provide a decision. An optimization model is needed for that purpose. Interest rates and inflation are extremely important factors in an economic analysis. Many authors have addressed the use of interest and inflation in an economic analysis (Refs 43, 44, 45, and 46).

Discount Rate or Time Value of Money

The significant key to LCC analysis is the economic evaluation. A discount rate is used to adjust future costs or benefits to present-day value, but it should not be confused with interest rate, which is associated with the actual cost of borrowing money. No reasonable economic analysis can be carried out without the use of a discount rate. In the pavement field, discount rates range from 4 to 10 percent. An important concept in the use of a discount rate is the opportunity cost of capital (Ref 44). Funds used for a pavement project are collected from the private sector, either by taxation or by borrowing, or from the government itself by diverting funds from other purposes. If left in the private sector, such funds would earn a return. If the funds are diverted to government use, the true cost of the diversion is the return that would otherwise have been earned. That cost is the opportunity cost of capital and is the correct discount rate for life-cycle costing of pavement design alternatives.

The use of inflation in a LCC analysis is also of concern to pavement management decision makers. Basically, inflation should not be used in the evaluation, except where substantial evidence exists that real prices will change (i.e., "real price" is the price in constant-value money). Lee and Grant in 1965 (Ref 45) suggest inflation should be ignored when forecasting future prices, costs, and benefits, and that current levels of prices should be used. An exception may be the cost of land (also applied to the road project as a whole) or inflation in the cost of money itself.

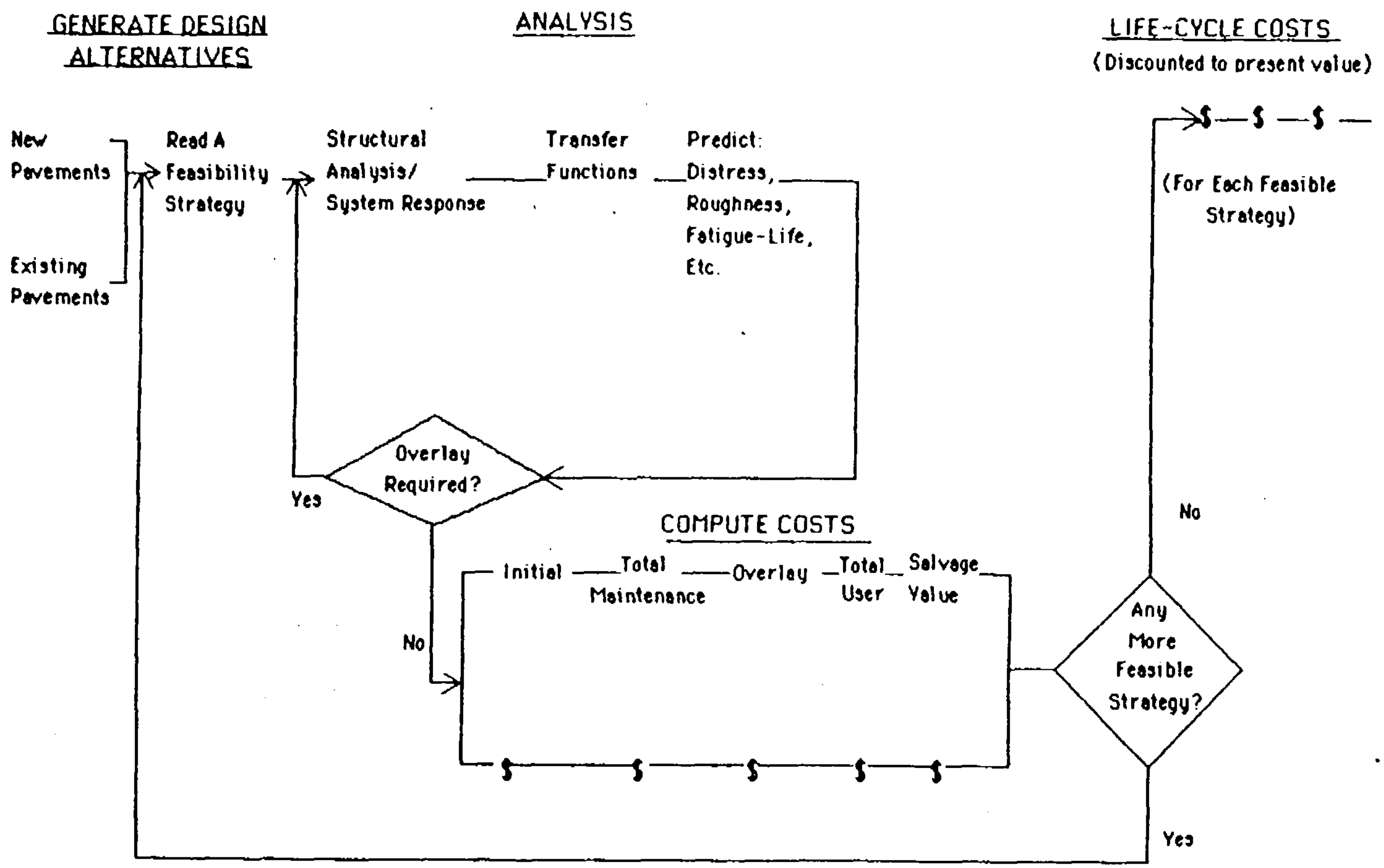


Figure 17. A conceptual illustration of life cycle costing. (Ref 27)

General inflation may be defined as an increase in the general level of prices and income throughout the economy. It should not be confused with differential price change which is the difference between the price trend of the goods and services being analyzed and the general price trend. Distortions in the analysis caused by general inflation can be avoided by appropriate decisions regarding the discount rate and the treatment of future costs. The discount rate should represent the opportunity cost of capital (prime interest). However, the market or nominal rate of interest includes an allowance for expected inflation as well as a return that represents the real cost of capital. For example, a market interest rate of interest of 12 percent may well represent a 7 percent opportunity cost component and a 5 percent inflation component.

Economic Analysis Methods

There are a number of methods of economic analysis applicable to the evaluation of alternative pavement design strategies.

1. Equivalent uniform annual cost method, often simply termed the "annual cost method"
2. Present worth method for:
   - (a) Cost,
   - (b) Benefits, or
   - (c) Benefits minus costs, usually termed the "net present worth" or "net present value method"
3. Rate-of-return method
4. Benefit-cost ratio method
5. Cost-effectiveness method

The mathematical details of the various economic analysis methods have been set out by several authors and do not need to be set forth here. After reviewing the practices of other highway agencies and evaluating the economic analysis methods, the net present value method is recommended.

Advantages and Disadvantages of the Net Present Value Method. There are a number of advantages inherent in the net present value method that make it perhaps the most feasible method for the highway field in comparison to the "traditional" annual cost and benefit-cost methods. These advantages include the following:

1. The benefits and costs of a project are related and expressed as a single value.
2. Projects of different service lives, and with stage development, are directly and easily comparable.
3. All monetary costs and benefits are expressed in present-day terms.
4. Non-monetary benefits (or costs) can be evaluated subjectively and handled with a cost-effective evaluation.
5. The answer is given as a total payoff for the project.
6. The method is computationally simple and straightforward.

There are several disadvantages to the net present value method, including the following:

1. The method cannot be applied to single alternatives where the benefits of those single alternatives cannot be estimated. In such cases, each alternative must be considered in comparison to the other alternatives, including the standard or base alternative.

2. The results, in terms of a lump sum, may not be easily understandable to some people as a rate of return or annual cost. In fact, the summation of costs in this form tend to act as a deterrent to investment in some cases.

The advantages offered by net present value outweigh the disadvantages. The other methods may, under certain situations, give incorrect or ambiguous answers.

INTEGRATION OF LCC WITH ADOT PRACTICES

According to Peterson (Ref 29), ADOT uses a lowest initial cost criteria for the selection of pavement design. As demonstrated in this chapter, Life Cycle Cost analysis is clearly superior to the initial cost method; particularly for the analysis of urban freeways where user costs are a major consideration. Development of a life cycle cost methodology for Arizona is entirely feasible and can be accomplished for a relatively low cost by building upon the experience of others. The steps for developing a LCC methodology are:

1. Obtain models from other states, particularly from Alaska, Texas and Pennsylvania (Ref 31, 42, 43).

2. Examine each computer program for modular design for ease of modification and throughness of the life cycle cost treatment.

3. Examine in particular the pavement performance models. The economic analysis models are universal and may generally be applied without concern for location. The pavement performance models are geographically bound and therefore would be prime candidates for revision.

4. Study the sensitivity of the LCC model to the parameters important for the design of pavements in Arizona.

5. Modify the models as required.

These steps will lead to a very suitable LCC model. However, it should be understood that the development of the final model will probably require several iterations through steps 3, 4, and 5.

Eventually, the pavement performance models should be developed from the pavement condition data base. However, this takes a great deal of time. In about 1972, McCullough initiated research into the performance of CRC pavements in Texas. The first comprehensive condition survey was in 1974. In 1979, the condition data were analyzed to determine the pavement condition rating scores and preliminary performance models.

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