Performance Models for Flexible Pavement Maintenance Treatments

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Using actual pavement performance data, nine flexible pavement maintenance performance models were developed. The models relate the pavement's present serviceability index (PSI) to its age, materials properties, traffic loadings, and environmental conditions. To develop the performance models, data collected by the Nevada Department of Transportation (NDOT) personnel over the life of 123 projects were used. Statistically significant samples were drawn from these projects for each of the three maintenance techniques that NDOT commonly employs. The maintenance techniques include flush seals, sand seals, and chip seals. To produce statistically accurate predictions, performance models for each technique were developed separately for each of NDOT's three districts. In cases where a large number of projects were available, some projects were set aside for a model verification study. Using the data from the set-aside projects, the nine models were tested by comparing the predicted performance to the performance observed at the projects. These comparisons showed excellent correlations between the PSI values predicted by the models and those observed.

The increasing interest in pavement performance studies is a result of their representing the final link between theory and practice. As the pavement engineering profession strives for better design procedures and more enduring materials, the evaluation of the long-term pavement performance becomes a critical step for every agency. Predicting the actual performance of specific pavement sections under the combined action of traffic loading and environment factors can provide valuable data to the various departments of a highway agency.

The pavement design engineer can use such data to check the validity of the design procedure and the appropriateness of the various assumptions that are made during the design process. The materials engineer can verify whether a given type of material is appropriate for the expected level of load and anticipated environmental conditions. As a result, design and construction practices may be altered to produce longer-lasting pavements.

Pavement management engineers tend to gain the most from such studies. They are usually responsible for recommending various maintenance alternatives for specific applications. This is becoming an increasingly critical task since highway agencies at all levels (city, county, and state) are generally operating under a limited budget that requires effective prioritization to provide the highest level of public service. Pavement management engineers are also responsible for setting up a pavement management system (PMS) and managing the collected data. Long-term pavement performance studies that develop performance models will help the engineers to evaluate the effectiveness of the PMS and determine the usefulness of the collected data.

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Four states (Arkansas, Iowa, Pennsylvania, and Washington) have recently completed studies to develop pavement performance curves (or equations) based on information in their existing data bases (*1*). All four of these states have chosen to use functional performance indicators. This is partially because functional performance indicators allow the states to establish and incorporate life cycle cost analysis into the models using their currently available data bases and existing PMS programs.

Arkansas used performance data to estimate a pavement's condition rating for the current year based on previous years' data. Components for pavement distress and ride are adjusted for traffic volumes. The pavement's condition rating is plotted against its age, on a yearly basis. From Arkansas's limited analysis it was concluded that even though the curves fit the data reasonably well, they would need to be revised to account for the effects of cumulative equivalent single axle loads (ESALs).

Iowa considered a more elaborate model that addressed some of the more obvious factors that could affect the performance of the overlay, such as thickness, aggregate durability, and base and subgrade characteristics. Sites were selected and divided by service levels and pavement type (rigid and composite). The model did allow the Iowa Department of Transportation to make some generalizations regarding material selection, but it also had several shortcomings. They included no allowance for maintenance and rehabilitation techniques (other than overlay), limited distribution of data points for loading and age, initial present serviceability indexes (PSIs) were all assumed to be constant, and only a few obvious variables that could affect the pavement performance were considered.

Pennsylvania generated performance curves from the roughness and traffic data for each of 22 monitored sites. The curves considered only rigid and composite pavement sections and while they do allow a reasonable prediction of PSI, the data considered were very limited.

Washington developed its curves based on the 5 years of data available in its data base. Washington considered a larger number of variables than the other three states. In all of its models, age was determined to be the most significant independent variable. Other variables such as overlay type showed generalized trends, but were not as significant.

None of the existing models considers the performance of pavement maintenance techniques. Therefore, there is a need to develop models that can be used to predict the performance of maintenance techniques used on flexible pavements as a function of traffic, environment, and pavement structural data. This research project dealt with the development of performance models for the flexible pavements maintenance techniques most commonly used by the Nevada Department of Transportation (NDOT).

SELECTION OF PROJECTS

A review of NDOT's historical maintenance records indicated that the most commonly used maintenance techniques include the following:

- Flush seal: applying an emulsion or liquid asphalt to the roadway at a prescribed rate.
- Sand seal: applying an emulsion or liquid asphalt to the roadway surface at a prescribed rate and applying a sand cover.
- Chip seal: applying a binder to a roadway at a prescribed rate, and covering the binder with rock screenings (chips). The binder is usually an emulsion with latex (LMRCRS-2 or LMCRS-2h). Emulsion without latex or a liquid asphalt may also be used for certain applications.

Following the selection of maintenance techniques, project selection guidelines were established. In establishing the project selection guidelines, one must keep in mind the overall objective of the research. As mentioned earlier, the developed models should be used to predict the future performance of the selected techniques. These models will use statistical analyses of actual PMS, environmental, structural, and materials data. Therefore, several minimum requirements must be satisfied to make the statistical analysis appropriate. The following criteria were selected as guidelines for project selection (*2*):

- A minimum of 20 replicate projects must be included.
- Each project should be at least 3 km long.
- Traffic data must be available for each selected project.
- Materials data must be available for each selected project.
- PMS performance data must be available for each selected project.

The existing NDOT district lines were used as regional boundaries (Figure 1), and projects were selected for each maintenance technique within each district. The project selection criteria were strictly followed with very few exceptions; some projects that were just under 3 km long were accepted due to the limited number of available projects. The projects selected for each treatment were as follows:

- Flush seal: 37 projects
- Sand seal: 38 projects
- Chip seal: 47 projects

DATA MANAGEMENT

Three categories of data were of interest: structural, environmental, and PMS. From each of these general categories, a list of factors that could possibly affect the performance life of the pavement system was derived. To be unbiased, the lists of factors were developed before any of the actual data sources were examined.

Structural Data

The structural data consisted of two parts: the first part was primarily the specific material and construction information used with the technique being examined; the second part consisted of structural and material information of all previous construction activities. If available, as-built plans are used to obtain the structural information. If the as-built plans are unavailable, copies of the contracts together with field notes and lab test results are used to determine the exact materials and quantities used.

Environmental Data

Nevada's diverse climatic conditions play a large role in the design, construction, and maintenance treatments throughout the state. Realizing that environmental factors can have a significant impact on pavement performance, it was decided that these factors should be included in the analyzed data sets. The available sources are the National Oceanic and Atmospheric Administration (NOAA) and the NDOT PMS system (*3*). The NOAA data are by far the most complete in terms of accuracy and amount of information, but are very limited in their coverage. NOAA data can only be obtained where there is an observation station; this left most of the road system in the state with no information.

The NDOT PMS system also contains weather data, and while they have several limitations, they cover the entire road system in Nevada. These data are limited by their not coming from actual observed field conditions; they are generated by a statistical model based on 30 years of NOAA weather data. The model divided the state into five zones and took NOAA data for all points within each zone and extrapolated them over the rest of the zone based upon elevation. The model can predict minimum and maximum average yearly temperatures, average number of wet days per year, average annual precipitation, and average number of freeze-thaw cycles per year at any location based on its elevation.

Pavement Management System Data

NDOT has had an operational PMS since 1980. While the system has undergone several changes in the last 13 years, most of the data in the system are available for all years since 1981 (*3*). The PMS contains ride data, condition data, traffic data, reduced calculated fields, calculated pavement ratings, and the weather data as described earlier. Using these data, the PSI is calculated from the AASHTO equation as follows (*4*):

$$\mathrm{PSI} = 5.03 - 1.91 \log_{10}(1 + SV) - 1.38\, RD^2 - 0.01\,(C + P)^{0.5} \quad (1)$$

The PSI ranges from zero to 5 with zero being the worst and 5 the best. A new pavement will generally not score above a 4.5, and pavements are generally not allowed to drop below 2 depending upon their system classification.

MODEL DEVELOPMENT

After the data for all the selected projects were collected and entered into the appropriate computer formats, the model development task was initiated. This task was a multifaceted operation that involved a great deal of testing as well as regression analysis. The purpose of the model development was to provide a conceptually simple method for examining the functional relationships among variables.

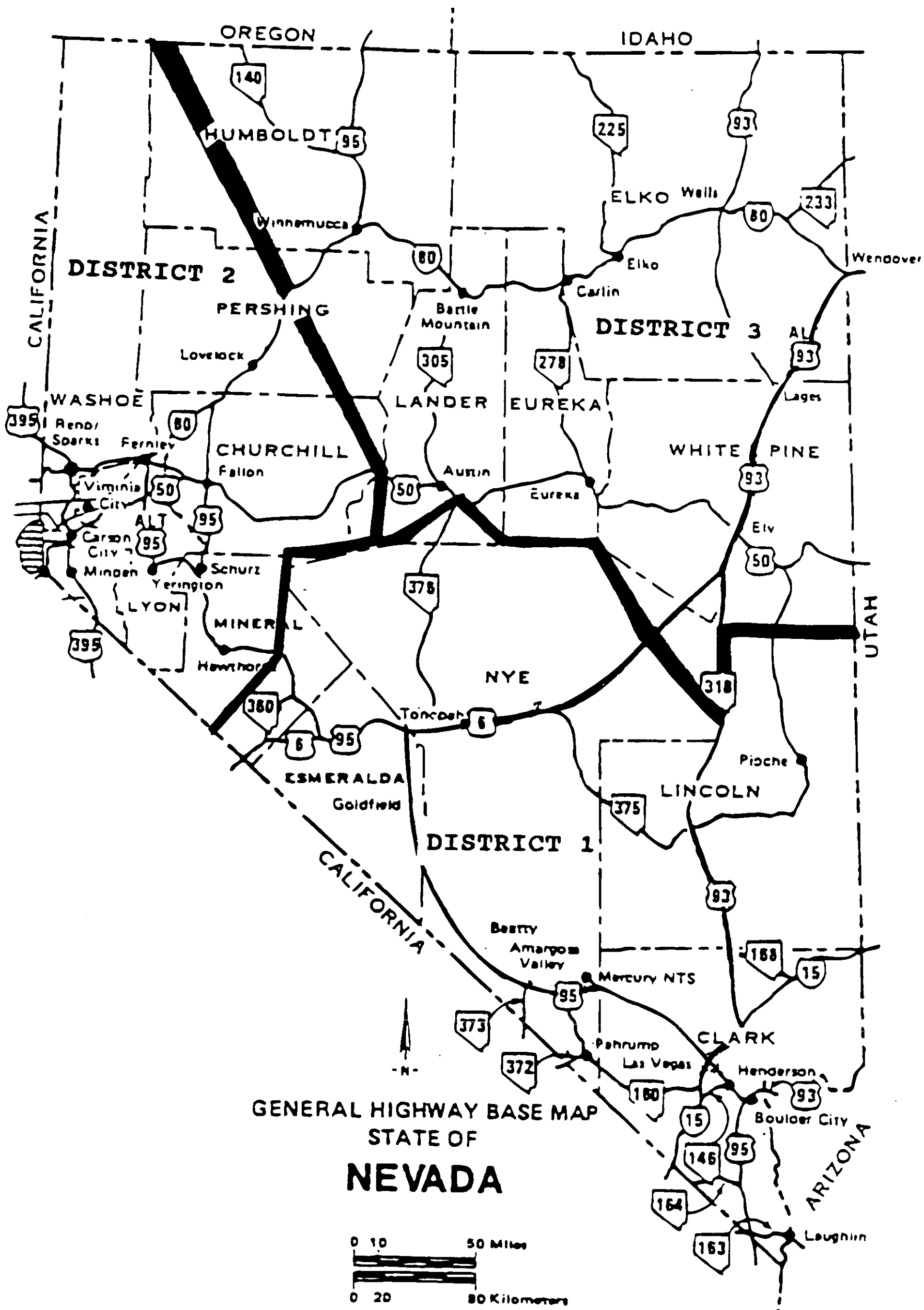

FIGURE 1 Geographical boundaries of NDOT districts.

The task was divided into the following processes: statistical analysis, data review, regression analysis, model review, tests of reasonability, model modification, additional regression analysis, model testing, and final model selection.

All of the statistical and regression analyses were performed using the SAS programming language (*5*). The SAS software is a combination of programs originally designed to perform statistical analyses of data, conduct complex data management, and provide a high-level programming language.

The box-plot statistical analysis was performed as a final check on the data prior to performing an actual regression analysis (*6*). This analysis calculates the mean and standard deviation for the PSI data for each pavement section. These values are then used to generate the acceptable range of data (e.g., plus or minus one standard deviation). Any observation that falls outside the acceptable range is considered an outlier. If data points appeared to be outliers, they were carefully examined for accuracy and reasonableness; any possible interactions among the independent variables were also carefully scrutinized to understand the possible physical representations and implications.

Regression Analysis

The General Linear Model procedure was used to develop a linear regression equation. In the first regression analysis, all the possible variables were considered. For each variable considered, a test statistic (t-value) was determined as part of the analysis. The test statistic is a representation of the significance of the individual variable in the model tested against the variable equal to zero. Variables that could be removed from the model were determined as those that had only a 5 percent chance of being significantly important to the model.

With those variables removed, a second regression analysis was performed on the remaining variables. In addition to checking the t-value of the individual variables, the Type I and Type II sums of squares of each variable were examined. The sums of squares provide an indication of any variables that may possibly be interrelated or interacting with each other. The Type I sums of squares indicate a variable's significance when considering removing the effects of the other variables, and the Type II sums of squares indicate that variable's significance after accounting for the effects of the other variables. Large differences in the t-values for variables indicate a possible interaction with other variables. If possible interactions were found, interaction terms were added to the regression analysis.

Another parameter that was of considerable importance was the sign of a variable's coefficient. In much of the previous pavement performance studies, signs were opposite of common belief or practice (*1*). For example, a positive coefficient for the 18-kip ESAL's term indicates that higher ESALs on the pavement section would generate a higher PSI. Although the models may appear to fit the data well, engineers tend to shy away from models that do not hold to traditional sign conventions. There were only a few cases in which sign conventions presented a problem in this study. In some cases, this was the result of outlier data points or misunderstood data information. The problem was corrected by simply removing the outliers. In other cases, the reversed signs were the result of a missed interaction term.

In most regression analyses, the fit of the model is described by an R-squared (R^2) value. The R^2 value is based on sample correlation coefficients that indicate the strength of the developed relationship between the response variable (PSI) and the independent variables (ESALs, AC type, aggregate rate, etc.) when compared to the observed data. R^2 may then be interpreted as the proportion of total variability in the dependent variable that can be explained by the independent variables. The R^2 can range from zero to one with the higher number indicating a better fit of the model to the actual data.

Model Testing and Selection

The tasks of model testing and model selection are interrelated. While R^2 indicates the model's fit to the analyzed data, it was more important to know how well the model can fit data not included in the analyzed data set. For the model to be accurate, it must be used within the range of parameters that were used during the development step. In other words, a model is valid only within the range of values from which it was developed. Every effort was made to maintain a data set that was representative of the entire range of variables that could be encountered on a particular project.

Verification projects were chosen at random from the original candidate list, and the data were examined to ensure that they met the required criteria for the model or models being considered. The independent variables were input into the developed regression models, and the PSIs predicted by the models were plotted against the actual recorded PSIs. Figures 2 through 7 show examples of the

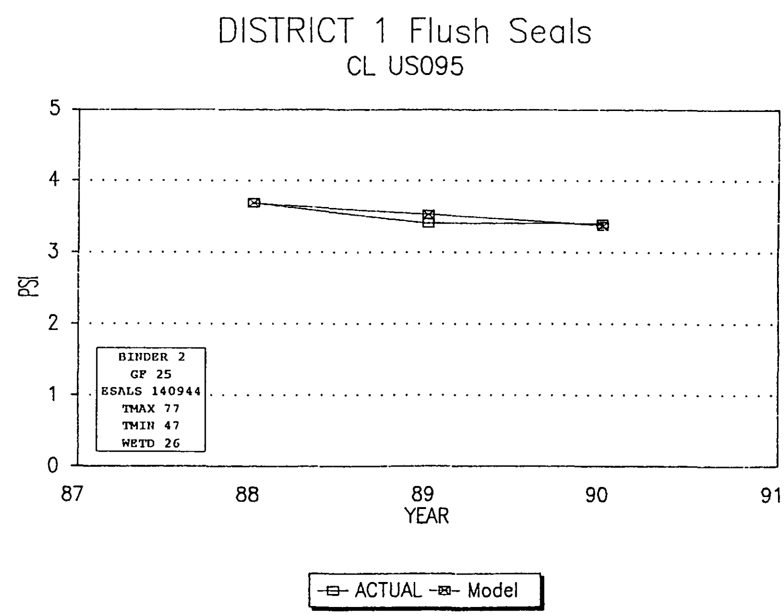

FIGURE 2 Actual and predicted PSI for flush seal model, District 1.

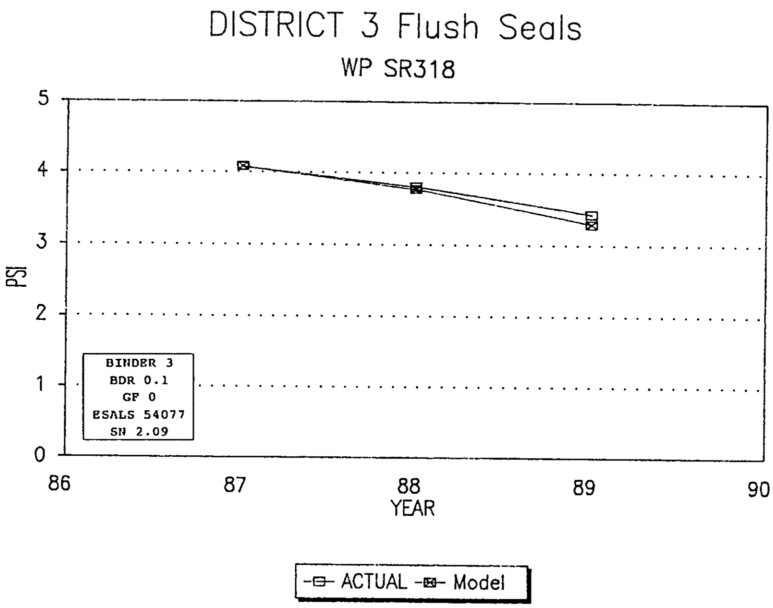

FIGURE 3 Actual and predicted PSI for flush seal model, District 3.

model verification data. In some cases, there is an excellent agreement between the actual data and the models (see Figures 2, 3, and 5). In other cases, the models showed more stable data trends than the actual data. In the case of chip seal in District 3 (Figures 6 and 7), the actual data indicate that the PSI of the pavement increases with time while the model showed a steady decrease in the PSI. There is no logical explanation of why the PSI should increase on these projects except that the collected data for that year may not be representative of the entire section.

The worst agreement between the actual data and the models was obtained in the case of sand seal in District 2 (Figure 4). This model has a relatively low R^2 value, which indicates that the model does not fit the data very well. The R^2 for this model is 0.6, which means that 40 percent of the variability in the data cannot be explained by

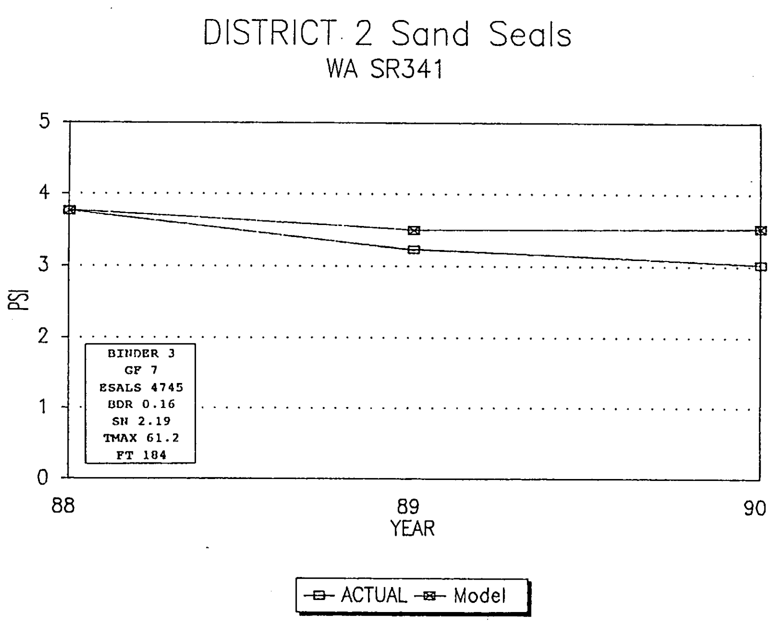

FIGURE 4 Actual and predicted PSI for sand seal model, District 2.

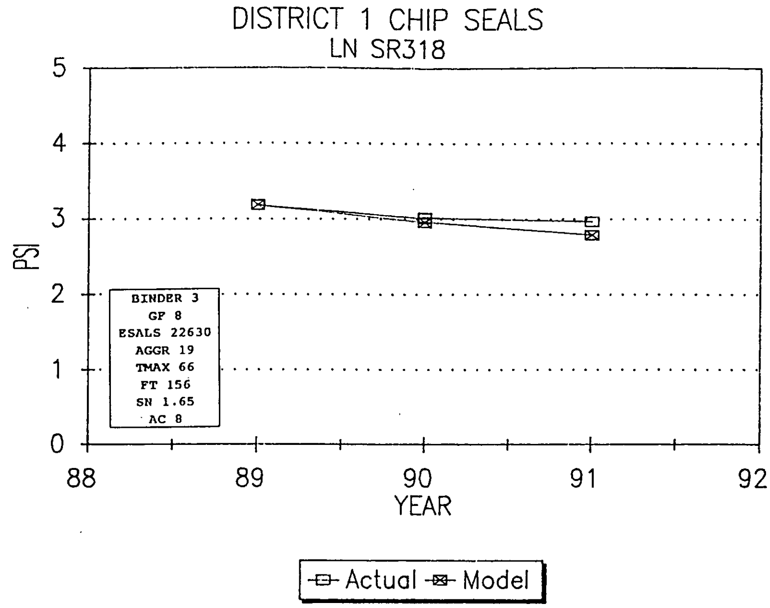

FIGURE 5 Actual and predicted PSI for chip seal model, District 1.

the model. The flush seal model in District 1 has an R^2 of 0.58, which is also low compared to the other models. However, in the case of the flush seal District 1 model, the agreement between the model and the actual data was excellent (Figure 2). This indicates that when the model has a low R^2 value (below 0.8), its performance becomes unpredictable. In other words, a model with an R^2 value below 0.8 may give excellent prediction for one project while showing poor prediction for another one. Based on this criterion, the flush seal (District 1) and the sand seal (District 2) models presented in this paper should be used with extreme caution. Tables 1 through 9 summarize the verified models for all techniques and all NDOT districts.

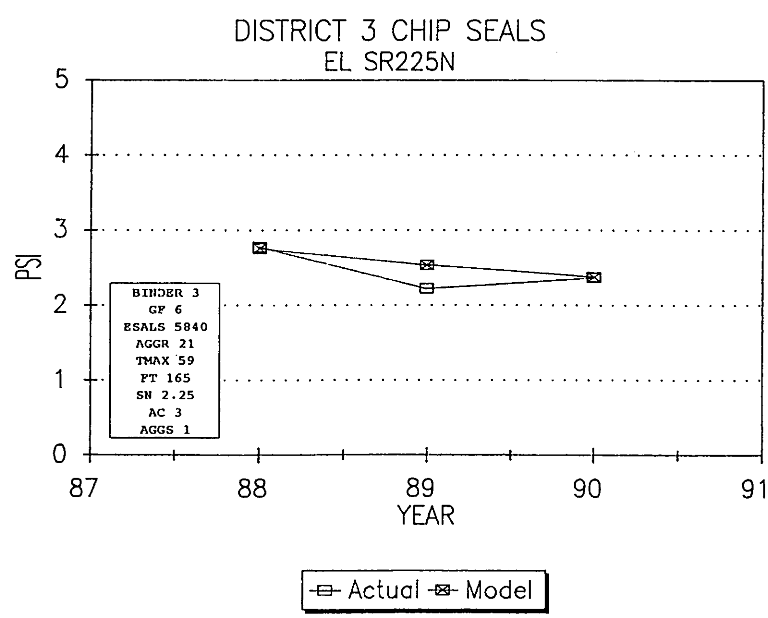

FIGURE 6 Actual and predicted PSI for chip seal (EL SR 225N) model, District 3.

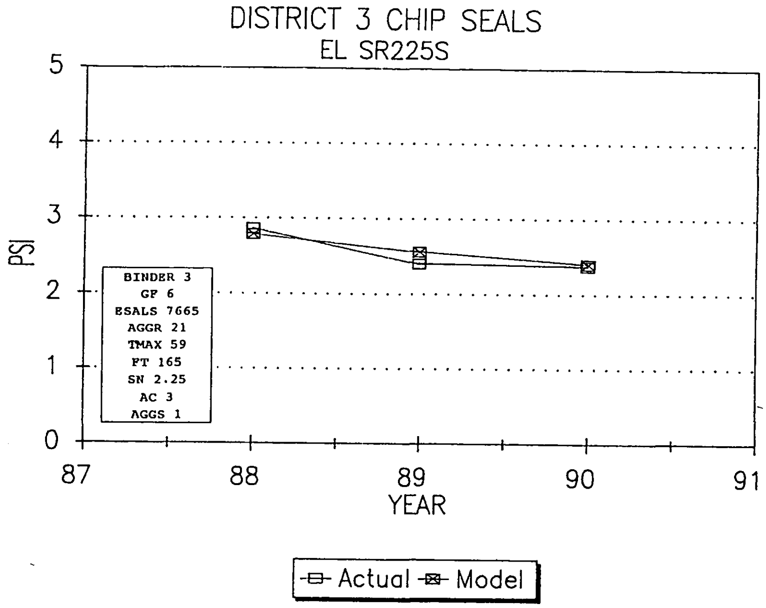

FIGURE 7 Actual and predicted PSI for chip seal (EL SR 225S) model, District 3.

Definition of Variables

The following represents a list of the variables included in the models shown in Tables 4 through 9.

AC: Type of binder used in the first structural layer below the flush, sand, and chip seals.

AGGR: Aggregate spread rate for chip and sand seal projects, lbs/yd^2 ($0.54\ kg/m^2$).

AGGS: Maximum nominal aggregate size used in chip seal projects.

BDR: Binder application rate for flush, sand, and chip seal projects, gal/yd^2 ($4.6\ L/m^2$).

Binder: Type of binder used in maintenance project.

CFT: Cumulative value of freeze-thaw cycles. It is obtained as cycles per year multiplied by year of project, (see FT for freeze-thaw cycle information).

ESALS: Cumulative value of 80-kN equivalent single axle loads calculated by multiplying the daily 80-kN ESALS by 365 and a

TABLE 1 Verified Flush Seal District 1 Model

Flush Seal District 1 Model	Number of Observations	R-Squared
$PSI = 36.03 + C1 + 2.8e\text{-}7ESALS - 0.18YEAR - 0.42TMAX + 0.14TMIN - 0.25WETD - 1.89e\text{-}13ESALS^2$	540	0.58
Variables	**Range**	
ESALS	365 - 2614313	
YEAR	1 - 3	
TMAX	58 - 81	
TMIN	27 - 50	
WETD	22 - 48	
Binder Type	**Constant (C1)**	
SS-1H	0.00	
MC-70	0.57856986	

TABLE 2 Verified Flush Seal District 2 Model

Flush Seal District 2 Model	Number of Observations	R-Squared
PSI = 3.27 + C1 + 2.86e-6ESALS - 0.56SN - 0.13YEAR	72	0.91
Variables	**Range**	
ESALS	365 - 1018350	
YEAR	1 - 3	
SN	1.00 - 3.48	
Binder	**Constant (C1)**	
SS-1H	0.00	
CRS-1	1.047347855	

TABLE 3 Verified Flush Seal District 3 Model

Flush Seal District 3 Model	Number of Observations	R-Squared
PSI = 11.96 + C1 + C2*BDR - 7.00e-7ESALS - 5.62SN - 0.34YEAR - 1.79e-13ESALS^2 + 0.92SN^2	288	0.88
Variables	**Range**	
ESALS	10950 - 3759135	
YEAR	1 - 3	
SN	1.30 - 4.18	
BDR	0.05 - 0.18	
Binder Type	**Constant (C1)**	
CRS-1	-0.0488592	
MC-250	24.7892223	
SS-1H	0.00	
Binder Type	**Constant (C2)**	
CRS-1	0.00	
MC-250	-228.2079830	
SS-1H	-1.7459573	

TABLE 4 **Verified Sand Seal District 1 Model**

Sand Seal District 1 Model	Number of Observations	R-Squared
PSI = -6.43 + C1 + 30.52BDR - 1.32e-6ESALS - 0.13YEAR	256	0.86
Variables	Range	
ESALS	9125 - 324120	
YEAR	1 - 5	
BDR	0.08 - 0.34	
Binder Type	Constant (C1)	
LMCRS	-0.50753824	
SS-1H	3.73656624	
CRS-1	6.51841777	
CRS-2H	-0.24556977	
ARA-A	7.83622503	
ARA-B	0.00	

TABLE 5 **Verified Sand Seal District 2 Model**

Sand Seal District 2 Model	Number of Observations	R-Squared
PSI = 6.23 + C1 - 0.51BDR + 3.95e-6ESALS + 0.24SN - 0.045TMAX - 9.8e-4CFT - 0.50YEAR + 3.50e- 10ESALS^2+ 0.12YEAR^2 - 8.93e-6ESALS*SN	314	0.60
Variables	Range	
ESALS	365 - 97455	
YEAR	1 - 5	
TMAX	46 - 69	
SN	1.10 - 2.99	
CFT	95 - 915	
BDR	0.11 - 0.25	
Binder Type	Constant (C1)	
MC-250	-0.232861533	
SS-1H	0.191551524	
CRS-1	0.00	

TABLE 6 Verified Sand Seal District 3 Model

Sand Seal District 3 Model	Number of Observations	R-Squared
PSI = 11.34 + C1 + 7.25BDR + 5.25e-6ESALS + 0.38SN - 0.15TMAX - 4.3e-3CFT + 0.26YEAR - 3.91e-13ESALS^2 + 0.069YEARS^2 - 2.47e-6ESALS*SN	224	0.80

Variables	Range
ESALS	365 - 1769885
YEAR	1 - 4
TMAX	59 - 67
SN	1.40 - 4.03
CFT	154 - 756
BDR	0.10 - 0.36

Binder Type	Constant (C1)
SS-1H	-1.55768840
LMCRS-2H	-1.41913898
MC-70	1.10471980
MC-800	-0.34928839
MC-250	0.00

growth factor and adding to the previous year, beginning with year zero of a project.

FT: Total number of freeze-thaw cycles that a pavement may experience over the course of one year.

TMAX: Maximum average yearly temperature that a pavement section may experience.

TMIN: Minimum average yearly temperature that a pavement section may experience.

SN: Structural number prior to application of a maintenance technique.

WETD: Total number of wet days.

YEAR: Service year of the project. The year of construction is represented by year zero.

SUMMARY AND CONCLUSIONS

Nine performance models were developed to cover all maintenance techniques for all three NDOT districts. The three techniques for which models were developed are flush seals, sand seals, and chip seals.

The majority of the models have R^2 values above 70 percent, indicating a very good fit between the models and the data. The verification study showed an excellent correlation between the measured PSI values and computed values for test sites that were not in the original data base.

Based on the analysis of the data and the verification study, the following recommendations can be made.

- The flush seal model for District 2 has only 12 reduced observations, which were obtained from four projects. Therefore, even though the R^2 for this model is very high (0.91), the model should be used with extreme caution because of the model's extremely limited data base.
- The models should not be used for situations that are outside the boundaries of the original data base. If a certain combination is desired that is outside the boundaries of the data base, an effort should be made to approximate the desired data with the closest variables that exist within the data base. For example, if a binder type is recommended for a flush seal project, and that binder is unavailable in the model's data base, then a binder that most closely resembles the desired binder, in performance characteristics, should be chosen.
- The developed models should undergo extensive implementation efforts and be updated annually during the first 3 to 5 years to accommodate the rapidly changing trends in material specifications and pavement performance monitoring.

TABLE 7 Verified Chip Seal District 1 Model

Chip Seal District 1 Model	Number of Observations	R-Squared
$PSI = 1.20 + C1 + C2 + C3 - 2.89e\text{-}7ESALS + 0.027AGGR - 0.013TMAX - 8.6e\text{-}3FT + 0.78SN - 0.28YEAR + 0.023YEAR^2$	284	0.84
Variables	**Range**	
ESALS	1095 - 523410	
AGGR	19 - 33	
TMAX	66 - 80	
FT	53 - 156	
SN	1.35 - 3.76	
YEAR	1 - 6	
Binder Type	**Constant (C1)**	
MC-800	1.021811264	
CRS-2/CRS-2H	0.135232398	
LMCRS-2	0.00	
AC	**Constant (C2)**	
60-70	1.660032310	
85-100	0.829006560	
SC-4	0.899722220	
SC-800	0.325306063	
MC-800	1.207444910	
AR-4000	0.00	
Binder - AC Combination	**Constant (C3)**	
MC-800 & 60-70	-0.705516471	
MC-800 & SC-800	0.284393056	
All other combinations	0.00	

TABLE 8 Verified Chip Seal District 2 Model

Chip Seal District 2 Model	Number of Observations	R-Squared
$PSI = -2.86 + C1 + C2 + C3 + C4 - 1.02e\text{-}4ESALS - 0.015AGGR + 0.075TMAX - 2.98e\text{-}3FT + 0.125SN - 0.33YEAR + 0.005YEAR^2$	234	0.87
Variables	**Range**	
ESALS	365 - 1647245	
AGGR	20 - 38	
TMAX	58 - 73	
FT	100 - 183	
SN	1.68 - 6.17	
YEAR	1 - 4	
Binder Type	**Constant (C1)**	
CRS-2/CRS-2H	1.281414527	
LMCRS-2	1.475765738	
AR-2000	0.00	
AC	**Constant (C2)**	
85-100	1.166532005	
120-150	-0.098528394	
SC-800	0.869102804	
AR-2000	0.143673193	
AR-4000	0.00	
AGGS	**Constant (C3)**	
3/8"	0.579529646	
1/2"	0.00	
Binder - AC Combination	**Constant (C4)**	
CRS-2/CRS-2H & 120-150	0.554234128	
CRS-2/CRS-2H & AR-4000	0.283288225	
All other combinations	0.00	

TABLE 9 Verified Chip Seal District 3 Model

Chip Seal District 3 Model	Number of Observations	R-Squared
PSI = -24.04 + C1 + C2 + C3 + C4 + 4.90e-7ESALS - 0.38AGGR + 0.83TMAX - 0.042FT - 1.32SN - 0.60YEAR + 0.056YEAR^2	150	0.92
Variables	**Range**	
ESALS	2190 - 1188805	
AGGR	20 - 30	
TMAX	57 - 67	
FT	145 - 216	
SN	1.65 - 5.41	
YEAR	1 - 4	
Binder Type	**Constant (C1)**	
CRS-2/CRS-2H	1.02686865	
LMCRS-2	0.27622556	
MC-3000L	0.00	
AC	**Constant (C2)**	
85-100	-0.13911552	
120-150	-6.00223816	
SC-800	-5.11758889	
MC-800	-8.10408550	
AR-4000	-4.16186176	
AR-1000	0.00	
AGGS	**Constant (C3)**	
3/8"	3.62555754	
1/2"	0.00	
Binder - AC Combination	**Constant (C4)**	
CRS-2/CRS-2H & 120-150	0.13670219	
CRS-2/CRS-2H & MC-800	-1.68689386	
All other combinations	0.00	

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