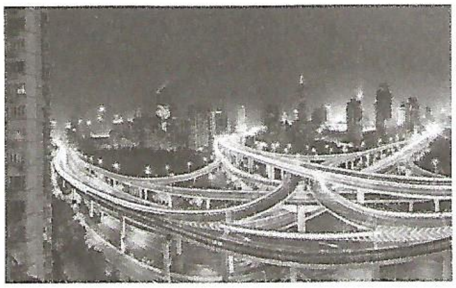
CHAPTER 21



Pavement Management

The nation's highway system will be required to accommodate increasing numbers of motor vehicles during the coming decades. Accordingly, rehabilitation of the existing system has become a major activity for highway and transportation agencies. With the nation's interstate highway system completed, the focus is shifting from new construction to maintaining, preserving, and rehabilitating highway assets. Preserving and managing the nation's highways is a challenge, and transportation professionals are investigating tools and techniques to assist in this endeavor. This chapter discusses pavement management strategies and the data required to evaluate pavement condition.

CHAPTER OBJECTIVES:

- Understand the problems of pavement rehabilitation.
- Learn the methods used to establish roadway pavement condition.
- Predict pavement condition using mathematical models.
- Identify and apply strategies to rehabilitate pavements or to correct deficiencies.
- Analyze and select a program of pavement rehabilitation based on condition assessment, priority assessment, and optimization.

21.1 PROBLEMS OF HIGHWAY REHABILITATION

A major problem that faces highway and transportation agencies is that the funds they receive are usually insufficient to adequately repair and rehabilitate every roadway section that deteriorates. The problem is further complicated in that roads may be in poor condition but are still usable, making it easy to defer repair projects until conditions become unacceptable. Roadway deterioration is not usually the result of poor design and construction practices but is caused by the inevitable wear and tear that occurs over a period of years. The gradual deterioration of a pavement occurs due to many factors, including variations in climate, drainage, soil conditions, and truck traffic. Just as a piece of cloth eventually tears asunder if a small hole is not immediately repaired, so too will a roadway unravel if its surface is allowed to deteriorate. Lack of funds often limits timely repair and rehabilitation of transportation facilities, causing a greater problem with more serious pavement defects and higher costs.

Because funds and personnel are often inadequate to address needs, the dilemma faced by many transportation agencies is to balance their work program between preventive maintenance activities and projects requiring immediate corrective action. When preventive maintenance has been neglected, roads will begin to deteriorate such that the basis for rehabilitation will be the extent of complaints by road users. The traveling public is unwilling to tolerate pavements that are extremely rough and cause vibration and severe damage to their vehicles. Poor-quality pavements may cause crashes to occur, and user costs will significantly increase. Ideally, preventive maintenance will be carried out in an orderly and systematic way and will be the least expensive approach in the long run. However, when funds are extremely limited, agencies often respond to either the most pressing and severe problems or the ones that generate the most vocal complaints.

21.1.1 Approaches to Pavement Management

The term *pavement management* refers to the various strategies that can be used to select a pavement restoration and rehabilitation policy. At one extreme, there is the "squeaky wheel" approach, wherein projects are selected because they have created the greatest attention. At the other extreme is a system wherein all roads are repaired on a regular schedule, for which money is no object. In realistic terms, pavement rehabilitation or repair strategies are plans that establish minimum standards for acceptable pavement condition and seek to establish the type of treatment required to maintain a minimum level of serviceability and the time frame for project completion. Rehabilitation management strategies include consideration of items such as pavement condition; first cost; annual maintenance; user costs; and safety, physical, environmental, and economic constraints. Life-cycle cost analysis is the basis for pavement management and consists of the total cost of the project, including initial construction, routine maintenance, and major rehabilitation activities over the lifetime of the pavement.

Pavement management is a systematic process for maintaining, upgrading, and operating physical pavement assets in a cost-effective manner. The process combines applications of established engineering principles with sound business practices and economic theory, thus assuring an organized and scientific approach to decision making.

Pavement management involves the following steps: (1) assess present pavement condition, (2) predict future condition, (3) conduct an alternatives analysis, and (4) select an appropriate rehabilitation strategy. The aforementioned process utilizes a computer-driven protocol called the pavement management system, which consists of the following elements: (1) an inventory and condition database, (2) mathematical models to forecast future pavement condition, (3) procedures for conducting alternative analyses, and (4) reporting and visualization tools to facilitate the interpretation and display of results.

21.1.2 Levels of Pavement Management

The total framework for pavement management illustrated in Figure 21.1 consists of two levels: the network level and the project level.

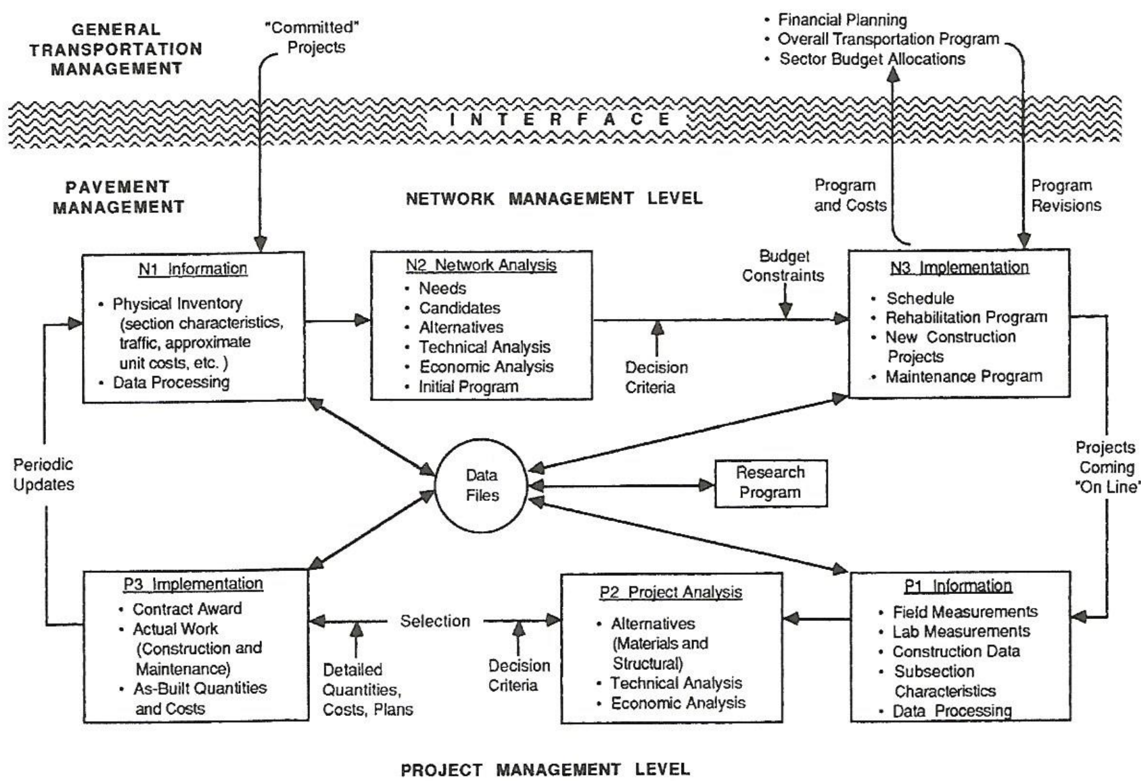


Figure 21.1 Framework for Total Pavement Management System

SOURCE: R. Haas, W. R. Hudson, and J. Zaniewski, *Modern Pavement Management*, Krieger Publishing, Malabar, FL, 1994, p. 38. Used with permission

The network level is concerned with the entire highway network and all of the pavement sections that comprise the system. At the network level, the pavement management process is strategic and seeks answers to questions such as:

1. What is the current condition of the pavement network?
2. What resources in time, material, and personnel will be required to maintain the network at a specified performance standard?
3. What should be the annual work program to address the most critical needs that reflect available resources?

Since the scope is system-wide, appropriate data are less precise than required for a pavement segment analysis. The data used by the network-level management process are typically less detailed than those required by the project-level process.

At the project level, attention is directed toward determining the maintenance and/or rehabilitation action needed to preserve a specific element or project (i.e., a pavement segment) that has been selected by the network-level process. A detailed condition evaluation survey is typically conducted for each project, and the most cost-effective strategy is selected based upon life-cycle cost analysis. The level of detail of the data required is greater than that at the network level. Furthermore, the project level does not consider resources that are required to maintain other elements in the network. Network-level analysis is emphasized in this chapter, as this is the essence of pavement management, whereas the project level is typically associated with pavement engineering and has been discussed in Chapters 18 through 20.

21.1.3 Importance of Pavement Condition Data

The first step in the process of pavement management is to secure data about the condition of each pavement section in the system. Originally, condition data were obtained by visual inspection that established the type, extent, and severity of pavement condition. However, they were subjective and relied heavily on judgment and experience for determining pavement condition and program priorities. Although such an approach can be appropriate under certain circumstances, possibilities exist for variations among inspectors, and experience is not easily transferable. In more recent years, visual ratings have been supplemented with standardized testing equipment to measure pavement roughness, pavement distress, pavement structural condition, and skid resistance, as described in the next section.

Pavement condition data are used for the following purposes:

1. *Establishing project priorities.* Data on pavement condition are used to establish the relative condition of each pavement and to establish project priorities. There are several methods of data acquisition, and each state selects that combination of measures it considers most appropriate.
2. *Establishing options.* Pavement condition data can be used to develop a long-term rehabilitation program. Data about pavement condition in terms of type, extent, and severity are used to determine which available rehabilitation options should be selected.
3. *Forecasting performance.* By use of correlations between pavement performance indicators and variables such as traffic loadings, it is possible to predict the likely future condition of any given pavement section. This information is useful for preparing long-range budget estimates of the cost to maintain the highway system at a minimum standard of performance or to determine future consequences of various funding levels.

21.2 METHODS FOR DETERMINING ROADWAY CONDITION

Four characteristics of pavement condition are used in evaluating pavement rehabilitation needs: (1) pavement roughness (rideability), (2) pavement distress (surface condition), (3) pavement deflection (structural failure), and (4) skid resistance (safety). These characteristics are described in the following sections.

21.2.1 Pavement Roughness

Pavement roughness refers to irregularities in the pavement surface that affect the smoothness of the ride. The serviceability of a roadway was initially defined in the AASHTO road test: a national pavement research project. Two terms were defined: (1) present serviceability rating (PSR) and (2) present serviceability index (PSI).

PSR is a number grade given to a pavement section based on the ability of that pavement to serve its intended traffic. The PSR rating is established by observation and requires judgment on the part of the individual doing the rating. In the original AASHTO road test, a panel of raters drove on each test section and rated the performance of each section on the basis of how well the road section would serve if the rater were to drive his or her car over a similar road all day long. The ratings ranged between 0 and 5, with 5 being very good and 0 being impassable. Figure 21.2 illustrates the PSR

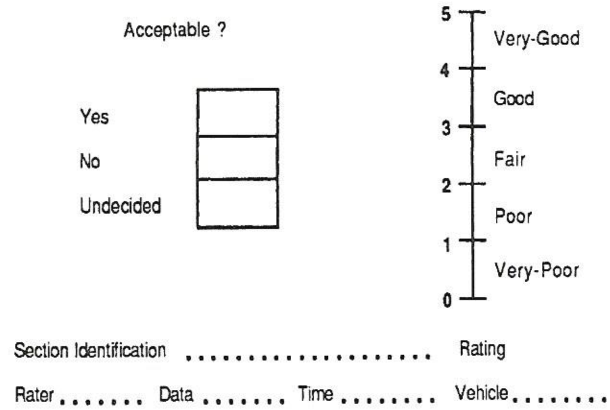


Figure 21.2 Individual Present Serviceability Rating

SOURCE: R. Haas, W. R. Hudson, and J. Zaniewski, *Modern Pavement Management*, Krieger Publishing, Malabar, FL, 1994, p. 80. Used with permission

as used in the AASHTO road test. Serviceability ratings are based on the user's perception of pavement performance and are determined from the average rating of a panel of road users.

PSI is a value for pavement condition determined as a surrogate for PSR and is based on physical measurements. PSI is not based on panel ratings, as the primary measure of PSI is pavement roughness. The PSI is an objective means of estimating the PSR, which is subjective.

The performance of a pavement can be described in terms of its PSI and traffic loading over time, as illustrated in Figure 21.3. For example, when a pavement is originally constructed, it is in very good condition, with a PSI value of 4.5 (see Figure 21.4). Then

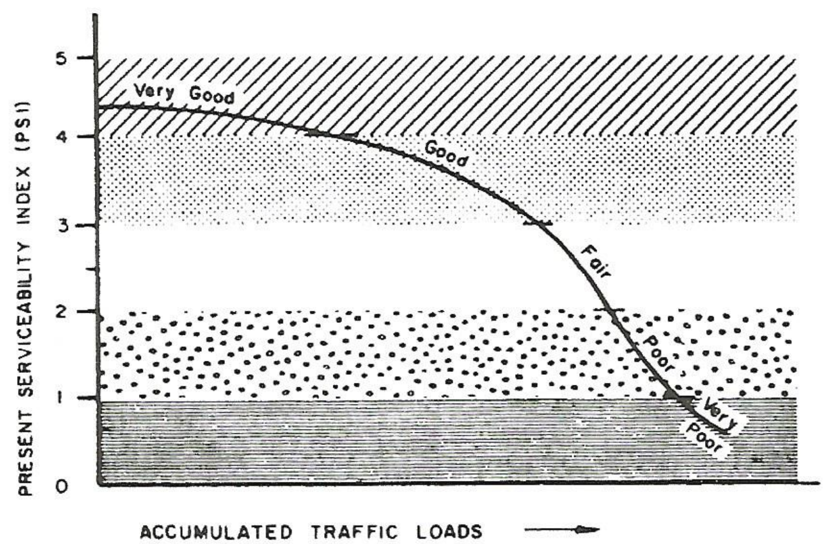


Figure 21.3 Typical Pavement Performance Curve

SOURCE: Modified from Peterson, D.E., NCHRP Synthesis 135: *Pavement Management Practices*, Transportation Research Board, National Research Council, Washington, D.C., 1987

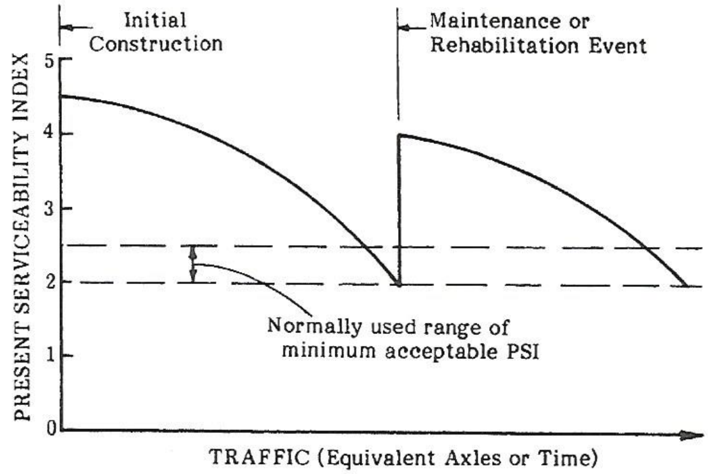


Figure 21.4 Performance History for Pavement Using PSI

SOURCE: Copas, T.L. and H.A. Pennock, *Collection and Use of Pavement Condition Data*, Transportation Research Board, National Research Council, Washington, D.C., 1981

as the number of traffic loadings increases, the PSI declines to a value of 2, which can be the minimum acceptable PSI value. After the pavement section is rehabilitated, the PSI value increases to 4; as traffic loads increase, the PSI declines again until it reaches 2 and rehabilitation is again required.

Equipment for measuring roughness is classified into two basic categories: response type and profilometers. Response-type equipment does not measure the actual profile of the road but rather the response of the vehicle to surface roughness. Equipment used includes: (1) Mays Ride Meter (MRM), (2) Bureau of Public Roads (BPR) Roughmeter, and (3) Cox Road Meter. The Mays Ride Meter (see Figure 21.5) measures the number of inches of vertical movement per mile: the greater the vertical movement, the rougher the road.

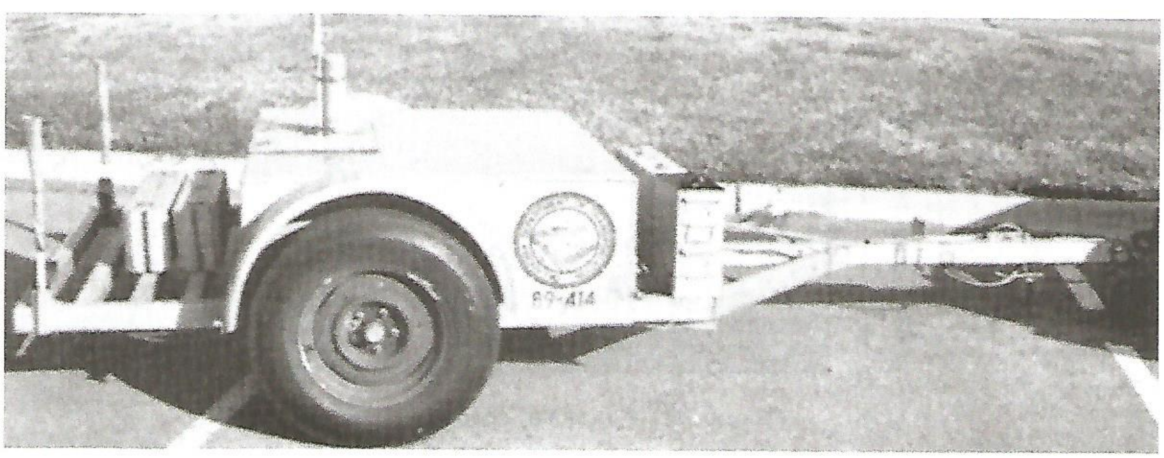


Figure 21.5 Mays Ride Meter Trailer Unit

SOURCE: Epps, J.A. and C.L. Monismith, NCHRP Synthesis of Highway Practice 126: *Equipment for Obtaining Pavement Condition and Traffic Loading Data*, Transportation Research Board, National Research Council, Washington, D.C., 1986

Originally, some type of car-mounted meter was used. The advantages are low cost, simplicity, ease of operation, capability for acquisition of large amounts of data, and output correlated with PSI. However, the vehicle itself influences the measure obtained, and now meters are usually towed in trailers. Response-type equipment must be calibrated frequently to ensure reliable results. Accordingly, such equipment is not widely used.

Profilometers are devices that measure the true profile of the roadway and provide accurate and complete reproductions of the pavement profile. Profilometers also eliminate the need for the time-consuming and labor-intensive calibration required for response-type equipment performance.

There are several types of profilometers. Some equipment uses inertial profilometry that includes the following basic components.

- A device to measure the distance between the vehicle and the road surface
- An inertial referencing device to compensate for the vertical movement of the vehicle body
- A distance odometer to locate the profile points along the pavement
- An on-board processor for recording and analyzing data

Acoustic or optic and laser devices are used for measuring the distance between the pavement surface and the vehicle, d_p. Acoustic systems are more widely used because of their lower cost and the reliability and adequacy of results. Figure 21.6 illustrates a surface dynamics profilometer.

The inertial referencing device is usually either a mechanical or electronic accelerometer mounted to represent the vertical axis of the vehicle. The accelerometer measures the vertical acceleration of the vehicle body. These accelerations are then integrated twice to determine the vertical movement, d_v. These movements are added to the distance measurements d_p to obtain elevations of the pavement profile. Some profilometers record the actual profile, whereas others process the data on board and give only a roughness summary statistic.

The two most popular models of profilometers are the K. J. Law profilometer and the South Dakota profilometer. The K. J. Law profilometer measures and records the road surface profile in each of the vehicle's two wheel paths. An optical measuring system, based on reflectivity from the road surface, and an accelerometer are used together to measure both the distance between the vehicle and the road surface and the vehicle vertical movement. Operating speeds range between 10 and 55 mi/hr. The South Dakota profilometer is used by most states. It costs less than the K. J. Law profilometer, although it is not as accurate. It has two additional sensors that can be used to automatically measure rut depth. Data can be collected at normal highway speeds, and about 700 miles of pavement can be measured within a single week.

A relationship exists among pavement roughness, distress condition, and crash frequency. The impact of rutting, road surface roughness, and the pavement PSI on crash frequency and crash type indicates that PSI is a pavement condition parameter that has a significant impact on crash frequency for all types of crashes considered (i.e., single-vehicle crashes, rear-end crashes, angle crashes, and sideswipe crashes). Lower values of the PSI are associated with a higher crash frequency. Moreover, improving the PSI by one unit (for example, from 3.0 to 4.0) can result in a decreased crash frequency.

21.2.2 Pavement Distress

The term *pavement distress* refers to the condition of a pavement surface in terms of its general appearance. A perfect pavement is level and has a continuous and unbroken surface. In contrast, a distressed pavement may be categorized as either fractured,

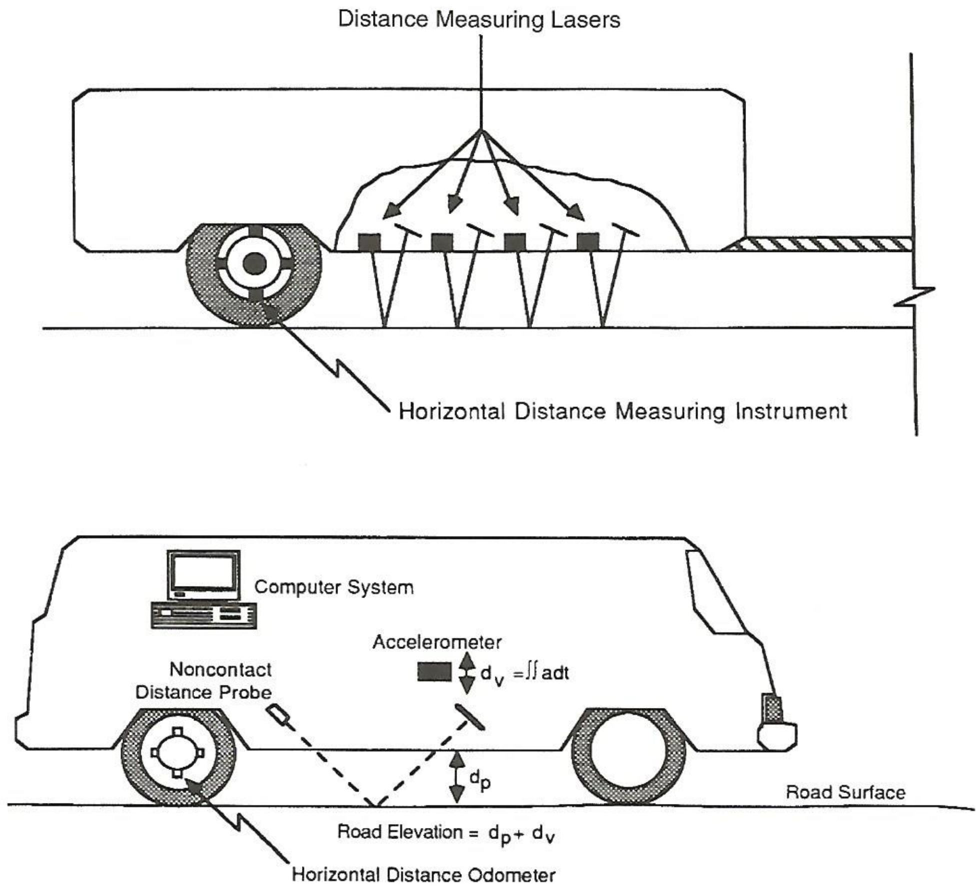


Figure 21.6 Example of Surface Dynamics Profilometer

SOURCE: R. Haas, W. R. Hudson, and J. Zaniewski, *Modern Pavement Management*, Krieger Publishing, Malabar, FL, 1994, p. 85. Used with permission

distorted, or disintegrated, or a combibation of distress types. These categories can be further subdivided. For example, fractures can be seen as cracks or as spalling (chipping of the pavement surface). Cracks can be further described as generalized, transverse, longitudinal, alligator, and block. Ruts or corrugation of the surface may be evidence of pavement distortion.

Pavement disintegration can be observed as raveling (loosening of pavement structure), stripping of the pavement from the subbase, and surface polishing. The types of distress data collected for flexible and rigid pavements vary from one state to another. Figure 21.7 lists the three pavement distress groups, the measure of distress, and the probable causes.

Many highway agencies use some measure of cracking in evaluating the condition of flexible pavements. The most common measures are transverse, longitudinal, and alligator cracks. Distortion is usually measured by determining the extent of rutting. Disintegration is measured by the amount of raveling. Each state or federal agency has its own procedures for measuring pavement distress. Consequently, there are many methods used to conduct distress surveys. Typically, the agency has a procedural manual that defines each element of distress, with instructions as to how these are to be rated

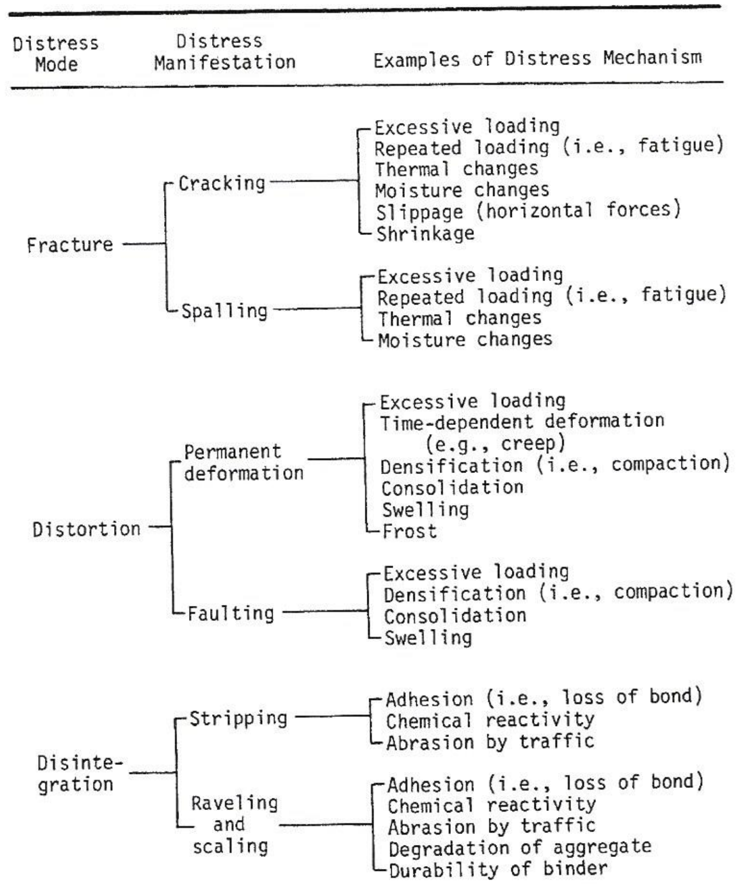


Figure 21.7 Pavement Distress Groups and Their Causes

SOURCE: Copas, T.L. and H.A. Pennock, *Collection and Use of Pavement Condition Data*, Transportation Research Board, National Research Council, Washington, D.C., 1981

on a given point scale. The survey forms distinguish between bituminous and Portland cement concrete pavements. For bituminous pavements, the items observed are corrugations, alligator cracking, raveling, rutting, longitudinal cracking, transverse cracking, roughness, and patching. For Portland cement concrete, the measures are cracking, raveling, joint spalling, faulting, and patching.

Distress data may be obtained by employing trained observers to make subjective judgments about pavement condition based on predetermined factors. Often, photographs are used for making judgments. Some agencies use full sampling, while others randomly select pavement sections.

Measurements are usually made on a regular schedule of one to three years. After the data are recorded, the results are condensed into a single number called a *distress* (or *defect*) *rating* (DR). A perfect pavement is usually given a score of 100; if distress is observed, points are subtracted. The general equation is

$$DR = 100 - \sum_{i=1}^{n} d_i w_i \tag{21.1}$$

where

d_i = the number of points assigned to distress type i for a given severity and frequency
n = number of distress types used in rating method
w_i = relative weight of distress type i

One of the major problems with condition or distress surveys is the variability in results due to the subjective procedures used. Other causes of error are variations in the condition of the highway segment observed, changes in evaluation procedure, and changes in observed location from year to year. The safety of pavement evaluators is of considerable concern.

Problems with manual measurements have been minimized through development of automated techniques for evaluating pavement distress. Film and video devices are used to record continuous images of the pavement surface for later evaluation; survey crews are not required to personally observe the pavement under hazardous traffic conditions, and a permanent record of the surface condition is created. There are many types of automated distress survey equipment, and the technology is constantly being improved.

The PASCO corporation has been developing a distress survey device since the 1960s. Figure 21.8 illustrates the PASCO ROADRECON system, which produces a continuous filmstrip recording of the pavement surface and a measure of roughness.

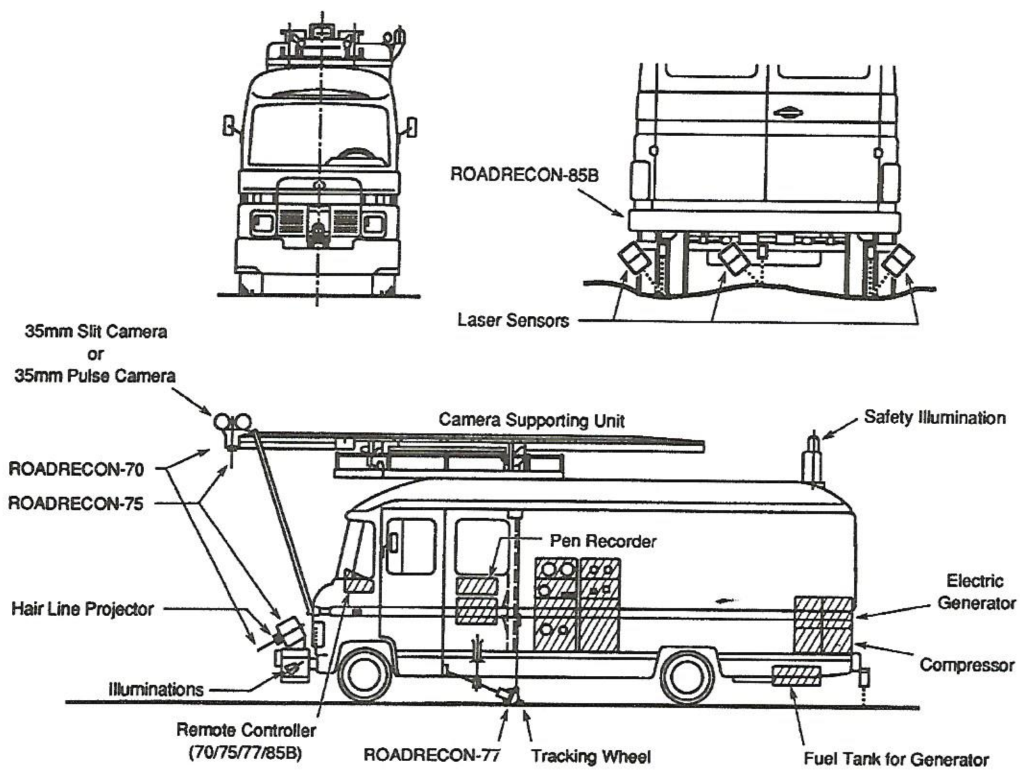


Figure 21.8 PASCO ROADRECON System for Distress Evaluation

SOURCE: R. Haas, W. R. Hudson, and J. Zaniewski, *Modern Pavement Management*, Krieger Publishing, Malabar, FL, 1994, p. 145. Used with permission

Photographs are taken at night with a controlled amount and angle of lighting. The vehicle can operate at speeds up to 50 mi/h. Manual interpretation of the photographs is still required for evaluating pavement distress. Computer vision technology is available to analyze images without human intervention.

Example 21.1 Computing Distress Rating of a Pavement Section

A pavement rating method for a certain state uses the following elements in its evaluation procedure: longitudinal or alligator cracking, rutting, bleeding, ravelling, and patching. The weighting factors are 2.4, 1.0, 1.0, 0.9, and 2.3, respectively. Each distress element is characterized by (1) its severity as not severe, severe, or very severe; and (2) its frequency as none, rare, occasional, or frequent. The categories for frequency are based on the percentage of area affected by a particular distress within the area of the section surveyed. For each combination of severity and distress, a rating factor is assigned, d_{id}, from 0 to 9, as shown in Table 21.1.

A one-mile section of roadway was observed with results shown in Table 21.2. Calculate the distress rating for the section.

Solution: Using the data in Table 21.2 and the rating factors (d_i) in Table 21.1, each distress is categorized with factors as follows.

Distress Characteristic	*Rating Factor, d_i*	*Weight, w_i*
Cracking	1	2.4
Rutting	4	1.0
Bleeding	9	1.0
Raveling	0	0.9
Patching	2	2.3

Applying the weighting values for each characteristic, the distress rating for the section is determined using Eq. 21.1:

$$\text{DR} = 100 - \sum_{i=1}^{n} d_i w_i$$

$$= 100 - (1 \times 2.4 + 4 \times 1 + 9 \times 1 + 0 \times 0.9 + 2 \times 2.3)$$

$$= 100 - 20 = 80$$

Table 21.1 Rating Factor, d_{id}, Related to Severity and Frequency

	Severity		
Frequency	*Not Severe (NS)*	*Severe (S)*	*Very Severe (VS)*
None (N)	0	0	0
Rare (R)	1	2	3
Occasional (O)	2	4	6
Frequent (F)	3	6	9

Table 21.2 Observed Distress Characteristics for Road Segment

Distress Characteristic	*Frequency*	*Severity*
Cracking	R	NS
Rutting	O	S
Bleeding	F	VS
Raveling	N	NS
Patching	R	S

Pavement Condition Index (PCI)

The Pavement Condition Index (PCI) is a widely used pavement distress index developed by the U.S. Army Corps of Engineers. PCI values range from 0 to 100 and are based on a visual condition survey that measures distress type, severity, and extent of pavement damage. The distress types that can be considered when using the PCI include the following.

- **Alligator cracking**. A series of interconnecting cracks that are caused by fatigue failure of the pavement surface under the repeated traffic loadings.
- **Bleeding**. A film of bituminous material on the pavement surface that becomes viscous when warm. It is caused by excessive amounts of bituminous material in the asphalt mix.
- **Block cracking**. Interconnected cracks that divide the pavement into rectangular pieces.
- **Corrugation**. A series of closely spaced ridges and valleys occurring at regular intervals.
- **Depressions**. Localized areas that are below the surrounding surface causing a "bowl-like" shape.
- **Longitudinal** and **tranverse cracking**. Cracks that are parallel or orthogonal to the centerline of the pavement.
- **Rutting**. A surface depression typically along the wheel paths of a road.
- **Raveling**. Wearing of the pavement surface caused by aggregate particles breaking loose and the loss of bituminous material binder.

For each distress type, the values to be deducted are determined by selecting a value from a chart or graph based on the survey results. Additional details regarding PCI calculations can be found in the references at the end of the chapter.

21.2.3 Pavement Structural Condition

The structural adequacy of a pavement is measured either by nondestructive means, which measure deflection under static or dynamic loadings, or by destructive tests, which involve removing sections of the pavement and testing them in the laboratory. Structural condition evaluations are rarely used by state agencies for monitoring network pavement condition due to the expense involved. However, nondestructive evaluations, which gather deflection data, are used by some agencies on a project basis for pavement design purposes and to develop rehabilitation strategies.

Nondestructive structural evaluation is based on the premise that measurements can be made on the surface of the pavement and *in situ* characteristics can be inferred from these measurements about the structural adequacy of the pavement. The four basic nondestructive test methods are (1) measurements of static deflection, (2) measurements of deflections due to dynamic or repeated loads, (3) measurements of deflections from a falling load (impulse load), and (4) measurements of density of pavement layers by nuclear radiation (used primarily to evaluate individual pavement layers during construction). Deflection data are primarily used for design purposes and not for pavement management. Some states use deflection equipment solely for research and special studies.

One method for measuring static deflections is the Benkelman beam, which is a simple hand-operated device designed to measure deflection responses of a flexible pavement to a standard wheel load. A probe point is placed between two dual tires and the motion of the beam is observed on a dial that records the maximum deflection. Other static devices that are used include the traveling deflectometer, the plate-bearing test, and the Lacroix Deflectograph. Most of these devices are based on the Benkelman beam principle, in which pavement deflections due to a static or a slowly moving load are measured manually or by automatic recording devices.

Another method for measuring pavement deflections is the Dynaflect. This device, shown in Figure 21.9, consists of a dynamic cyclical force generator mounted on a two-wheel trailer, a control unit, a sensor assembly, and a sensor calibration unit. The system provides rapid and precise measurements of roadway deflections,

Figure 21.9 Dynaflect Deflection Sensors

SOURCE: Epps, J.A. and C.L. Monismith, NCHRP Synthesis of Highway Practice 126: *Equipment for Obtaining Pavement Condition and Traffic Loading Data*, Transportation Research Board, National Research Council, Washington, D.C., 1986

which in this test are caused by forces generated by unbalanced flywheels rotating in opposite directions. A vertical force of 1000 lb is produced at the loading wheels, and deflections are measured at five points on the pavement surface located 1 ft apart.

Most states use falling load-type equipment, referred to as "falling weight deflectometers" (FWDs), because force impulses created by a falling load more closely resemble the pulse created by a moving load than those created by either the vibratory or static load devices. Figure 21.10 illustrates the basic principle of a falling weight deflectometer.

Variations in the applied load may be achieved by altering either the magnitude of the mass or the height of drop. Vertical peak deflections are measured by the FWD in the center of the loading plate and at varying distances away from the plate. These data are used to draw what are known as "deflection basins."

21.2.4 Skid Resistance

Safety characteristics of a pavement are another measure of its condition, and highway agencies continually monitor this aspect to ensure that roadway sections are operating at the highest possible level of safety. The principal measure of pavement safety is its skid resistance. Other elements contributing to the extent to which pavements can perform safely are eliminating rutting (which causes water to collect that creates hydroplaning) and adequacy of visibility of pavement markings.

Skid resistance data are collected to monitor and evaluate the effectiveness of a pavement in preventing or reducing skid-related accidents. Skid data are used by highway

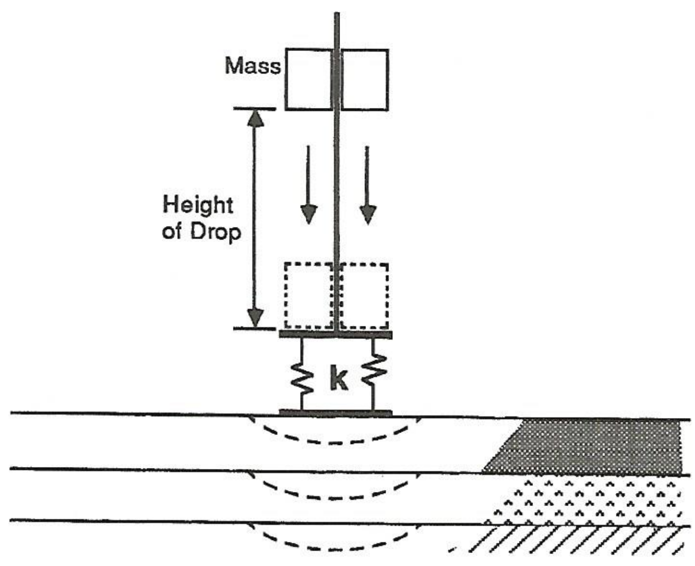


Figure 21.10 Principle of the Falling Weight Deflectometer

SOURCE: R. Haas, W. R. Hudson, and J. Zaniewski, *Modern Pavement Management*, Krieger Publishing, Malabar, FL, 1994, p. 120. Used with permission agencies to identify pavement sections with low skid resistance, to develop priorities for rehabilitation, and to evaluate the effectiveness of various pavement mixtures and surface types.

The coefficient of sliding friction between a tire and pavement depends on factors such as weather conditions, pavement texture, tire condition, and speed. Since skidding characteristics are not solely dependent on the pavement condition, it is necessary to standardize testing procedures and in this way eliminate all factors but the pavement. The basic formula for friction factor *f* is

$$f = \frac{L}{N} \tag{21.2}$$

where

L = lateral or frictional force required to cause two surfaces to move tangentially to each other
N = force perpendicular to the two surfaces

When skid tests are performed, they must conform to specified standards set by the American Society for Testing and Materials (ASTM). The test results produce a skid number SK, where

$$\text{SK} = 100f \tag{21.3}$$

The SK is usually obtained by measuring the forces obtained with a towed trailer riding on a wet pavement, equipped with standardized tires. The principal methods of testing are (1) locked-wheel trailers, (2) Yaw mode trailers, and (3) the British Portable Tester. Locked-wheel trailers, illustrated in Figure 21.11, are widely used skid-measuring devices. The test involves wetting the pavement surface and pulling a two-wheel trailer

Figure 21.11 Locked-Wheel Skid Trailer

SOURCE: Epps, J.A. and C.L. Monismith, NCHRP Synthesis of Highway Practice 126: *Equipment for Obtaining Pavement Condition and Traffic Loading Data*, Transportation Research Board, National Research Council, Washington, D.C., 1986

whose wheels have been locked in place. The test is conducted at 40 mi/h with standard tires each with seven grooves. The locking force is measured, and from this an SK value is obtained.

The Yaw mode test is done with the wheels turned at a specified angle to simulate the effects of cornering. The most common device for this test is a Mu-Meter, which uses two wheels turned at 7.5 degrees. The trailer is pulled in a straight line on a wetted surface with both wheels locked. Since both wheels cannot be in the wheel paths, friction values may be higher than those obtained by using a locked-wheel trailer.

The most common method for determining skid resistance is the locked-wheel trailer, and most state highway agencies own one or more of these devices. Several states use the Mu-Meter (a Yaw mode device). Figure 21.12 illustrates typical skid results for various pavement conditions. Skid resistance data are not typically used in developing rehabilitation programs. Rather, they are used to monitor the safety of the highway system and to assist in reducing potential crash locations.

High-skid-resistant pavements can help reduce the likelihood of skid-related crashes, whereas pavement surfaces with inadequate skid resistance can pose a safety risk. Skid resistance is a function of several factors, including pavement texture, tire condition, speed, and weather conditions such as rain or snow. Two parameters of pavement texture are: (1) micro-texture, which refers to fine-scale surface irregularities (≤ 1.0 mm depth) in the stone or aggregate particles making up the pavement mix; and (2) macro-texture, which refers to the large-scale roughness or variations in the road surface (in the range of 0.5 mm to 50 mm) at the pavement surface resulting from the way the aggregates are arranged. Both parameters have a direct impact on the pavement skid resistance, with micro-texture having the dominant impact at speeds less than 30 mi/h and macro-texture becoming more important at high speeds.

Mix design of asphalt can influence skid resistance and safety. However, the actual threshold value that may signal the need for pavement maintenance and rehabilitation on the basis of safety considerations is not fully understood. A skid number, SK, less than 35 suggests that a safety issue may exist.

Example 21.2 Measuring Skid Resistance

A 10,000-lb load is placed on two tires of a locked-wheel trailer. At a speed of 30 mi/h, a force of 5000 lb is required to move the device. Determine the SK and the surface type, assuming that treaded tires were used.

Solution:

$$\text{SK} = 100f = (100)\frac{L}{N}$$

$$= 100 \times \frac{5000}{10{,}000} = 50$$

From Figure 21.12, at 30 mi/h and SK = 50, the surface type is coarse-textured and gritty.

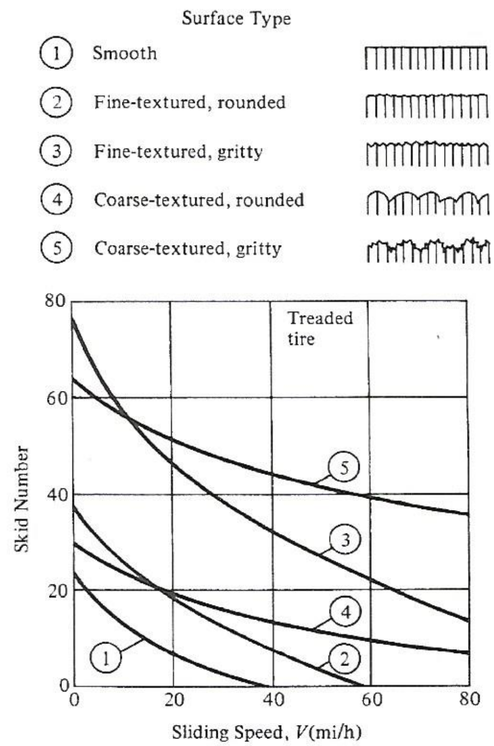


Figure 21.12 Skid Data for Various Pavement Surface Types

SOURCE: Redrawn from H.W. Kummer and W. E. Meyer, *Tentative Skid Resistance Requirements for Main Rural Highways*, NCHRP Report 37, Transportation Research Board, National Research Council, Washington, D.C., September 1967

21.2.5 Intelligent Transportation Systems and Pavement Condition Monitoring

In recent years, there has been increased interest in applying advances in information technologies (i.e., sensing, computing, communications, and control) to improve the efficiency, safety, resiliency, and environmental friendliness of the transportation system. This body of knowledge is based on Intelligent Transportation Systems (ITS), which envisions a totally networked environment supported by continuous wireless applications, such as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Other (V2O) communications.

Previous research to develop a fully integrated transportation system has focused on applications to improve the system's safety and efficiency. The envisioned system provides opportunities for pavement condition and ride quality monitoring. This potential is being investigated involving vehicles equipped with accelerometers and Global Positioning System (GPS) receivers. These devices can detect potholes and other types of pavement distress, but it is more challenging to pinpoint the spatial location of the pavement distress and thus to allow direct averaging of the results from the different vehicles. The ITS connected-vehicle approach is a potential option that collects pavement distress and ride quality data, thus supplementing methods currently in use.

21.3 PAVEMENT CONDITION PREDICTION

The results of pavement rating measurements can be used to predict pavement condition in future years. When data are collected over time, the results can be used to develop mathematical models that relate pavement condition to age of pavement. Condition prediction models are essential to the pavement management process at both the network and the project level. At the network level, prediction models forecast the future condition of the network and are the basis of budget planning, inspection scheduling of maintenance, and rehabilitation activities. At the project level, prediction models are used in specific project life-cycle cost analyses to select the most cost-effective maintenance and rehabilitation strategy.

Prediction models are used in forecasting deterioration trends of pavement sections before and after a major rehabilitation strategy has been selected. For example, these models can predict the condition of newly constructed sections as well as the condition of overlaid sections. There are two main approaches that have been considered to develop prediction models for pavements: (1) deterministic models, which are developed through regression analysis, and (2) probabilistic models, which are based on tables that furnish the probability of a pavement rating change from one year to the next. Each of these methods is described in the following sections.

21.3.1 Deterministic Models

Many states accumulate pavement distress data for specific roadway sections. As is expected, with pavement aging, the distress rating will decrease. Figure 21.13 illustrates the variation in pavement condition (PCR) versus age for pavements in the state of Washington. There is a wide range of results, suggesting that a pavement model should only be used in circumstances similar to those existing when the data were collected (i.e., climate, subgrade strength, axle loads, etc.). Prediction models (such as the one shown in Figure 21.13) can be used to predict future pavement condition, which is information that is required to determine appropriate rehabilitation programs. Two regression-based prediction models are presented: (1) family based and (2) multiple regression.

Family-Based Prediction Models

This approach is referred to as "family-based" because different pavement sections are segmented into groups or families in such a manner that all pavement sections in a specific group or family have similar deterioration trend characteristics. Group selection is based on factors such as traffic volumes, climate, structural strength, and surface type.

Having defined each group or family of pavement sections, regression analysis is used to develop a separate prediction model for each family. The dependent variable is the pavement's condition index (PCI), and the independent variable is the corresponding number of years (age) since the pavement was constructed or resurfaced. The single independent variable—age—is sufficient to predict pavement condition since all other variables are classified and thus similar for this data set (or "family"). Pavement sections have already been grouped into families with similar deterioration trends, thus accounting for other factors that affect deterioration.

This technique is used for the prediction model in MicroPAVER, a pavement management software package developed by the U.S. Army Corps of Engineers. Pavements are divided into families based on factors such as pavement type (asphalt concrete, Portland cement concrete, asphalt concrete overlay, etc.), roadway classification (primary,

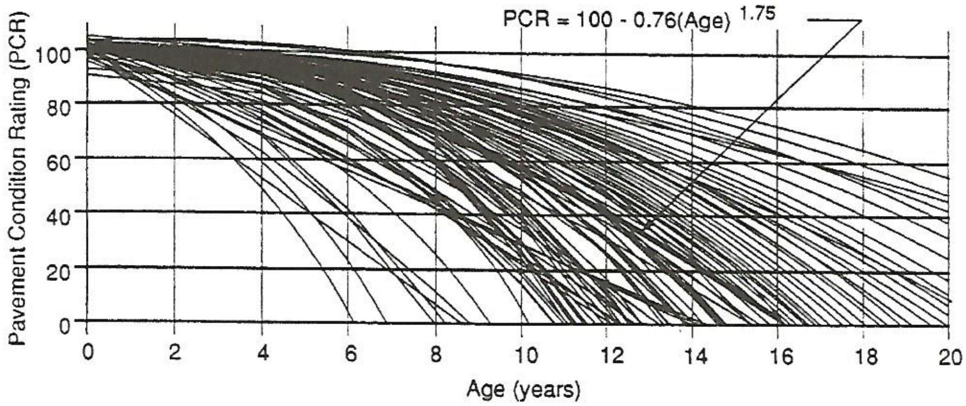


Figure 21.13 Pavement Condition versus Pavement Age

SOURCE: *An Advanced Course in Pavement Management Systems* (course text), Federal Highway Administration, Washington, D.C., 1990

secondary, etc.), and climatic conditions. For each family classification, MicroPAVER generates a data file that includes pavement section identification, age, and PCI. MicroPAVER contains a feature that allows the user to remove incorrect data points and outliers. The technique produces a mathematical fit to the data as a polynomial regression. This method for modeling curvature in the relationship between a response variable (y) and a predictor variable (x) extends a simple linear regression model by including higher order predictors, x^2 and x^3. Thus, the MicroPAVER model is expressed as follows.

$$P(x) = a_0 + a_1 + a_2x^2 + a_3x^3 + a_4x^4 \tag{21.4}$$

where

$P(x)$ = pavement condition index (PCI)
x = pavement age in years
$a_{0,1,2,3,4}$ = constants

By using the transformed variables (x^2, x^3, and x^4), a nonlinear model can be created using simple linear regression. The form of the model must be specified in advance. A characteristic of polynomial regression is that an increase in the slope of the curve can occur, which contradicts a physical reality that the pavement condition cannot improve as age increases. MicroPAVER recognizes this anomaly by imposing constraints on the regression to eliminate the contradiction.

Example 21.3 Developing a Family-Based Prediction Model

Table 21.3 lists inspection data that were recorded for a subset of pavement sections that are part of a statewide highway network. The PCI, the number of years since construction (age), the average annual daily traffic ($AADT$), and the structural number

(SN) are listed for each section. Develop a family-based prediction model based on the pavement section data in Table 21.3.

Solution: Based on the data shown in Table 21.3, the eight pavement sections are divided into two families based solely on the *AADT* values, since the values for the SN are not sufficiently distinctive to warrant further classification based on this independent variable. *AADT* values are segmented into two categories: (1) sections with an $AADT < 10{,}000$ veh/day/ln and (2) sections with an $AADT \geq 10{,}000$ veh/day/ln.

Table 21.3 Pavement Section Data

ID	*PCI*	*Age*	*AADT*	*SN*
1	100	0	8700	4.3
1	98	0.5	8700	4.3
1	96	1.2	8700	4.3
1	93	3	8700	4.3
1	87	5	8700	4.3
2	100	0	14,000	4.7
2	95	1	14,000	4.7
2	89	3	14,000	4.7
2	83	5	14,000	4.7
2	78	7	14,000	4.7
3	100	0	9800	4.1
3	93	2	9800	4.1
3	88	4	9800	4.1
3	86	7	9800	4.1
4	100	0	18,000	4.9
4	93	1.5	18,000	4.9
4	87	3.5	18,000	4.9
4	79	6	18,000	4.9
5	100	0	8000	4.2
5	95	2	8000	4.2
5	90	4	8000	4.2
5	83	8	8000	4.2
6	100	0	12,000	4.5
6	90	3	12,000	4.5
6	78	7	12,000	4.5
6	75	9	12,000	4.5
7	100	0	9500	4.4
7	92	3	9500	4.4
7	85	6	9500	4.4
7	82	9	9500	4.4
7	81	10	9500	4.4
8	100	0	17,000	4.8
8	91	2.5	17,000	4.8
8	84	4.5	17,000	4.8
8	75	8	17,000	4.8
8	71	10	17,000	4.8

Polynomial regression is used to develop the prediction models using an x^2 term such that the regression model is

$$\text{Pavement Condition Index, PCI} = a_0 + a_1(\text{age}) + a_2(\text{age})^2 \qquad (21.5)$$

Sections belonging to each family are shown in Tables 21.4 and 21.5, with the new variable (age^2) added.

Table 21.4 Family 1 Sections ($AADT < 10{,}000$)

ID	*PCI*	*Age*	*Age^2*
1	100	0	0
1	98	0.5	0.25
1	96	1.2	1.44
1	93	3	9
3	100	0	0
3	93	2	4
3	88	4	16
3	86	7	49
5	100	0	0
5	95	2	4
5	90	4	16
5	83	8	64
7	100	0	0
7	92	3	9
7	85	6	36
7	82	9	81
7	81	10	100

Table 21.5 Family 2 Sections ($AADT \geq 10{,}000$)

ID	*PCI*	*Age*	*Age^2*
2	100	0	0
2	95	1	1
2	89	3	9
2	83	5	25
2	78	7	49
4	100	0	0
4	93	1.5	2.25
4	87	3.5	12.25
4	79	6	36
6	100	0	0
6	90	3	9
6	78	7	49
6	75	9	81
8	100	0	0
8	91	2.5	6.25
8	84	4.5	20.25
8	75	8	64
8	71	10	100

A spreadsheet or statistical analysis software is used to determine the constant values, *a*, in the prediction models based on the data in Tables 21.4 and 21.5. The results are

$$\text{Family 1: } AADT < 10{,}000$$
$$\text{PCI} = 99.84 - 3.04(\text{age}) + 0.12(\text{age})^2 \quad R^2 = 0.99 \tag{21.6}$$

The value $R^2 = 0.99$ indicates a very good fit between the model and the data. This can be demonstrated in Figure 21.14, which shows a plot of the model results versus the actual data.

$$\text{Family 2: } AADT \geq 10{,}000$$
$$\text{PCI} = 99.74 - 3.99(\text{age}) + 0.12(\text{age})^2 \quad R^2 = 0.99 \tag{21.7}$$

Again, the value $R^2 = 0.99$ indicates a very good fit between the model and the data. This can be demonstrated in Figure 21.15, which shows a plot of the model results versus the actual data.

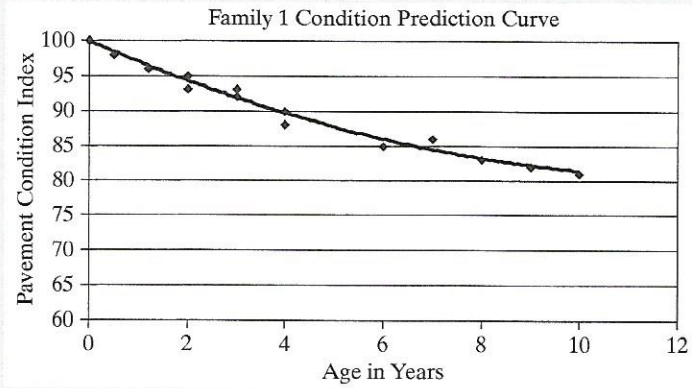


Figure 21.14 Condition Prediction Model: Pavement Sections $AADT < 10{,}000$

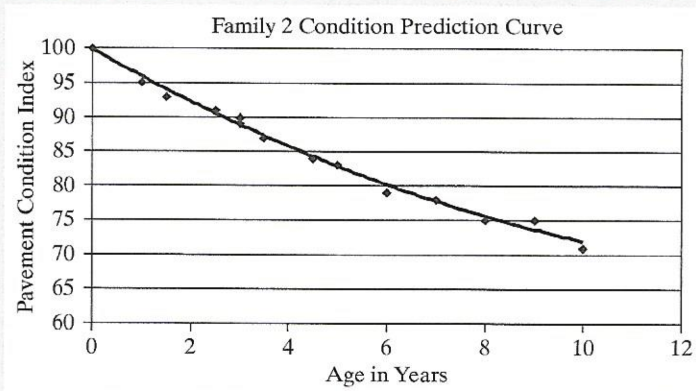


Figure 21.15 Condition Prediction Model: Pavement Sections $AADT > 10{,}000$

Example 21.4 Age When Pavement Resurfacing Is Required

Determine the number of years (age) before a pavement section belonging to Family 2 ($AADT \geq 10{,}000$) in Example 21.3 will need to be resurfaced if pavement overlays are necessary when the PCI value falls below 74.

Solution: Using the model previously developed as Eq. 21.7, determine the age at which the section will reach a PCI of 74 as follows:

$$74 = 99.74 - 3.99(\text{age}) + 0.12(\text{age})^2$$

Therefore,

$$0.12(\text{age})^2 - 3.99(\text{age}) + 25.74 = 0$$

Solve this quadratic equation as follows.

$$\text{Age} = \frac{+3.99 - \sqrt{3.99^2 - 4(0.12)(25.74)}}{2(0.12)} = 8.75 \text{ years}$$

Multiple-Regression Prediction Models

In contrast to family-based prediction models, which relate an element's condition index to a single independent variable, multiple-regression prediction models relate the PCI for a given highway section to several factors that affect deterioration, such as age, usage level, climatic and environmental conditions, structural strength, and construction materials. An example of a multiple-regression model follows.

Example 21.5 Developing a Multiple-Regression Prediction Model

Develop a multiple-regression-type prediction model using the data shown in Table 21.3. The form of the regression model is shown as Eq. 21.8.

$$\text{CI} = a + b(\text{age}) + c(AADT) + d(\text{SN}) \qquad (21.8)$$

Solution: A spreadsheet or statistical analysis software is used to develop the prediction model based on the data in Table 21.3. The results are shown in Eq. 21.9.

$$\text{CI} = 101.48 - 2.46(\text{age}) - 0.5 \times 10^{-3}(AADT) + 0.81(\text{SN}) \quad R^2 = 0.97 \qquad (21.9)$$

The value $R^2 = 0.97$ indicates a very good fit between the model and the data.

Table 21.6 Probabilities of Pavement Condition Changes

		To PCR State									
		9 *100 to 90*	*8* *89 to 80*	*7* *79 to 70*	*6* *69 to 60*	*5* *59 to 50*	*4* *49 to 40*	*3* *39 to 30*	*2* *29 to 20*	*1* *19 to 10*	*P*
From PCR State	*9* *100 to 90*	0.90	0.10								1.0
	8 *89 to 80*		0.70	0.30							1.0
	7 *79 to 70*			0.60	0.30	0.10					1.0
	6 *69 to 60*				0.50	0.30	0.15	0.05			1.0
	5 *59 to 50*					0.30	0.40	0.30			1.0
	4 *49 to 40*						0.30	0.70			1.0
	3 *39 to 30*							0.60	0.35	0.05	1.0
	2 *29 to 20*								0.20	0.80	1.0
	1 19 to 10									1.0	1.0

21.3.2 Probabilistic Models

Probability methods are based on the assumption that future conditions can be determined from the present state if the probabilities of given outcomes are known. An example of this approach is a Markovian model illustrated in Table 21.6, which shows the probability that the pavement condition in state i will change to a pavement condition in state j. For example, if in the current year the pavement condition (PCR) is within 70 to 79 (state 7), then the probability is 0.3 that in the next year the pavement condition will be within 60 to 69 (state 6). The probabilities shown in Table 21.6 can be used for successive years in a so-called Markovian chain. The assumption of Markovian models is that the future state is dependent on the current state regardless of how the pavement reached that current state.

Example 21.6 Predicting Future Condition Using a Markovian Model

A state DOT district office is responsible for maintaining a network of 1000 mi. The results of the annual survey in a given year showed that the current network condition of these roads is

- Group 1: 600 mi with a PCR between 90 and 100
- Group 2: 300 mi with a PCR between 80 and 89
- Group 3: 100 mi with a PCR between 70 and 79

Using the probability matrix given in Table 21.6, determine the condition of the network in year 1 and year 2.

Solution:

Step 1. Determine the current state of each of the three groups.

Group 1: state 9
Group 2: state 8
Group 3: state 7

Step 2. Determine probabilities of outcomes for each year, in one year.

For Group 1, state 9:
90% in state 9
10% in state 8

For Group 2, state 8:
70% in state 8
30% in state 7

For Group 3, state 7:
60% in state 7
30% in state 6
10% in state 5

Step 3. Determine the number of miles involved.

Group 1:
$0.9 \times 600 = 540$ mi in state 9
$0.1 \times 600 = 60$ mi in state 8

Group 2:
$0.70 \times 300 = 210$ mi in state 8
$0.30 \times 300 = 90$ mi in state 7

Group 3:
$0.60 \times 100 = 60$ mi in state 7
$0.30 \times 100 = 30$ mi in state 6
$0.10 \times 100 = 10$ mi in state 5

Step 4. Summarize the mileage of highway in each PCR category.

$540 = 540$ mi will be in state 9 (PCR between 90 & 100)
$60 + 210 = 270$ mi will be in state 8 (PCR between 80 & 89)
$90 + 60 = 150$ mi will be in state 7 (PCR between 70 & 79)
$30 = 30$ mi will be in state 6 (PCR between 60 & 69)
$10 = 10$ mi will be in state 5 (PCR between 50 & 59)

For year 2, the procedure is the same. Each PCR state is determined, followed by appropriate probabilities. Then calculations are made as shown in Step 3 and summarized in Step 4. The solution is left to the reader.

21.4 PAVEMENT REHABILITATION

A variety of methods can be used to rehabilitate pavements or to correct deficiencies in a given pavement section, including using overlays, sealing cracks, using seal coats, and repairing potholes.

21.4.1 Rehabilitation Techniques and Strategies

Rehabilitation techniques are classified as (1) corrective, which involves the permanent or temporary repair of deficiencies on an as-needed basis; or (2) preventive, which involves surface applications of either structural or nonstructural improvements intended to keep the quality of the pavement above a predetermined level. Corrective maintenance is analogous to repairing a small hole in a cloth whereas preventive maintenance can be thought of as sewing a large patch or replacing the lining in a suit. Just as with the sewing analogy, corrective measures can serve as prevention measures as well. To illustrate, sealing a crack is done to correct an existing problem, but it also prevents further deterioration that would occur if the crack were not repaired. Similarly, a chip seal coat (which is a layer of gravel placed on a thin coating of asphalt) is often used to correct a skid problem but also helps prevent further pavement deterioration.

Pavement rehabilitation strategies can be categorized in a variety of ways. One approach is in terms of the problem being solved, such as skid resistance, surface drainage, unevenness, roughness, or cracking. Another approach is in terms of the type of treatment used, such as surface treatment, overlay, or recycle. A third approach is in terms of the type of surface that will result from the process, such as asphalt overlay, rock seal coat, or liquid seal coat. The latter approach is the most commonly used because it enables the designer to consider each maintenance alternative in terms of a final product and then select the most appropriate one in terms of results desired and cost. Thus, the repair strategy information provides a means by which the problem at hand can be identified and the most economical alternative (based on annual cost and life expectancy) can be selected.

21.4.2 Alternatives for Repair and Rehabilitation

Figure 21.16 illustrates a variety of pavement repair and rehabilitation alternatives and differentiates between preventive and corrective approaches. For example, preventive strategies for pavement surfaces include fog-seal asphalt, rejuvenators, joint sealing, seal coats (with aggregate), and a thin blanket. This figure is provided to assist understanding the purpose for which a given treatment is intended.

There are a variety of pavement rehabilitation techniques for both flexible and rigid pavements, and they may be corrective or preventive depending on the circumstances. For example, patching is always considered to be corrective and can be effective if properly done. Many patching materials are available. At the other extreme, overlays are both corrective and preventive and are considered to be an effective technique. Surface treatments can be either preventive or corrective and are considered an effective means of maintaining roads on a regular basis.

Another method of describing pavement rehabilitation alternatives is to identify deficiencies and select the most appropriate treatment. If distress types are known in terms of severity and if the repair is considered temporary or permanent, then a repair strategy can be selected. For example, for flexible pavements, alligator cracking is repaired by removal and replacement of the surface course, by permanent patching or scarifying, and by mixing the materials with asphalt.

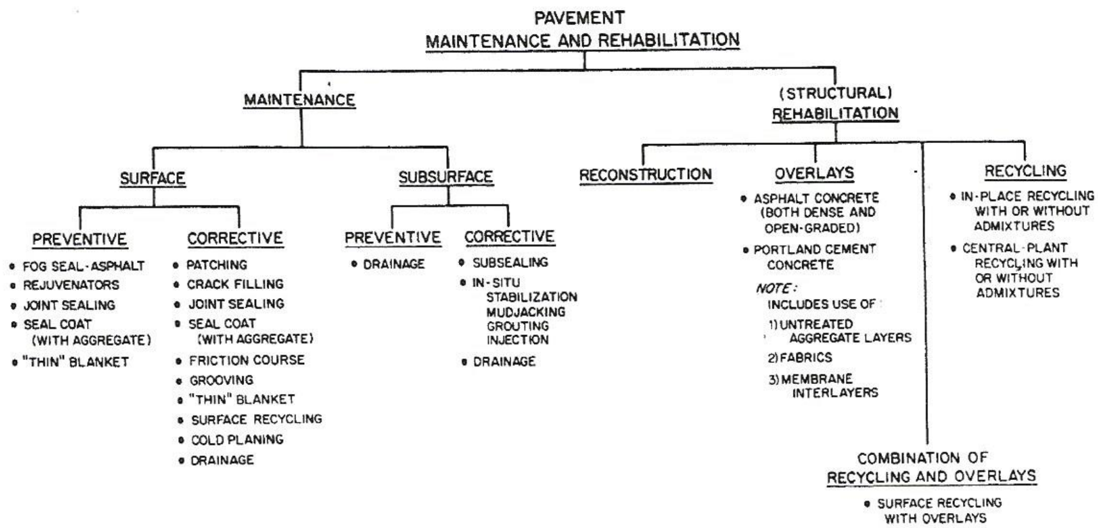


Figure 21.16 Pavement Maintenance and Rehabilitation Alternatives

SOURCE: Figure reproduced with permission of TRB, from C. L. Monismith, *Pavement Evaluation and Overlay Design Summary of Methods*, Transportation Research Record No. 700, Transportation Research Board, National Research Council, Washington, D.C., 1979

The state of the practice of pavement rehabilitation has been considerably advanced in recent years as a result of research on Long Term Pavement Performance (LTPP) supported by the Strategic Highway Research Program (SHRP). A list of the reports prepared through this program is available on the Federal Highway Administration Web site at www.fhwa.dot.gov. Additional reports produced by the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board are available on the TRB Web site at www.trb.org. Several relevant NCHRP synthesis reports are listed in the references section at the end of this chapter.

21.4.3 Expert Systems as a Tool to Select Maintenance and Rehabilitation Strategies

Expert systems (a branch of artificial intelligence) can be used in the selection of maintenance and rehabilitation strategies. Expert systems (ES) are computer models that exhibit, within a specific domain, a degree of expertise in problem solving that is comparable to that of a human being. The knowledge required to build the expert system is obtained by interviewing pavement engineers who have extensive experience and knowledge about pavement management. The acquired knowledge is stored in the expert system and then can be used to recommend appropriate maintenance or rehabilitation strategies. Since the information is stored in a computer knowledge base, diagnostic advice is available to inexperienced users.

21.5 PAVEMENT REHABILITATION PROGRAMMING

In previous sections, we described how pavement condition is measured and discussed the alternatives and strategies available to repair and rehabilitate these surfaces. In this section, we describe the process used to select a specific program for rehabilitation.

Decisions are required about the type of repair or restoration technique that should be used for a given pavement section and about the timing (or programming) of the project. These decisions consider the design life of the pavement, the cost and benefits of the project, and other physical and environmental conditions.

Transportation agencies use various methods for selecting a program of pavement rehabilitation. According to the *AASHTO Guidelines for Pavement Management Systems*, analysis techniques are divided into three main groups: (1) condition assessment, (2) priority assessment, and (3) optimization. Each technique is used to determine the type of treatment needed and the schedule for rehabilitation, as described in the following section.

21.5.1 Condition Assessment

This method is used to develop single-year programs. The agency establishes criteria for the different measures of pavement condition against which comparison of the actual measurements can be made. If the measurement exceeds this limit or "trigger point," then a deficiency or need exists.

Figure 21.17 illustrates this concept. For example, if a limit of PSI of 2.5 has been set as the minimum acceptable roughness level for a particular class of pavement, then any section with a PSI less than 2.5 will represent a current deficiency. The fixed trigger point thus resolves the timing issue in a simple manner. Whenever the condition index falls below the given trigger point (criterion), it is assumed that rehabilitation is needed. Therefore, by using the trigger criterion, all sections are separated into two groups: "now needs" and "later needs."

In this method, the concern is only with the "now needs." Having decided upon the sections that need action, the next step is to select a treatment for each of these "now needs." This could involve simple economic analysis methods such as the net present worth (NPW) or benefit–cost ratio (BCR) based on approximate estimates of the expected life of the different alternatives. After deciding on the treatment, three possible situations may arise: (1) the needs match the budget, (2) the needs exceed the budget, or (3) the needs are less than the budget.

Of the three situations, the most common occurs when needs exceed the available funds, and so a ranking of these projects is often needed. The purpose of this ranking

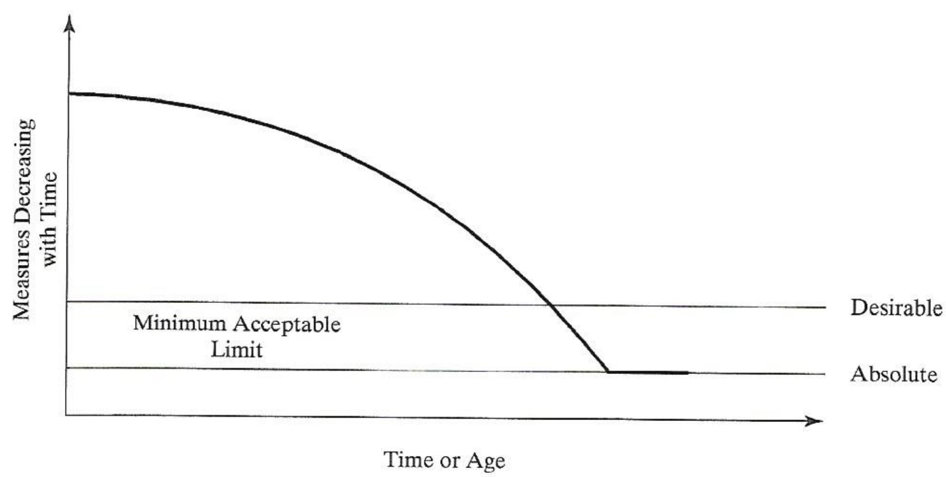


Figure 21.17 Determining Rehabilitation Needs Based on Established Criteria

is to determine which needs could be deferred to the following year. There are several possible alternatives for ranking. Projects may be ranked by distress, a combination of distress and traffic, the NPW, or the BCR. Sections are then selected until the budget is exhausted.

The rational factorial ranking method (FRM) is an example of a ranking method. It uses a priority index that combines climatic conditions, traffic, roughness, and distress. The priority index is expressed as

$$Y = 5.4 - (0.0263X_1) - (0.0132X_2) - [0.4 \log (X_3)] + (0.749X_4) + (1.66X_5) \quad (21.10)$$

where

Y = the priority index ranging from 1 to 10, with 1 representing very poor and 10 representing excellent. Thus, a low value indicates a pavement that is a high priority for treatment.
X_1 = average rainfall (in./yr)
X_2 = freeze and thaw (cycle/yr)
X_3 = traffic ($AADT$)
X_4 = present serviceability index
X_5 = distress (a subjective number between −1 and +1)

Example 21.7 Determining the Order of Priority for Rehabilitation

Three sections of highway have been measured for surface condition with results as shown in Table 21.7. Also shown are climatic and traffic conditions for each section. Use the rational factorial rating method to determine the order of priority for rehabilitation.

Solution: Using Eq. 21.10,

$$Y = 5.4 - (0.0263X_1) - (0.0132X_2) - [0.4 \log (X_3)] + (0.749X_4) + (1.66X_5)$$

The priority index (Y) for each section is:

- Section 1:

$$Y = 5.4 - (0.0263 \times 10) - (0.0132 \times 5) - [0.4 \log (10{,}000)] + (0.749 \times 2.4) + (1.66 \times 0.5) = 6.099$$

- Section 2:

$$Y = 5.4 - (0.0263 \times 30) - (0.0132 \times 15) - [0.4 \log (5000)] + (0.749 \times 3.2) + (1.66 \times (-0.2)) = 4.998$$

- Section 3:

$$Y = 5.4 - (0.0263 \times 15) - (0.0132 \times 0) - [0.4 \log (20{,}000)] + (0.749 \times 3.0) + (1.66 \times 0.8) = 6.86$$

Since low index values indicate poor condition, section 2 should receive highest priority, followed by section 1, and lastly, section 3.

Table 21.7 Condition, Climatic, and Traffic Data for Highway Sections

Section	*Rainfall*	*Freeze/Thaw*	*AADT*	*PSI*	*Distress*
1	10 in./yr	5 cycles/yr	10,000	2.4	+0.5
2	30 in./yr	15 cycles/yr	5000	3.2	−0.2
3	15 in./yr	0 cycles/yr	20,000	3.0	+0.8

21.5.2 Priority Assessment Models

Priority assessment is used to develop multiyear programs, an extension of the single-year model described. It addresses the question of when the "later needs" are to be addressed and what action is required. To use this method, performance prediction models are required. For developing multiyear programs using ranking methods, either fixed-trigger-point or variable-trigger-point methods are used.

Trigger-Point Ranking

Models are used to predict when each road section will reach its trigger point. That is, instead of separating the network into two groups (present needs and later needs), this method separates the pavement sections into, say, six groups, according to the year when action will be needed, as illustrated in Figure 21.18. The process from this point is essentially the same as the previous method, except that more accurate economic analysis is possible as a result of the availability of prediction models. The use of a fixed-trigger-point method was illustrated in Example 21.4.

A variable-trigger-point ranking, as illustrated in Figure 21.19, is based on economic analysis models to establish the type of treatment as well as the timing. The advantage of using this method is that timing and treatment selection decisions are made simultaneously instead of being treated as two distinct stages in a sequential process, as was the case with the previous methods.

Near-Optimization Methods

Near-optimization methods are based on a heuristic approach that can usually yield good results. The marginal cost-effectiveness method illustrates near-optimization methods that have been widely applied. For this method, the cost effectiveness of various combinations of highway system project sections, maintenance/rehabilitation strategies, and their timing is computed.

Effectiveness is estimated by computing the area under the condition prediction model between the curve and the established critical value for highway condition. Effectiveness is calculated for a planning horizon (e.g., 10 years). Areas above the critical value are positive, and those below the critical value are negative. The section length and the average annual daily traffic (*AADT*) are multiplied by the net area. The result

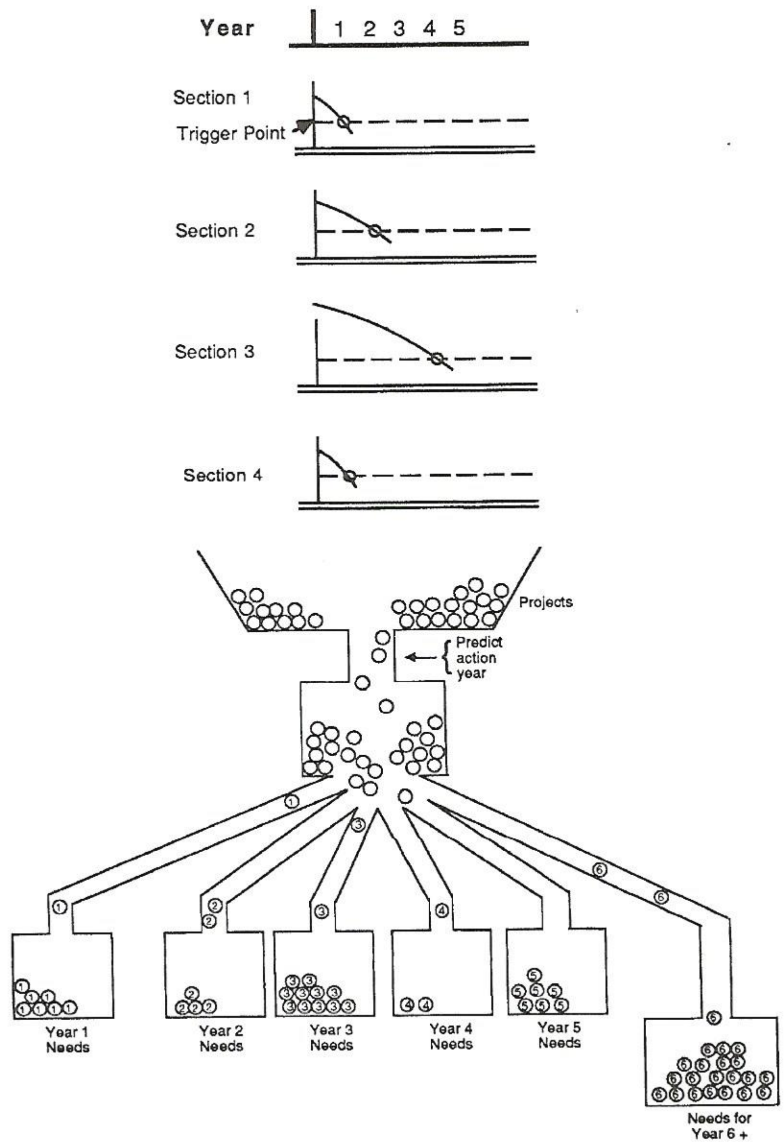


Figure 21.18 Fixed-Trigger-Point Ranking for Pavement Rehabilitation Programming

SOURCE: W. D. Cook and R. L. Lytton, "Recent Developments and Potential Future Directions in Ranking and Optimization Procedures for Pavement Management," *Second North American Conference for Managing Pavements*, vol. 2, 1987, p. 2.144

is a measure of the effectiveness of the maintenance or rehabilitation strategy being considered. Figure 21.20 illustrates the calculation procedure. The value of effectiveness is computed as the shaded area to the right of the rehabilitation strategy minus the shaded area to the left, which is then multiplied by the traffic volume and by the length of the transportation element, as shown in Eq. 21.11.

$$\text{Effectiveness} = [\text{area}\,1 - \text{area}\,2] \times [AADT] \times [\text{length of section}] \qquad (21.11)$$

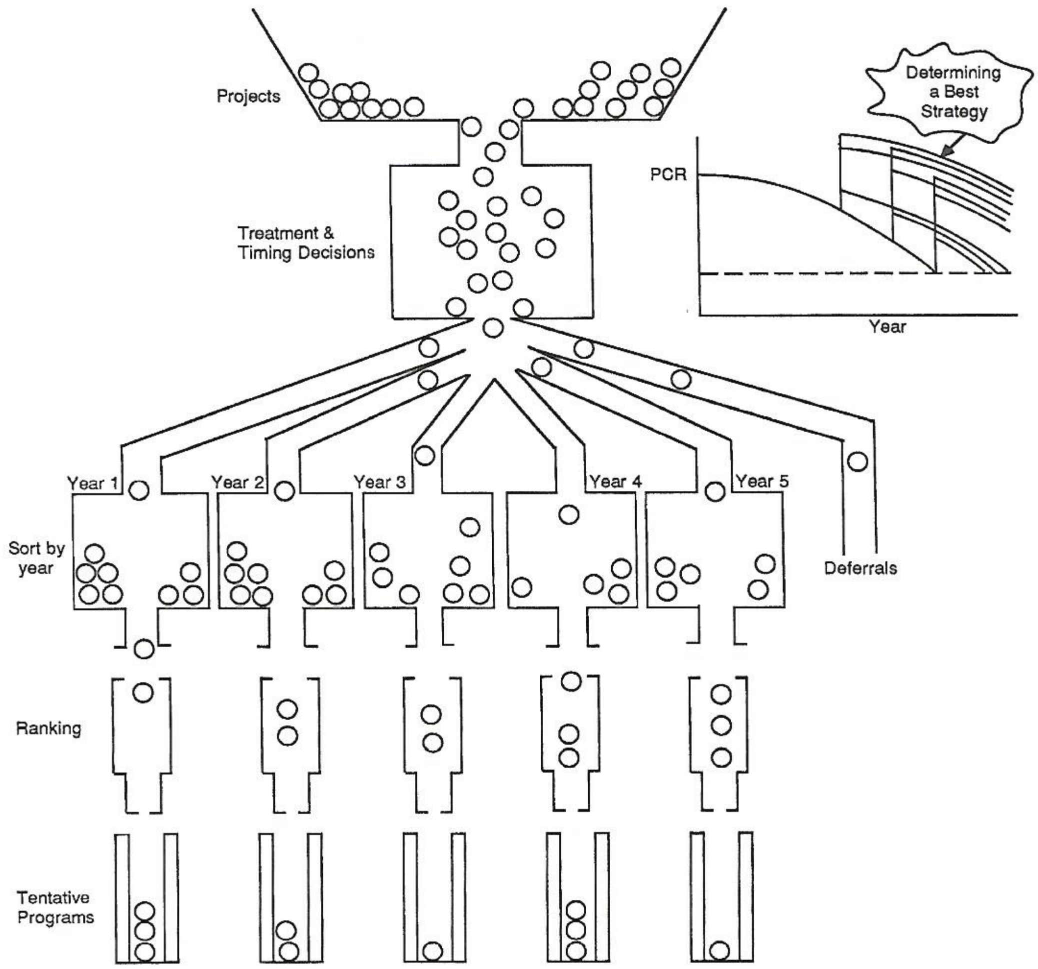


Figure 21.19 Variable-Trigger-Point Ranking Method for Pavement Rehabilitation Programming

SOURCE: W.D. Cook, R.L. Lytton, "Recent Developments and Potential Future Directions in Ranking and Optimization Procedures for Pavement Management," *Second North American Conference for Managing Pavements*, vol. 2. 1987, p. 2.144

The cost of the maintenance/rehabilitation project includes the cost of materials and construction on an in-place quantity basis, such as $/mi, and user costs include delays and additional vehicle operating costs incurred during construction. Cost effectiveness of a given project is computed as

$$\text{Effectiveness ratio} = \frac{\text{effectiveness}}{\text{cost}}$$

The following steps are used to compute the marginal cost effectiveness.

Step 1. For each highway section, select the combination of treatment alternative and year with the highest E/C ratio.

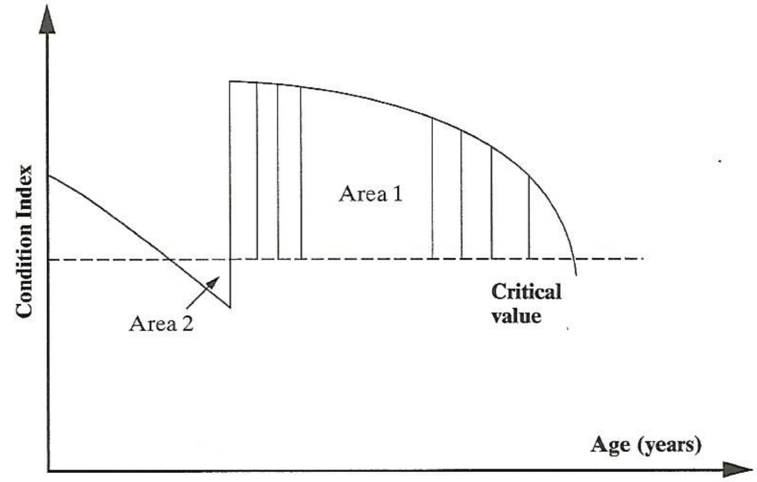


Figure 21.20 Calculating the Effectiveness of Maintenance and Rehabilitation Strategies

Step 2. Compute the marginal cost effectiveness, MCE, of all other strategies (i.e., the combinations of other treatments and other timings) for each element, as

$$MCE = (E_s - E_r)/(C_s - C_r) \quad (21.12)$$

where

E_s = effectiveness of the selected combination
E_r = effectiveness of the combination being compared
C_s = cost of the combination selected
C_r = cost of the combination being compared

Step 3. If MCE is negative, or if $E_r < E_s$, then the comparative strategy is removed from further consideration. If not, it replaces the selected combination.

Step 4. Repeat the comparison process until the total cost of the selected projects utilizes the funding available.

Example 21.8 Effectiveness of Rehabilitation Strategies

The traffic volume of a 2-mile pavement section is 10,000 veh/day. The deterioration relationship for sections in this family group is

$$PQI = 10 - 0.50(\text{age}) \quad (21.13)$$

where

PQI = pavement quality index with values between 0 and 10
age = pavement age in years

The highway agency policy is to maintain pavement sections with a PQI < 5. Resurfacing the pavement section will increase the PQI to a value of 9. After resurfacing, the section is expected to deteriorate at a rate of 1.50 PQI points per year.

Determine the effectiveness of resurfacing the pavement section 12 years after construction. What would the effectiveness be if the resurfacing is postponed until year 13?

Determine the time it would take for the resurfaced pavement to deteriorate to a PQI value of 5.0.

Solution: Figure 21.21 illustrates the deterioration trend for the pavement section before and after the application of the rehabilitation strategy in year 12. The section condition deteriorates to a PQI value of 4.0 in year 12. After rehabilitation, the PQI value is restored to a value of 9. Following rehabilitation, the deterioration rate is much faster than the deterioration rate of the original pavement structure and is governed by the following equation.

$$PQI = 9 - 1.50 \times \text{age (number of years after rehabilitation)} \qquad (21.14)$$

To determine when PQI will reach a value of 5.0 after rehabilitation, substitute 5.0 for PQI in Eq. 21.14 and solve for age (after rehabilitation) as follows.

$$5.0 = 9.0 - 1.50 \times \text{age (after rehabilitation)}$$

Therefore,

$$\text{Age after rehabilitation} = (9.0 - 5.0)/1.50 = 2.667 \text{ years}$$

Compute the area in Figure 21.22 to the right (area 1) and to the left (area 2) of the rehabilitation strategy as follows.

$$\text{Area 1} = \tfrac{1}{2} \times 2.667 \times 4.0 = 5.334$$
$$\text{Area 2} = \tfrac{1}{2} \times 2.0 \times 1.0 = 1.0$$

Use Eq. 21.11 to compute effectiveness.

$$\text{Effectiveness} = [\text{area 1} - \text{area 2}] \times [AADT] \times [\text{length of section}]$$
$$\text{Effectiveness} = (5.334 - 1.0) \times 10{,}000 \times 2 = 86{,}680$$

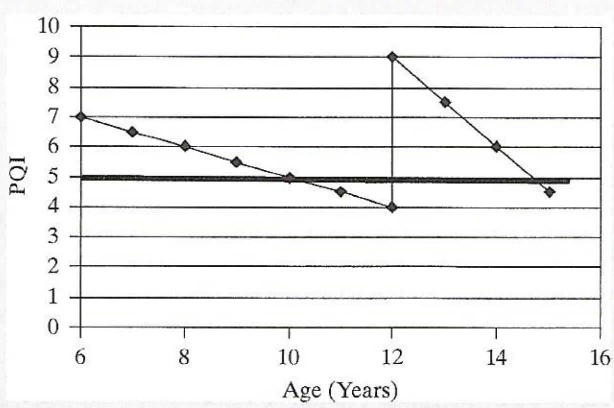


Figure 21.21 Deterioration Trend in Example 21.8: Rehabilitation in Year 12

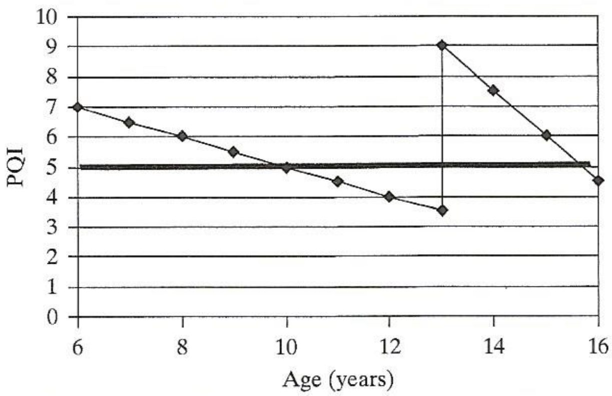


Figure 21.22 Deterioration Trend for the Pavement Section of Example 21.8: Rehabilitation Performed in Year 13

If resurfacing is postponed to year 13, the deterioration trend can be expressed as shown in Figure 21.22. Note that the PQI will be 5.0 in approximately 2.67 years following resurfacing (i.e., between years 15 and 16).

In this case, the area calculations are as follows.

$$\text{Area 1} = \tfrac{1}{2} \times 2.67 \times 4.0 = 5.334$$
$$\text{Area 2} = \tfrac{1}{2} \times 3.0 \times 1.5 = 2.25$$

Therefore,

$$\text{Effectiveness} = (5.334 - 2.25) \times 10{,}000 \times 2 = 61{,}680$$

21.5.3 Optimization Techniques

Optimization models provide the capability for the simultaneous evaluation of an entire pavement network, and as such, represent another method for scheduling rehabilitation programs in which alternative strategies satisfy an objective function subject to constraints. Optimization involves the following: (1) identifying the decision variables and determine optimal values, (2) formulating an objective function to be optimized, and (3) establishing the constraints of the model.

Identify Decision Variables

Decision variables reflect the selections regarding: (1) which pavement sections must be maintained, (2) the appropriate maintenance or rehabilitation strategy to select, and (3) the year when maintenance work is required. The following set of binary variables with values of 1 or 0 is used to represent these decisions.

$X_{ijt} = 1$, if section i is maintained using alternative j applied in year t

$X_{ijt} = 0$, if section i is not maintained using alternative j applied in year t

Formulate an Objective Function

The objective function is the value to be maximized or minimized. For example, if the objective is to use available resources effectively, the objective function is stated in terms of maximizing the effectiveness of the work program. Effectiveness calculations (as explained in Example 21.8) can assume a variety of planning horizons—for example, calculating the effectiveness of the different courses of action over the next 10 years. An objective function can be formulated as follows.

$$\text{Maximize} \sum_{i=1}^{m} \sum_{j=1}^{k} \sum_{t=1}^{T} X_{ijt} B_{ijt} \tag{21.15}$$

where

X_{ijt} = the binary decision variable
B_{ijt} = effectiveness of maintenance strategy j for highway section i in year t, calculated using the appropriate prediction curve

Establish Constraints

Constraints are restrictions on the numerical value of a decision variable and reflect the limitations on available resources, including money, time, personnel, and materials. One inevitable constraint is that expenditures in a given year cannot exceed the available budget, which is formulated as follows.

$$\sum_{i=1}^{m} \sum_{j=1}^{k} X_{ijt} D_{ijt} \leq B_t \quad (\text{for } t = 1, 2, \ldots, T) \tag{21.16}$$

where

D_{ijt} = the cost of maintenance strategy j for highway section i in year t
B_t = budget allocation in year t

An additional constraint is required to ensure that each section receives only one maintenance or rehabilitation strategy during the planning period which is formulated as follows.

$$\sum_{t=1}^{T} \sum_{j=1}^{k} X_{ijt} \leq 1 \quad (\text{for } i = 1, 2, \ldots, m) \tag{21.17}$$

where X_{ijt} represents binary variables that take a value of 0 or 1.

Equations 21.15 through 21.17 can be combined to optimize the total present value of m highway improvement projects with k different maintenance strategies, and a planning horizon of T years which is formulated as follows.

$$\text{Maximize} \sum_{i=1}^{m} \sum_{j=1}^{k} \sum_{t=1}^{T} X_{ijt} B_{ijt}$$

subject to

$$\sum_{i=1}^{T} \sum_{j=1}^{k} X_{ijt} \leq 1 \quad (\text{for } i = 1, 2, \ldots, m)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{k} X_{ijt} D_{ijt} \leq B_t \quad (\text{for } t = 1, 2, \ldots, T)$$

21.6 GIS AND PAVEMENT MANAGEMENT

Geographic Information Systems (GIS) are a set of computer software, hardware, data, and personnel that store, manipulate, analyze, and present geographically referenced (or spatial) data. GIS can link spatial information on maps (such as roadway alignment) with attribute or tabular data. For example, a GIS—a digital map of a road network—would be linked to an attribute table that stores pertinent information regarding each road section on the network. This information could include items such as the section ID number, length of section, number of lanes, condition of the pavement surface, and average daily traffic volume. By accessing a specific road segment, a complete array of relevant attribute data become available.

Figure 21.23 illustrates one application of GIS in infrastructure management. The computer-generated map shows the major roads and is color-coded based upon the values of the Ride Index (a measure of pavement surface condition). An attribute table is provided for pertinent information related to a specified road segment.

GIS includes procedures for: (1) data input; (2) data storage and retrieval; (3) data query, analysis, and modeling; and (4) data output. Data are accepted from a wide range of sources, including maps, aerial photographs, satellite image, and surveys. GIS also includes a comprehensive relational database management system (DBMS), which uses geo-references as the primary means of indexing information. GIS allows presentation of the data in a meaningful way, including map and textural/tabular reports. It provides

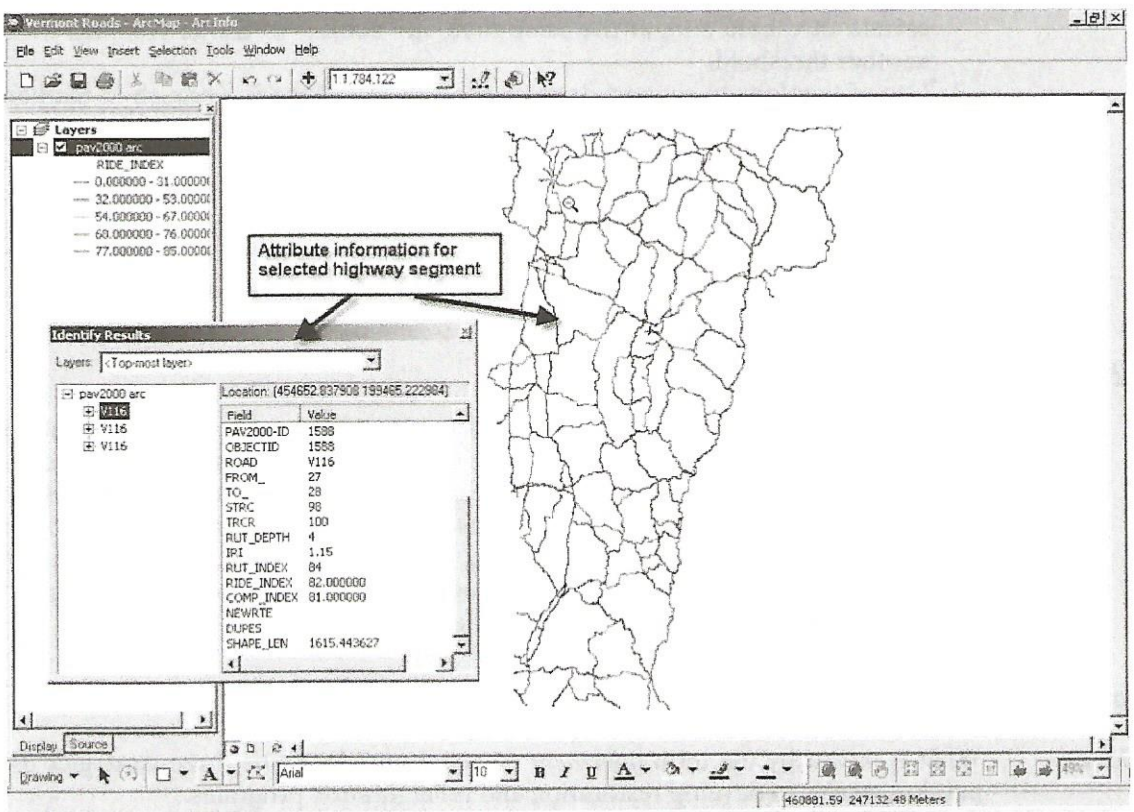


Figure 21.23 Use of GIS in Pavement Management

spatial analysis and modeling procedures that perform computations on data groups or layers and identifies patterns and relationships.

Due to the special capabilities of GIS (including data storage, retrieval, analysis, and presentation capabilities), the use of GIS for pavement management systems is increasing. Pavement management requires both spatial and attribute data; for example, location of pavement sections (i.e., spatial or location-type data) and the condition of those assets (i.e., attribute-type data). Other pertinent information is required regarding each highway section, such as year of construction, condition history, and maintenance history. For these reasons, GIS is an ideal application for pavement management.

There are several advantages of GIS over other forms of data presentation and analysis:

1. The ability to overlay different layers of information. Road surface condition can be stored in one layer, pavement construction information in another, and so forth. These different layers have a common coordinate system, allowing them to be overlaid on top of one another.
2. Provision of "intelligent maps," which access significant amounts of attribute data linked to the geographic features of the map. These "intelligent maps" can convey more information than may be immediately apparent. In addition, these maps can be managed, analyzed, queried, or presented in a more effective way than is possible with physical hard-copy maps, such as by identifying all pavement sections below a specified value for a condition index. Advanced queries and data analyses are also possible; for example, to identify sections whose condition is below a certain threshold and, at the same time, are subject to traffic volumes exceeding another threshold.
3. Use of topology to support decision making. Topology is a branch of mathematics that deals with the spatial relationships among features. It identifies features that are within a certain distance from another feature, or features totally within another feature, including ones that are adjacent to one another, and so forth. These functions can greatly support the decision-making capabilities of a pavement management system for a wide range of applications, including the ability to coordinate the work schedules of different components or subsystems of the highway system.

21.7 SUMMARY

This chapter has described the procedures used to develop a pavement rehabilitation program. The specifics may vary from one state to another, but there is agreement on the need for a rational and objective process to ensure that funds are efficiently used for pavement improvements. The benefits of using pavement management systems are (1) improved performance monitoring, (2) a rational basis for legislative support, (3) determination of various funding consequences, (4) improved administrative credibility, and (5) engineering input in policy decisions.

PROBLEMS

21-1 What is meant by the term *pavement management*? Describe three strategies used by public agencies to develop restoration and rehabilitation programs.

21-2 What are the three principal uses for pavement condition data?

21-3 What is the difference between PSI and PSR?