Distress Prediction Models for a Network-Level Pavement Management System

CHHOTE L. SARAF AND KAMRAN MAJIDZADEH

Distress prediction models play an important role in a pavement management system (PMS). These models are used to predict the condition of pavements treated with given maintenance and rehabilitation (M&R) action. They can also be used to compare the economics of various maintenance alternatives. The development of distress prediction models for a network-level PMS recently developed for the Ohio Department of Transportation is described. Five M&R actions or maintenance alternatives were included. Visual condition surveys of overlaid pavements (composite) currently include 14 distresses. These distresses were grouped into four distress groups each having its own severity and extent. Thus, 8 equations were developed for each M&R action, resulting in 40 equations for all five M&R actions and four distress groups. The models were used to predict distresses and pavement condition rating (PCR), which were compared with the corresponding distresses and PCR calculated from field observations. These comparisons indicated that the models were capable of predicting with reasonable accuracy the condition of a highway network as well as an individual pavement segment. Limited data for 5 years were available at the time of analysis; this should be kept in mind while the models are extrapolated for traffic loadings beyond these limits.

Highway engineers use a pavement management system (PMS) to develop information that can be applied to make cost-effective decisions about the type of maintenance needed as well as the place and time it is to be performed (*1*). Distress prediction models play an important role in this process. These models help in predicting performance of pavements treated with given maintenance and rehabilitation (M&R) actions. The effects of alternative M&R actions on the future performance of a pavement can also be assessed with the help of these models. Then engineers can use the information to select appropriate M&R strategies that satisfy their budget and performance constraints.

Pavement distress data collected from field surveys are generally used to develop distress prediction models. Visual and objective measurements have been used to collect pavement condition data from field surveys. The field data used in this study were collected by the Ohio Department of Transportation (ODOT), which employed a visual method called pavement condition rating that is described in the ODOT manual (*2*). The data collected from these surveys have been recorded annually since 1985 for all Interstate and other divided highways in Ohio. Therefore, 5 years of data were available when analysis was performed for this study.

The distress prediction models described in this paper were developed for the third-generation PMS (PMS-III) recently developed for ODOT. This is a network-level system that provides optimal maintenance strategies for the divided highway network of the state of Ohio. The system also includes features that allow users to estimate long-range budget allocations for a 6-year planning period and present assessment and forecasting of the network conditions and rehabilitation needs for the planning period (*3,4*).

This paper briefly describes the procedure to develop distress prediction models of composite pavements after jointed rigid pavements (JCPs) were overlaid with asphalt concrete overlays. Although these models were developed for the analysis of pavements at the network level, the estimated performance was also compared with the field observations of individual pavement's condition. This comparison indicated that the models can be used to predict with reasonable accuracy the distresses of individual pavements as well as groups of pavements.

DISTRESSES DEFINED FOR STUDY

ODOT engineers have defined 14 distresses for a composite pavement. A list of these distresses is presented in Table 1. All of these distresses are recorded visually by properly trained surveyors. The *ODOT Pavement Condition Rating Manual* (*2*) contains descriptions and photographs of each distress and its levels. Observations of the severity and extent of each distress are recorded in data forms as letter and number codes. These codes are then converted into numerical values with the help of distress weights and severity and extent weights as listed in Table 1. The following relationship is used for this purpose:

$$\text{deduct points} = \text{distress weight} \times \text{severity weight} \times \text{extent weight} \quad (1)$$

where deduct points represent the amount of damage caused by the distress present at the time of observation. The relative weights assigned to each distress and up to 100 when all 14 distresses are present in the pavement at their highest severity and extent levels. Therefore, the total deduct points vary from 0 to 100: 0 represents no visual damage and 100 represents total damage. The pavement condition rating (PCR) of a pavement is calculated from deduct points as follows:

$$\text{PCR} = 100 - \text{sum of deduct points of all visible distresses in the pavement} \quad (2)$$

The scale of PCR values is also from 100 to 0. A PCR of 100 represents a pavement with no visible damage, and a PCR

Resource International, Inc., 281 Enterprise Drive, Columbus, Ohio 43081.

TABLE 1 COMPOSITE PAVEMENT DISTRESSES AND THEIR WEIGHTS, INCLUDING SEVERITY AND EXTENT WEIGHTS

Distress	Distress Weight (di)	Severity Weight* (si) L	M	H	Extent Weight** (ei) O	F	E
Raveling	10.0	.3	.5	1.0	.3	.5	1.0
Bleeding	7.0	.4	.49	1.0	.4	.49	1.0
Patching	7.0	.3	.6	1.0	.3	.6	1.0
Surface Disintegration or Debonding	7.0	.38	.65	1.0	.38	.65	1.0
Rutting	8.0	.41	.68	1.0	.41	.68	1.0
Pumping	9.0	.3	.6	1.0	.3	.6	1.0
Shattered Slab	8.0	.3	.65	1.0	.3	.65	1.0
Settlement	5.0	.38	.74	1.0	.38	.74	1.0
Transverse Cracking							
Unjointed Base	20.0	.2	.6	1.0	.2	.6	1.0
Jointed Base							
(1) Joint Reflection Cracks	12.0	.2	.6	1.0	.2	.6	1.0
(2) Other	8.0	.2	.6	1.0	.2	.6	1.0
Longitudinal Cracking	7.5	.27	.51	1.0	.27	.51	1.0
Pressure Damage/Upheaval	6.0	.3	.67	1.0	.3	.67	1.0
Crack Sealing Deficiency	5.0	1.0	1.0	1.0	.6	.72	1.0

* L = LOW
M = MEDIUM
H = HIGH

** O = OCCASIONAL
F = FREQUENT
E = EXTENSIVE

of 0 represents a pavement with total damage. Although some of these original definitions of deduct points and PCR were retained, it was necessary to redefine the distresses of these pavements so that 14 distresses used for rating could be reduced. Thus, they were divided into four groups, as shown in Table 2, for which prediction models were developed. This reduced the number of equations from 28 (14 equations for severity and 14 for extent) to 8 for each M&R action.

A method was developed to estimate the severity and extent of each distress group. This method is summarized by the following relationships (see Table 1):

$$Ds = \left(\sum_{i=1}^{n} di\ si \right) / GW \tag{3}$$

$$De = \left(\sum_{i=1}^{n} di\ ei \right) / GW \tag{4}$$

TABLE 2 DISTRESS GROUPS CREATED FOR STUDY, WITH THEIR COMPONENT DISTRESSES AND GROUP WEIGHTS

Distress Groups	Weight (GW)	Component Distresses (See Table 1)
1. Structural 1	30	Raveling Bleeding Longitudinal Cracking Crack Sealing Deficiency
2. Structural 2	20	Rutting Surface Disintegration or Debonding Settlement
3. Joint 1	30	Pressure Damage/Upheaval Patching Pumping Shattered Slab
4. Joint 2	20	Unjointed Base Transverse Cracking or Jointed Base Joint Reflection Cracks Other Reflection Cracks

where

Ds = distress group severity,
De = distress group extent,
di = weight of ith component distress,
si = severity weight of ith component distress,
ei = extent weight of ith component distress, and
GW = total weight of distress group (see Table 2).

The following example illustrates the use of Equations 3 and 4 to calculate the severity and extent of each distress group from the field observations of severity and extent of component distresses.

The following distresses were recorded during the field survey of a hypothetical pavement:

Distress	*Severity*	*Extent*
Longitudinal cracking	*L*	*F*
Crack sealing deficiency	*L*	*O*

Because both distresses belong to Distress Group 1, the severity and extent of Distress Group 1 is calculated from Equations 3 and 4 using the numerical values associated with each observation (see Table 1 for the numerical values of *L*, *F*, and *O* of respective distresses and Table 2 for *GW*:

$$\text{severity} - Ds = (0 + 0 + 0.27 \times 7.5 + 1.0 \times 5)/30 = 0.234$$

$$\text{extent} - De = (0 + 0 + 0.51 \times 7.5 + 0.56 \times 5)/30 = 0.221$$

GENERAL FORM OF DISTRESS PREDICTION MODEL

It can be hypothesized that a pavement treatment with a major maintenance action (such as an overlay) will develop distresses at an increasing rate with increasing time or traffic, as illustrated in Figure 1. However, the field observations indicate that the distresses develop in steps (Figure 1). This is because measurements of component distresses are discrete (zero, low, medium, etc.). Therefore, it will be more realistic to use a step function form for a distress prediction model. But because of the complex nature of step functions, a continuous function form was considered suitable for this study, with a modification to the last part of the curve so that maximum value of distress will not exceed unity (see Equations 3 and 4). This defined the general shape of the distress function as a curve with a slow rate of growth in the initial part, an increasing rate in the middle, and a flat part (or almost constant value) at the end. This may be called a S-shaped curve also. An equation of the following form was assumed to represent this shape:

$$D = e^{-(A/T)} \qquad (5)$$

where

D = distress in the pavement (severity or extent),
T = time or traffic at which distress D is observed, and
A = parameter that represents the pavement characteristics.

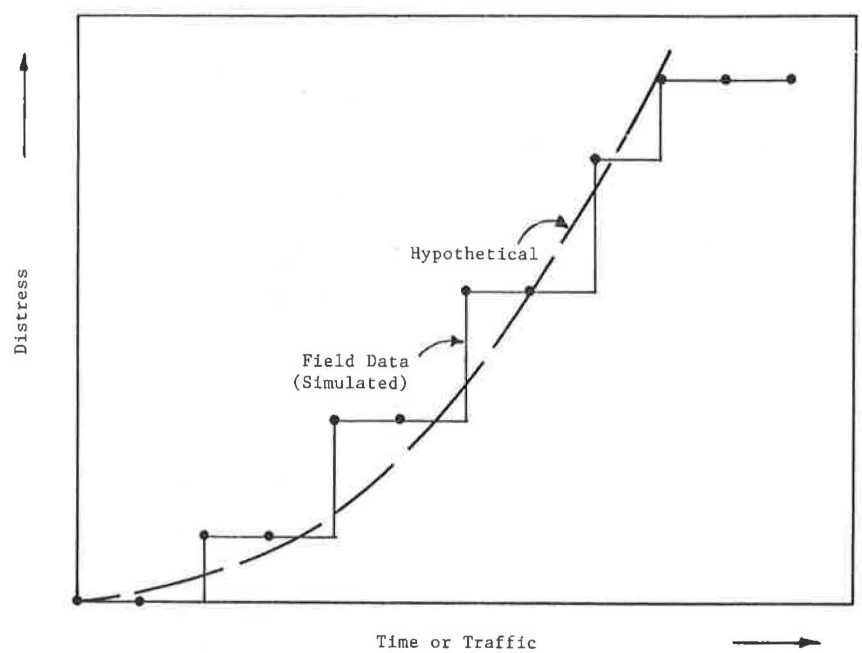

FIGURE 1 Plots of hypothetical distress and simulated field distress data.

Typical curves for three different values of Parameter A are shown in Figure 2. These curves indicate that the general form of the model represented by Equation 5 will satisfy the expected requirements of the distress function described.

Several parameters affect the development of distresses in pavements. Pavement type, M&R action, layer thicknesses and their strengths, properties of subgrade soil, and environment are some of the parameters considered important in this case, and their inclusion in the model was investigated. The results of these investigations indicated that the effects of layer thicknesses and their moduli of elasticity can be combined into a single parameter, H, defined as follows:

$$H = 0.1\left[\sum_{m=1}^{n} Hm\ (Em/20{,}000)^{1/3}\right] \qquad (6)$$

where

H = pavement layer parameter,
Em = modulus of elasticity of mth layer of pavement,
Hm = thickness of mth layer of pavement, and
n = number of layers in the pavement above subgrade.

Similarly, the subgrade characteristics were related to pavement performance via a parameter, I, defined as follows:

$$I = Es/1{,}000 \qquad (7)$$

where I is the subgrade parameter and Es is the modulus of elasticity of subgrade material.

Because it was decided to develop separate distress prediction models for each M&R action, and each distress group severity and extent, it was not necessary to include these variables in the equation. The effect of environmental factors was not included at this time either because AASHTO Regional Factor does not vary significantly over Ohio. Therefore, Constant A was related to other parameters as follows:

$$A = a1\ H^{a2}\ I^{a3} \qquad (8)$$

where $a1$, $a2$, and $a3$ were assumed to be constants to be determined from the regression analysis of appropriate data, as will be explained later. Thus, Equation 5 was rewritten as follows:

$$D = \exp[-(a1\ H^{a2}\ I^{a3})/(T + 1)^{a4}] \qquad (9)$$

where T was assumed to represent cumulative traffic since the time of last major maintenance. The value of T was estimated in terms of millions of 18-kip equivalent single axle loads (or E-18). A constant of 1 was added to avoid any numerical inconsistency when T is equal to zero.

DATA COLLECTION

The following data were collected for this study:

- Thickness and modulus of elasticity of pavement layers,
- Subgrade strength,
- Traffic data, and
- PCR data.

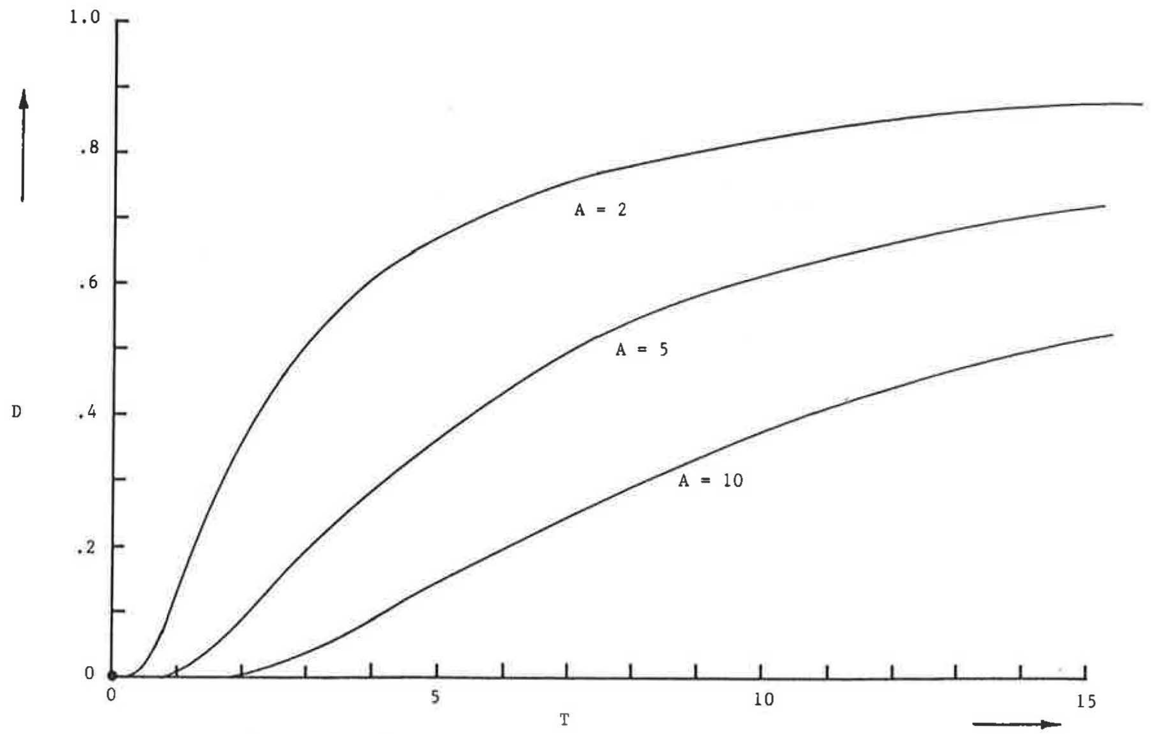

FIGURE 2 Typical plots of assumed distress function (Equation 5).

Most of the data were available in the computer files maintained by ODOT. Thickness of original pavement and the types of layer materials were recorded in the design file. This file also contained the subgrade soil classification (according to ODOT classification system). Maintenance data files contained information related to past maintenance performed on the pavement including the thickness and material types of overlays. Therefore, the data required to calculate *H*- and *I*-parameters of Equations 6 and 7 respectively were obtained from these two files. Because only material codes were recorded in these data files, a representative modulus of elasticity was used for each material code. The information for this purpose was obtained from ODOT engineers. Table 3 summarizes the strength properties of ODOT's pavement materials. The soil classification obtained from design files was converted into modulus of elasticity as indicated in Table 4.

Traffic data used in this study were obtained from the road inventory files maintained by ODOT. These files contained traffic count summaries and the years of these surveys. Total traffic and percentage of B- and C-trucks (ODOT's designation of heavy vehicles) are recorded in these files for all roads in Ohio. These data were used to estimate the parameter *T* used in Equation 9.

Pavement condition rating (or PCR) surveys conducted annually on all Interstate and other divided highways of Ohio are recorded in the PCR files of ODOT. PCR records for 1985–1989 were available when analysis was performed for this study. Therefore, the same were used to calculate the distresses in the pavements.

TABLE 4 STRENGTH PROPERTIES OF ODOT'S SOILS

Soil Type	CBR[1]	Es psi[2]
A-1, A-2, A-3	11.0	13,200
A-4	8.4	10,100
A-5	7.3	8,800
A-6	6.5	7,800
A-7	5.2	6,200

1. CBR values were obtained from the ODOT Design Manual Chart.
2. Modulus of elasticity, Es was determined by the following relationship:

$$Es = 1,200 * CBR$$

The values of Es were rounded to the nearest 100 psi.

DATA ANALYSIS

Computer programs were developed to extract and process the data contained in each file mentioned. The data from

TABLE 3 STRENGTH PROPERTIES OF ODOT'S PAVEMENT MATERIALS

Code	Description	E, psi
	Up through 1965	
T-71	Reinforced Portland Cement Conc. Pavement	4,500,000
I-22	Subbase	20,000
T-33	Bitum. Macadam Surface Course, Type A or B	100,000
I-18	Stabilized Crushed Aggregate Shoulder	50,000
B-21	Waterproofed Aggregate Base Course	100,000
T-31	Asph. Conc. Surface Treatment Using No. 6 Aggregate and Bituminous Materials	450,000
B-35	Asph. Conc. Leveling Course or Base Course	300,000
I-19	Insulation Course, Water, Gran., Blast	100,000
T-35	Asphaltic Concrete Surface Course	450,000
B-70	Portland Cement Concrete Base Course	4,500,000
B-33	Bituminous Aggregate Base	200,000
B-219	Waterproofed Aggregate Base Course	100,000
I-7	Reinforced Concrete Pavement for Ramps	4,500,000
B-20	Waterbound Macadam Base Course Using No. 2 Stone	100,000
	1966 - present	
451	Reinforced Portland Cement Conc. Pav.	4,500,000
404	Asphalt Concrete	450,000
402	Asphalt Concrete Leveling Course	450,000
403	Asphalt Concrete Preleveling Course	450,000
301	Bituminous Aggregate Base	450,000
310	Subbase	20,000
409	Seal Coat Cover Aggregate Using No. 8 Aggregate and Bituminous Material	200,000
305	Portland Cement Concrete Base	4,500,000
304	Aggregate Base	50,000
453	Continuously Reinforced Portland Cement Concrete Pavement	4,500,000
848	Asphalt Concrete	450,000
804	Cement Stabilized Base or Subbase	3,500,000
302	Asphalt Concrete	450,000
453	Continuously Reinforced Portland Cement Concrete Pavement	4,500,000
801	Portland Cement Concrete Base	4,500,000

TABLE 5 PARTIAL LISTING OF DATA PREPROCESSED FOR DEVELOPING DISTRESS PREDICTION MODELS

District	County	Route	Beginning Mile Post	Ending Mile Post	Pvt. Type	M&R Action	Traffic Param. T in E-18 (millions)	H	I	Distress Group #1 Ds	Distress Group #1 De	Distress Group #2 Ds	Distress Group #2 De	Distress Group #3 Ds	Distress Group #3 De	Distress Group #4 Ds	Distress Group #4 De
01	ALL	030	0	2.7	4	050	0.442552	7.909	6.200	0.20	0.43	0.00	0.00	0.00	0.00	0.15	0.25
01	ALL	030	0	2.7	4	050	0.907228	7.909	6.200	0.22	0.43	0.00	0.00	0.00	0.00	0.25	0.29
01	ALL	030	2.7	12.7	4	070	0.351849	7.062	6.200	0.10	0.33	0.00	0.00	0.00	0.00	0.12	0.60
01	ALL	030	2.7	12.7	4	070	0.721287	7.062	6.200	0.27	0.50	0.00	0.00	0.00	0.00	0.36	0.60
01	ALL	030	2.7	12.7	4	070	1.109193	7.062	6.200	0.33	0.57	0.08	0.08	0.00	0.00	0.36	0.60
01	ALL	030	2.7	12.7	4	070	1.516500	7.062	6.200	0.39	0.57	0.06	0.10	0.00	0.00	0.60	0.68
01	ALL	075	0	9.2	4	050	2.235982	7.627	6.200	0.25	0.49	0.08	0.14	0.00	0.00	0.36	0.40
01	ALL	075	0	9.2	4	050	3.438490	7.627	6.200	0.48	0.59	0.13	0.24	0.00	0.00	0.28	0.46
01	ALL	075	0	9.2	4	050	4.701141	7.627	6.200	0.32	0.51	0.16	0.34	0.00	0.00	0.49	0.55
01	ALL	075	0	9.2	4	050	6.026914	7.627	6.200	0.37	0.60	0.27	0.40	0.00	0.00	0.36	0.60
01	ALL	075	0	9.2	4	050	7.418986	7.627	6.200	0.52	0.61	0.27	0.40	0.04	0.02	0.89	0.74

these files were combined into the file that contained the required information for each pavement of the highways. This file was further processed by another computer program to estimate the parameters H and I of each pavement as well as T and distress group severity (Ds) and extent (De) for each pavement selected for this study. The most recent maintenance action and the year it was performed were also recorded in this file. The output of this program (see Table 5 for a typical output) was used to develop distress prediction models for various M&R actions. A simplified flowchart of major steps in this process is presented in Figure 3. Following examples briefly illustrate the method of calculating various parameters of distress prediction model represented by Equation 9.

Calculation of Parameters *H* and *I*

An asphalt overlay 6 in. thick was placed on an existing rigid pavement (JRCP) in 1985. The rigid pavement is 9 in. thick and is supported on a 6 in. granular subbase. The subgrade soil at the site was A-6 (ODOT classification).

Using these data, material properties of pavement layers were determined from Tables 3 and 4 as follows (see Equation 6):

	Hm (*in.*)	Em (*psi*)
Overlay (AC)	6	450,000
Base (PCC)	9	4,500,000
Subbase (granular)	6	20,000
Subgrade (A-6)	–	7,800

The value of the parameter H is calculated as follows:

$$H = 0.1[6.0\,(450{,}000/20{,}000)^{1/3} + 9(4{,}500{,}000/20{,}000)^{1/3} + 6(20{,}000/20{,}000)] = 7.768$$

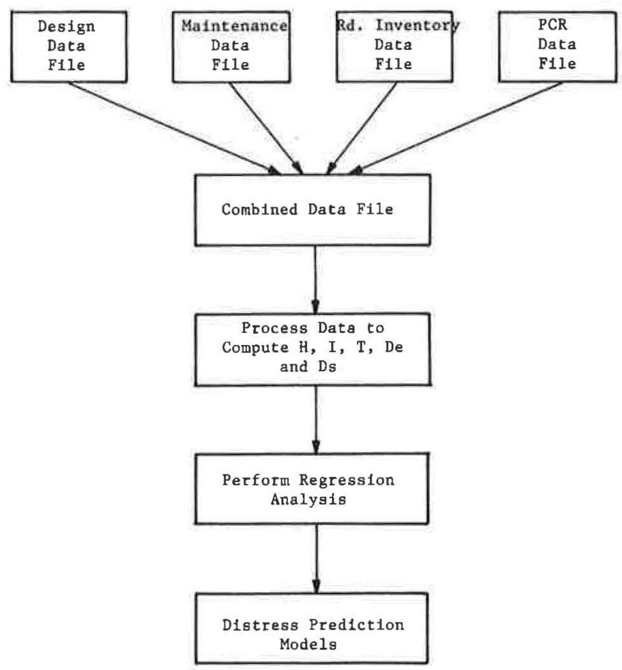

FIGURE 3 Simplified flowchart of process to develop distress prediction models.

Similarly, the parameter I is calculated as follows (see Equation 7):

$$I = 7{,}800/1{,}000 = 7.8$$

Calculations of Parameter *T*

The following traffic data were obtained for the pavement of the preceding example:

Traffic Data	*Value*
Total B- and C-trucks per day	3,000
Functional class of highway	01 (see Table 6)
Number of lanes in both directions	6
Year of traffic surveys	1987

These data were used to calculate the parameter T as illustrated:

1. Total number of B- and C-trucks in one direction = 3,000 × 0.5 = 1,500/day (assuming a 50-50 distribution in each direction.
2. Total number of trucks in the design lane = 1,500 × 0.8 = 1,200/day (0.8 is the design lane factor for a six-lane highway as recommended in ODOT design manual).
3. Number of B- and C-trucks in the design lane: the proportions of B- and C-trucks in the truck traffic were obtained from the ODOT data. A complete list of B- and C-truck distributions for various functional classes of roads in Ohio is presented in Table 6. Using values from this table for Functional Class 01, the numbers of B- and C-trucks in the design lane are as follows:

number of B-trucks/day = 0.875 × 1,200 = 1,050

number of C-trucks/day = 0.125 × 1,200 = 150

4. Calculations of E-18: these calculations require equivalency factors developed by the ODOT engineers for rigid and flexible pavements listed in Table 6. Because the original pavement was a rigid pavement, the E-18 factors related to rigid pavements were used for these calculations.

E-18 equivalent of B-trucks/day = 1,050 × 2.0591
= 2,162.06

E-18 equivalent of C-trucks/day = 150 × 0.2883 = 43.25

total E-18/day = 2,162.06 + 43.25 = 2,205.31

therefore,

total E-18/year = 2,205.31 × 365 = 804,938

5. Calculations of T for PCR years: the estimates of E-18 relate to the traffic survey of 1987. This pavement was overlaid in 1985, so traffic estimates for 1985 and 1986 were also required to calculate the appropriate value of T. This was done by assuming a constant traffic growth rate of 2 percent, which is an average value recommended by ODOT for highly populated areas represented by Functional Classes 01, 02, and 03 in Table 6. Traffic on all other classes of roads is assumed to grow at 1.5 percent per year. The calculations of the T-parameter for this example are summarized in Table 7.

Calculations of Distress Values *Ds* and *De*

The relationships represented by Equations 3 and 4 were used to estimate the distress group severity (*Ds*) and extent (*De*) of all observed distresses in each pavement. An example following these equations illustrates the method of calculating *Ds* and *De* of each distress group.

All available data for composite pavements of divided highways were analyzed using the method outlined in this section. As mentioned, a computer program was developed to perform these calculations. A partial listing of relevant data obtained from the output of this program is given in Table 5.

REGRESSION ANALYSIS OF DATA TO DEVELOP DISTRESS PREDICTION MODELS

Distress prediction models were developed by performing a regression analysis of data obtained from various ODOT files and processed as outlined. The general form of distress prediction models was represented by Equation 9. It is a nonlinear equation, therefore nonlinear regression analysis of the data was performed using the statistical package SAS. How-

TABLE 6 DISTRIBUTION OF B- AND C-TRUCKS AND 18-kip ESALs FOR VARIOUS FUNCTIONAL CLASSES OF ROADS (BASED ON ODOT'S 1986–1987 DATA)

Funct. Class	Descript.	Distribut.		18K-ESAL (Rigid)		18K-ESAL (Flexible)	
		B	C	B	C	B	C
01	Rural Interstate	0.875	0.125	2.0591	0.2883	1.5085	0.2744
02	Rural Principal Arterial	0.800	0.200	2.0836	1.8464	1.4969	1.1817
03	Rural Minor Arterial	0.333	0.667	2.0836	1.8464	1.4969	1.1817
41	Urban Interstate	0.667	0.333	2.1503	0.8846	1.5888	0.6698
42	Urban Fwy & Exwy	0.250	0.750	2.1503	0.8846	1.5888	0.6698
43	Urban Principal Arterial	0.500	0.500	1.5690	0.7034	1.1803	0.6092
44	Urban Minor Arterial	0.143	0.857	1.5690	0.7034	1.1803	0.6092

TABLE 7 SUMMARY OF CALCULATIONS TO ESTIMATE TRAFFIC PARAMETER *T*

Year	Annual Truck Traffic Millions of E-18	Cumulative Traffic, T Millions of E-18	Remarks
1985	0.7737	0	Major Maintenance Performed
1986	0.7892	0.7737	
1987	0.8049	1.529	Traffic Survey Year
1988	0.8210	2.3678	
1989	0.8375	3.1888	

ever, initial trials indicated that this method was not suitable for the type of data available for the study. The scatter as well as limited number of data (data were available for 5 years only) did not make it possible to obtain reasonable models from engineering considerations. Therefore, the equation was converted into a linear model and linear regression analysis was performed to obtain coefficients $a1-a4$ (see Equation 9). This transformation was performed by taking the natural log of both sides of the equation twice, as indicated later. The first transformation resulted in the following form of equation:

$$\ln D = -(a1\ H^{a2}\ H^{a2}\ I^{a3})/(T + 1)^{a4}$$

Because the estimated value of D varies from 0 to 1, the left side (1n D) is zero or negative (≤ 0). Therefore, multiplying both sides of the equation and taking the natural log of both sides, the equation will transform to the form:

$$\ln(-\ln D) = \ln a1 + a2 \ln H + a3 \ln I - a4 \ln(T + 1) \qquad (10)$$

Equation 10 is a linear combination of transformed variables, so a linear regression analysis was performed after transforming the original variables into $[\ln(-\ln D)]$, $\ln H$, $\ln I$, and $\ln(T + 1)$. The regression coefficients $a1-a4$ were thus obtained for each prediction model.

As indicated earlier, distress prediction models were obtained for each distress group severity and extent. This resulted in eight models for each M&R action. There were five different M&R actions considered as flexible overlays on the existing rigid pavements by the ODOT engineers. A brief description of these overlays, along with their code numbers as assigned by ODOT engineers, is as follows:

Description of M&R Action	*Action Code*
Nonstructural AC overlay with minimum repair (thickness $\leq$ 3 in.)	050
Nonstructural AC overlay with repairs	060
Structural AC overlay with minimum repair (thickness > 3 in.)	070
Structural AC overlay with repairs	080
Crack and seat with AC overlay	090

Forty equations were thus developed for the composite pavements. A partial listing of regression coefficients $a1-a4$ obtained from this analysis is shown in Table 8.

The results of this analysis indicated that because of considerable scatter in the data, the coefficients $a2$ and $a3$ were

TABLE 8 REGRESSION COEFFICIENTS OF DISTRESS PREDICTION MODEL FOR M&R ACTION 050

Distress Group	Distress	a1	a2	a3	a4
#1	Ds	1.00	0.1197	0	-0.1718
	De	.52	0.1318	0	-0.1926
#2	Ds	2.78	0.0693	0	-0.3718
	De	2.04	0.0814	0	-04.188
#3	Ds	3.63	0.1830	0	-0.2308
	De	3.89	0.1607	0	-0.2037
#4	Ds	1.58	-0.1417	0	-0.8623
	De	0.69	0.1210	0	-0.4476

sometimes negative. A negative sign for either of these coefficients means that increasing values of H or I will result in more damage, so this was considered impractical. Therefore, the analysis was performed without the parameter that was associated with the negative coefficient. The listing of coefficients $a1-a4$ shown in Table 8 shows that the coefficient $a3$ is zero for the M&R Action 050. This decision was made after the statistical significance of coefficient $a3$ in the equation was checked with the help of an F-test. In this case it was found that its presence in the equation was not statistically significant at a 95 percent confidence level.

COMPARISON OF RESULTS WITH FIELD OBSERVATIONS

The distress prediction models developed for various M&R actions were used to compare the estimated distress values with those directly calculated from field data. A typical example of this comparison is shown in Table 9. Distress data for a segment of Interstate Route 75 in Allen County, Ohio, is listed in this table. The estimated values of Ds and De for each distress group are also listed in the last column of this table. These comparisons show that the estimates obtained from prediction models are comparable with those obtained from field data within the practical limits.

Several pavements were selected to compare the estimated PCR values with the observed PCR values. These comparisons also indicated that the estimated PCR values were comparable with the PCR calculations from field data. An example of these comparisons is shown in Table 10, which includes two pavements.

Highway segments along Interstate and state routes were also analyzed to compare the estimated PCR for the entire route (simulated network) with the PCR calculated from field data. Space limitations will not allow these comparisons to be documented. However, Table 11 shows a typical comparison of PCR estimates with those obtained from field data of State Route 033 during 1987–1990. These segments were treated with M&R Action 060 in 1986.

The comparisons indicated that the models were capable of producing comparable estimates of Ds, De, and PCR in most of the cases. Therefore, these models were considered suitable for use with the PMS-III program as originally intended.

TABLE 9 COMPARISON OF OBSERVED AND ESTIMATED DISTRESSES (ALLEN COUNTY, ROUTE I-75, MILEPOST 0.00, M&R ACTION 050)

I T E M		T mil E-18	Observed Distress	Estimated Distress
Distr. grp. # 1	Sev	2.236	0.25	0.353
		3.438	0.48	0.373
		4.701	0.32	0.388
		6.027	0.37	0.402
		7.419	0.52	0.413
	Ext	2.236	0.49	0.582
		3.438	0.59	0.600
		4.701	0.51	0.615
		6.027	0.60	0.627
		7.419	0.61	0.637
Distr. grp. # 2	Sev	2.236	0.08	0.126
		3.438	0.13	0.159
		4.701	0.16	0.187
		6.027	0.27	0.212
		7.419	0.27	0.235
	Ext	2.236	0.14	0.230
		3.438	0.24	0.275
		4.701	0.34	0.313
		6.027	0.40	0.345
		7.419	0.40	0.373
Distr. grp. # 3	Sev	2.236	0.00	0.018
		3.438	0.00	0.024
		4.701	0.00	0.030
		6.027	0.00	0.035
		7.419	0.04	0.040
	Ext	2.236	0.00	0.014
		3.438	0.00	0.019
		4.701	0.00	0.023
		6.027	0.00	0.027
		7.419	0.02	0.030
Distr. grp. # 4	Sev	2.236	0.36	0.650
		3.438	0.28	0.721
		4.701	0.49	0.768
		6.027	0.36	0.802
		7.419	0.89	0.828
	Ext	2.236	0.40	0.594
		3.438	0.46	0.636
		4.701	0.55	0.667
		6.027	0.60	0.692
		7.419	0.74	0.712

TABLE 10 COMPARISON OF OBSERVED AND ESTIMATED PCR FOR INDIVIDUAL HIGHWAY SEGMENTS (M&R ACTIONS 050 AND 060)

Seg. #	M&R ACTION	H	I	T Mil E-18	OBSERVED PCR	ESTIMATED PCR
1	050	7.9	6.2	8.118	71	72
				9.840	74	70
				11.596	74	69
				13.388	74	68
				15.216	69	67
				17.080	69	66
2	060	7.4	6.2	5.008	78	80
				6.323	74	78
				7.665	74	77
				9.003	70	76
				10.429	69	74
				11.853	69	73

TABLE 11 COMPARISON OF OBSERVED AND ESTIMATED PCR FOR ROUTE 033 IN OHIO (ALL SEGMENTS TREATED WITH M&R ACTION 060 IN 1986)

Beg. M.P.	Length Miles	Estimated PCR 1987	1988	1989	1990
21.70	0.04	92	91	90	89
22.50	3.80	92	91	90	89
26.30	3.50	91	90	89	87
29.80	0.30	90	89	87	85
30.10	0.70	90	89	87	85
Weighted Avg. of Estimates		91	90	89	88
Weighted Avg. of Field Data		98	90	90	87

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This paper describes an analytical procedure to develop distress prediction models suitable for a network-level PMS. The data were obtained from the ODOT files for road design, road maintenance, road inventory, and PCR.

Computer programs were developed to process the data in these files and combine all required data into one file (see Figure 3). These data were further processed to obtain suitable input for regression analysis so that the regression coefficients $a1-a4$ of Equation 9 could be determined. The linear transformation of Equation 9 as represented by Equation 10 was used to analyze the available data.

Distress prediction models were obtained for rigid pavements overlaid with AC of various thicknesses as well as cracked and seated rigid pavements overlaid with AC. Five different M&R actions were identified by the ODOT staff, which related to flexible overlays on existing rigid pavements. Eight equations were developed for each M&R action: one equation for each distress group severity and one equation for its extent. Thus, 40 equations were developed to satisfy the needs of prediction models for asphalt overlays on rigid pavements.

The predictive capabilities of the models were assessed as the estimated distress values were compared with the field-observed distress values of several pavements. The PCR estimates of selected pavements were compared with the PCR values calculated from field data (PCR surveys), and the PCR estimates of several pavements located on selected routes were compared with the calculated PCR obtained from field data. All these comparisons indicated that the predictive capabilities of the models obtained from the procedure described were reasonable. Some typical comparisons are shown in Tables 9, 10, and 11. The results of these comparisons indicated that distresses in rigid pavements overlaid with AC layer(s) can be predicted by the component layer thickness and its modulus of elasticity, subgrade soil strength, and traffic. A general form of relationship represented by Equation 9 was found to be suitable for this purpose.

Pavement condition records were available for 5 years. Therefore, these limits should be kept in mind if the models are to be extrapolated beyond the range of data used to develop them. A periodic updating of these models with future data will expand the range of their applicability.

ACKNOWLEDGMENTS

The study was sponsored by ODOT. The support of the sponsoring agency and the Resource International staff is appreciated by the authors.

REFERENCES

1. *AASHTO Guide for Pavement Management Systems*. AASHTO, Washington, D.C., July 1990.
2. K. Majidzadeh and M. S. Luther. *Pavement Condition Rating System*. Interim Report. Resource International, Inc., Columbus, Ohio; Ohio Department of Transportation, Columbus, 1980.
3. K. Majidzadeh, C. L. Saraf, and J. C. Kennedy, Jr. Ingredients of a Third-Generation Pavement Management System for the Ohio Department of Transportation. *Pavement Management Implementation*, ASTM, Special Technical Publication 1121. (F. B. Holt and W. G. Gramling, eds.), Philadelphia, Pa., 1991.
4. K. Majidzadeh, G. J. Ilves, and C. L. Saraf. *Implementation of Ohio Pavement Management System*, Vol 1. Final Report. Resource International, Inc., Columbus, Ohio; Ohio Department of Transportation, Columbus, Jan. 1992.

Publication of this paper sponsored by Committee on Pavement Management Systems.