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DEVELOPMENT of PERFORMANCE CURVES for PAVEMENT REHABILITATION and MAINTENANCE TREATMENTS

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16. Abstract

Using linear regression analysis, 16 flexible-pavement performance models were generated: nine maintenance models and seven rehabilitation models. The models related the pavement's Present Servicability Indenx to its age, materials properties, traffic loadings, and environmental conditions. Eleven of the models have R-squared values exceeding 70 percent—indicating a good correlation between the regression models and the data used to develop them. All of the models have R-squared values exceeding 57 percent.

To develop the performance models, data collected by Nevada Department of Transportation personnel over the life of 208 projects were used. Statistically significant samples were drawn from these projects for each of the three maintenance and three rehabilitation techniques that NDOT commonly employs. The maintenance techniques include flush seals, sand seals, and chip seals. The rehabilitation techniques include flexible overlays, mill/overlays, and roadbed modifications. To product statistically accurate predictions, performance models for each technique were separately developed for each of NDOT's three districts (except that a statewide model was developed for milling/overlaying).

In most 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, twelve out of the sixteen 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.

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1.0 INTRODUCTION

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 in order 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 which 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 which develop performance models will help the engineers to evaluate the effectiveness of the PMS and determine the usefulness of the collected data.

The most common method of monitoring pavement performance is through field testing and surveys of actual road sections on a periodic basis. Pavement management systems are usually implemented for this purpose. Highway agencies have also been implementing highly effective quality control/assurance programs to measure materials properties considered to be critical to the long-term performance of the pavement. Development of pavement performance models which can tie the PMS data with materials properties is by far the most effective approach.

1.1 Objective

The objective of this research is to develop performance curves for the major group of pavement rehabilitation and maintenance techniques used by the Nevada Department of Transportation (NDOT). The data collected by NDOT personnel over the lifetime of each of these techniques, employed in various projects, have been gathered and used to develop the performance curves. A performance curve is a model in which traffic, environmental, materials, and mixtures data are used in conjunction with actual performance data, as measured by the present serviceability index (PSI), to predict the long-term performance of a rehabilitation and maintenance technique. The

developed performance models and computer programs are verified through statistical analyses to prove their validity.

2.0 BACKGROUND

Attempts have been made over the last 30 years to develop models that can accurately predict the deterioration of highway pavements over time. In most cases the deterioration has been predicted by theoretical modeling and actual in-service pavement data was not used. In the cases where modeling was performed on in-service data, models were generally developed as a function of the pavement performance parameters alone - and environmental, materials and structural data were not included. Many of the pavement performance models that exist in the literature are very simple and include only some explanatory variables. The models generally do not account for common maintenance procedures and their effect on the pavement's rate of deterioration (Ramaswamy 1990). The more complex models that account for a large number of variables as well as the effects of maintenance have been found to be more realistic, but have proven to fit the data very poorly. A series of models that can provide a proper balance between realism and proper fit of in-service data are the key to effective use of modeling within the pavement management system.

2.1 In-Service Data

Theoretical modeling may develop a model that can produce deterioration rates which appear reasonable and can be extrapolated over a large range with few constraints. However, theoretical modeling suffers the major constraint of being dependent upon the expected theoretical behavior of the materials and the environment. This is acceptable when modeling materials with known properties and small expected deviations. Since pavement materials are much more variable than most other engineered materials, theoretical modeling has the tendency to produce unreasonable results. This method has been used primarily in the development of models focusing on individual damage or distress types. This is due to the fact that individual distress modes can generally be simulated in the laboratory.

The most accurate method for developing pavement performance models is the use of a large number of test sections under tightly controlled conditions. The problem with this method is that it can be very costly and may not always allow for exact duplication of field data. This method has been successfully used for modeling a single type of rehabilitation procedure in a specific geographic location (Matthews).

Therefore the most reasonable method for developing pavement performance models is the use of actual field performance data. Statistical modeling eliminates most of the before-mentioned problems but does add one major limitation. The model can only be used within the constraints of the in-service data from which it was developed.

2.2 Pavement Performance

There are three generally accepted measures of pavement performance: safety, structural performance, and functional performance. Safety is most commonly measured in terms of the pavement's frictional characteristics. Structural performance is a measure of the pavement's ability to resist deformations under traffic loads; it is most commonly measured in terms of the various distresses such as cracking or rutting. Functional performance is a measure of the pavement's ability to serve the user over time. It is usually measured in terms of the roughness or ride quality of the pavement surface.

Functional performance has been the one most commonly modeled and the one used in this research. This is partially attributed to the fact that most network PMS in use today are designed to measure the pavement's functional condition. This is achieved through the use of a previously calibrated performance index formula to weigh each of the measured distress modes. One of the most widely used functional performance indicators is the present serviceability index (PSI). The PSI is the performance measure used in this study.

The PSI was developed as a result of the AASHO Road Test in 1960. It is calculated for flexible pavements based on observations of rut depth (RD), slope variance (SV) and the extent of cracking (C) and patching (P) (in square feet per 1,000 ft^2) using the following formula:

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

The PSI has a range from 0.0 to 5.0 with 0.0 being the worst and

5.0 the best. A new pavement generally will not score above a 4.5, and pavements are generally not allowed to drop below a 2.0 depending upon their system classification. As can be seen from Equation (1), PSI is driven primarily by the slope variance of the pavement with the other factors only providing small contributions.

2.3 Existing Models

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 (Bednar 1989). All four of these states have chosen to use functional performance indicators. This is partially due to the fact that 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 pavements condition rating is plotted against its age, on a yearly basis. From Arkansas' limited analysis it was concluded that even though the curves fit the data reasonably well, they would have to be revised to account for the effects of cumulative ESAL's. Unfortunately Arkansas' limited traffic data base is going to slow the development of their final models.

Iowa considered a more elaborate model which addressed some of the more obvious factors that could affect the performance of the overlay, such as thickness, aggregate durability, base and subgrade characteristics. Sites were selected and divided by service levels and pavement type (rigid and composite). The model did allow Iowa DOT to make some generalizations regarding material selection, but it also had several shortcomings. These included no allowance for maintenance and rehabilitation techniques, limited distribution of data points for loading and age, initial PSI's 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 was very limited.

Washington developed their curves based on the 5 years of data available in their data base. They considered a larger number of variables than the other three states and as a result their models produced good statistical correlations (R^2>.70). In all of their 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.

Aside from the individual limitations of each model, all the models shared the common limitation of being very generalized. In most cases this is because very few variables have been included in the final models. The model limitations can be attributed to the original data sets from which the models were developed; in most cases the data set included only a few specific test sections believed to be representative of the entire system.

The validity of the four states models' depend on the degree to which the pavement sections used in developing the regression equations are representative of the entire system. Another limiting factor that most states have encountered is the limited amount of available data. Few states have enough data to develop models that can represent the entire life of the pavement. Five years of data may be adequate for developing equations for minor maintenance techniques, but falls short when considering a model for the life of a reconstruction job or a major overlay. It should also be noted that all of the above states except Washington, considered only one single model, typically an overlay model. Washington's model accounted for any type of maintenance work. Most other models tend to ignore any maintenance work.

3.0 REHABILITATION AND MAINTENANCE TECHNIQUES

Routine maintenance and rehabilitation activities must be conducted in a timely manner to maintain an acceptable level of the present serviceability index (PSI) for a given pavement section. The major difference between maintenance and rehabilitation activities is that maintenance does not show an initial increase in the current level of PSI and only helps in slowing down the rate of deterioration while rehabilitation does show an initial increase in the PSI level and may completely change the rate of deterioration. Figure 1 shows the difference between the two techniques.

For example, when applying a chip seal, which is a maintenance treatment, an immediate increase in PSI is not noticed because a chip seal does not reduce roughness, a major component of the PSI equation. However, applying a chip seal, reduces or eliminates water penetration through the surface, thereby slowing further deterioration of the entire pavement structure. On the other hand, applying a thick overlay, which is a rehabilitation technique, immediately increases the current PSI of the road as well as slowing the rate of deterioration.

Usually the cost of a maintenance alternative is less than the cost of a rehabilitation technique. Therefore, in order to optimize the available budget and satisfy the needs of the entire system, highway agencies including NDOT strive to determine a balance between the maintenance and rehabilitation activities.

NDOT uses several maintenance treatments as well as various rehabilitation techniques. The objective of this task was to identify the various maintenance treatments and rehabilitation techniques most commonly used by NDOT. The performance data of the selected projects will constitute the data base for the development of the performance curves.

3.1 Major Rehabilitation and Maintenance Techniques Used by NDOT

The primary goal of the selection process was to assure that the techniques to be modeled had been used often enough that they would provide a useful final product for NDOT. If a technique was used only on a limited basis, then the available performance data would be very limited and the developed model would not be extremely useful.

The initial selections were made based on several working meetings between the researchers and NDOT engineers from the Materials and Operations Analysis Divisions. These initial selections were then presented to the pavement management working committee, which has representatives from NDOT, FHWA, and UNR, for final approval. The final list included three maintenance treatments and three rehabilitation techniques which NDOT uses on a regular basis.

Maintenance Techniques	Rehabilitation Techniques
Flush Seals	Flexible Overlays
Sand Seals	Roadbed Modifications
Chip Seals	Mill and Overlays

Several other techniques were proposed such as flexible overlays over rigid pavements, rigid overlays over rigid pavements, rigid overlays over flexible pavements, and recycling of flexible pavements. After reviewing these techniques with NDOT personnel, it was decided that these techniques have not been used often enough to develop a sufficient data base for analysis.

3.2 Project Selection Criteria

Once the final list of maintenance and rehabilitation techniques was established, the research concentrated on establishing guidelines for the selection of projects within each technique. 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, 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:

1. **Minimum Number of Replicates:** Since the models will be based on statistical analyses, there must be multiple sets of data which share a common basis. For example, there must be multiple projects which share the same geographical location for the same treatment type. For this purpose, the existing NDOT districts were used as various regions and

replicate projects were selected within each district. For the districts where large number of projects were available, a maximum number of twenty sites were selected. For districts where a limited number of projects existed, all of the available projects were selected.

In addition to the projects selected for the model development analysis, verification projects were also selected to validate the final models. At least two projects per district were set aside for the model verification study.

2. **Minimum Site Length:** When using actual field data, it is very important to select sites that are representative of the entire pavement section. Short projects may suffer from atypical data especially toward the beginning and end of a project. In addition, short sections may have been constructed in response to a localized condition and not as a normal construction project. Therefore, it was decided that a minimum site length of two miles must be maintained to eliminate any unusual or localized conditions.

3. **Availability of Traffic History:** Traffic loads are the most important factors influencing the long-term performance of pavements. The traffic data can be expressed in many different formats, including vehicles per day, percent trucks, ESAL's, etc.. It was decided that each project must have traffic loading data. Since any type of traffic data can be converted to the required format

providing that the appropriate conversion factors exist, the criterion for traffic data consisted of the availability of both traffic volumes and the appropriate conversion factors.

4. **Availability of Materials Data:** The unique feature of this study is the inclusion of materials data into the performance models. Therefore, the availability of materials data was considered as a criterion for the selection of any project. It was anticipated that in some cases elaborate materials data would exist while in other cases the data would be limited.

5. **Availability of Structural Information:** It is well known that the performance of a treatment will depend on the quality of the supporting structure. For example, a flexible overlay will perform better on a structurally strong pavement than on a weak pavement. Therefore, the structural information criterion included the availability of information on the thickness and type of the supporting layers.

6. **Availability of PMS Data:** As mentioned earlier, the actual field performance data represents the backbone of this study. Such data is summarized in a PMS data base. Therefore, the availability of the PMS data for the selected project is a very important criterion and must always be satisfied, otherwise the project can not be selected for analysis.

3.3 Selection of Projects

The existing NDOT districts lines were used as regional boundaries. Projects were selected for maintenance and rehabilitation techniques within each district. The projects selection criteria were strictly followed with very few exceptions; some projects that were just under 2 miles long were accepted due to the limited number of available projects. The selected projects are summarized in Tables 1 through 6.

4.0 DATA COLLECTION

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. In order to be unbiased, the lists of factors were developed before any of the actual data sources were examined.

The lists were organized into standard data collection forms to expedite the collection process. The forms became known as "wish lists," as they contained all of the information the researchers hoped they could obtain. The forms were divided into four primary sections:

1. Project identification and information;
2. Specific material and construction information on the technique of interest;
3. Information desired from the PMS data base, including environmental data;
4. Information on any past construction techniques and materials used within the bounds of the current project.

Standardizing the data collection forms created more efficient collection and reduction of the large amount of information. Figure 2 is an example of the form used for the flush seals; standard forms used for other techniques may be found in Appendix A.

4.1 Structural Data

Each standard data collection form consisted of two pages, the first page was primarily for the specific material and construction information used with the technique being examined, the second page consisted of structural and material information of all previous construction activities. Together this information composed what is referred to as the overall structural data.

The structural data came from a variety of sources by numerous methods. The boundaries of the project were located in books containing the road life histories of every mile of road within the current and past state systems. These books are commonly referred to as RL-7's, they identify by project or completion number every recorded maintenance, rehabilitation, and reconstruction activity known to have occurred on a section of highway since its incorporation into the state highway system. Many records date back to the early 1910's. While they are not always entirely accurate, the RL-7's are the only source for much of the structural information. The RL-7's alone do not contain enough information to develop the structural history of the pavement, but they do provide the contracts and completion numbers from which more complete information may be obtained.

Once the list of contract numbers is generated, individual contracts are carefully examined. If available, as-built plans are used to obtain the structural information. If the as-built plans are not available, copies of the contracts together with field notes and lab test results are used to determine the exact materials and quantities used. Detailed information for section one of the overall structural data collection forms can also be obtained at this time if the specific project was performed under contract and not by state forces.

In the case of work done by state forces, the project is not assigned a contract number. It is generally referred to by a job authorization or a job completion number depending on the time period in which it was completed. Job authorization numbers (JA's) were assigned to all state force jobs completed during the 1970's. Information on JA's is generally available on microfilm in the records department of NDOT. Job completion numbers (JC's) were assigned to all state force jobs completed during the early 1980's. JC's can be found on hard copy in a series of books that maintenance keeps on file. State force jobs completed in the late 1980's can only be found in Maintenance on hard copy, without reference numbers, only a location description. The quantity and quality of the information that can be obtained on state force jobs vary widely from excellent to non-existent.

Due to the long period of time and large number of contracts that many of the histories covered, uniformity of the data was a significant problem. While many of the newer contracts and state force jobs contained the detailed information on the "wish list," these contracts composed only a small portion of the entire list of projects. Many of the older contracts were quite vague and while they provided material types and thicknesses, they did not contain any site specific properties of the material. As a result, much the of the desired information could not be obtained. In order to maintain a uniform data set, much of the information obtained from the newer contracts had to be discarded. The final result was that only the material type and layer thicknesses could be used in the final data set.

Detailed information was obtained on most of the techniques being considered. However, in order to comply with the PMS data availability criterion, only projects constructed within the past 12 years were selected.

4.2 Environmental Data

Nevada's diverse climatic conditions play a large role in the design, construction, and techniques used 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 challenge came in selecting a source for the environmental data. The available sources are the National Oceanic and Atmospheric Association (NOAA) and the NDOT PMS system. The NOAA data is by far the most complete in terms of accuracy and amount of information, but is very limited in its coverage. NOAA data can only be obtained where there is an observation station, this left most of the road miles in the state with no information.

The NDOT PMS system also contains weather data, and while it does have several limitations, it does cover every single road mile in Nevada. It is limited by the fact that it is not actual observed field conditions; it is based upon a 30 year weather model that was developed in the early 1980's based on NOAA 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 milepost based on its elevation. Unfortunately the NOAA modeling did not include the period of the 1980's, which is the time period from which the construction projects of interest were taken, and therefore the weather data used in the development of the pavement performance curves is only as accurate as the weather model.

There are several key advantages to using the PMS's weather data, the most significant is that it is currently part of the state's PMS data and therefore can be readily accessed, both for modeling purposes and for state use. This maintains the basic objective in developing models with data that is part of the existing system, or which could easily be incorporated into the system.

4.3 Pavement Management System Data

NDOT has had an operational PMS since 1980, and while the system has undergone several changes in the last 13 years, most of the data in the system is available for all years since 1981; in most cases the 1980 data is not complete.

The PMS data is composed of individual records for each directional lane mile currently on the NDOT highway system. Each record is composed of 331 characters making up 104 fields, divided into 8 sections. The sections include record identification, skid resistance data, ride data, condition data, traffic data, reduced calculated fields, calculated pavement ratings, and the weather data as described above.

The skid, ride, condition, and traffic data sections are the actual field observations. Each of the fields within these sections is used to calculate the reduced fields. The calculated fields include: PSI, percent alligator cracking, percent linear cracking, percent patching, average rut depth, slope variance, and adjusted skid. The equation used to calculate PSI is the same as Equation 1 shown in page 6.

Percent alligator cracking, percent linear cracking, percent patching and average rut depth are calculated by taking the field observations of 1,000 square foot section in each mile and extrapolating the severity and extent over the entire mile. Slope variance is calculated from the counts per mile obtained by driving a calibrated ride vehicle over each mile of highway. Adjusted skid number is calculated based on the values obtained from friction resistance testing of each road mile. In all cases except for the frictional resistance testing, all values are measured annually; friction resistance is measured annually on Interstate Routes, every two year on US Routes and every three years on State Routes.

In general the data found in the reduced calculated fields gives a better representation of the actual road conditions, eliminating the high variability usually associated with raw data. The calculated data also represents the latest conversions currently used by NDOT. It is for these reasons that, with the exception of the traffic and environmental data, all the distresses and other variables used in the development of models were obtained from the calculated data fields.

4.4 Data Standardization

Essential to all statistical analyses is the necessity of a standardized set of values across all the records within a given data set. In some cases this was easily accomplished through the use of the calculated fields as discussed above. However, in the cases of traffic and structural data there was still the need for data standardization. The largest challenge was to establish all of the data on the same working platform so that it could be analyzed together.

Since the personal computer (PC) platform is becoming the more common, it was determined that the modeling should be performed at this level. This required that all data be translated to the PC level. All of the structural and contract information was on hard copy or microfilm; this required that all of this data be hard keyed into the computer. All of the PMS and environmental data was in the 331 character format on the State of Nevada mainframe computer. These were downloaded to floppy diskettes in ASCII text format. The challenge was to translate the 331 character format into a 256 character format that the PC level can use. Most PC base programs are only capable of handling 256 characters per line, while the ASCII format from the mainframe contained 331 characters. NDOT provided a PC version of their mainframe editor, which saved many additional hours of editing. This program allowed line formats greater than the standard 256 characters. Using this program the 331 character data set was reduced to less than 256 characters by removing several of the fields which were not used in the data analysis such as skid, ride, and raw condition data.

Most PC based statistical programs allow for the direct input of standard data base information, and most spreadsheets allow for the creation of data base format data, while still maintaining the ability to quickly and easily do relational plots of multiple data fields. For this reason a spreadsheet was chosen as the universal program on the PC platform. The reduced PMS and environmental data could easily be imported into the spreadsheet and parsed into proper fields, and the structural data could easily be hand entered into the corresponding milepost locations.

Once in the spreadsheet, the data still required some standardization and editing before the statistical analysis could be performed. Due to the limited amount of overall structural data, it was determined that the only format that would be useful was in the form of a structural number (SN). From the structural histories, material types and layer thicknesses were obtained, the data can be reduced to a single structural number using the following equation:

$$SN = \Sigma a_i t_i \qquad (2)$$

where **SN** is the structural number, **n** is the number of layers, **a** is the layer coefficient, and **t** is the layer thickness. Values used for a were the standard values currently in use by NDOT and are listed in Appendix B. (sample calculations are also included).

The other number that required standardization was the number of 18-thousand-pound (18-Kip) equivalent single axle loads (ESAL's). While the PMS data base does contain a value for cumulative ESAL's this value is cumulative since the last reconstruction. For the purposes of the performance modeling, cumulative ESAL's just since the beginning of the specific technique were required. Using the PMS value for daily 18-Kip ESAL's, the cumulative value was obtained by multiplying the daily 18-Kip ESAL's by 365 and summing them over the entire number of years for the specific project. The PMS daily 18-Kip value already included adjustments for average daily traffic, percent trucks, and load equivalency factors for each specific site.

Elimination or correction of outlier data points was also incorporated into the process of data standardization. Outlier data points can be described as data that is not representative of the entire population. These points can occur as a result of

5.0 MODEL DEVELOPMENT

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

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

5.1 Statistical Analysis

The box-plot statistical analysis was performed as a final check of the data prior to performing an actual regression analysis. This analysis calculates the mean standard deviation for the PSI data for each pavement section. These values are then used to generate the acceptable range of data (e.g. +/- one standard deviation). Any observation that falls outside the acceptable range is considered an outlier. This allowed for easy identification of possible outliers, unrepresentative, or skewed data points as well as providing a preliminary indication as to possible interactions between variables. Initially, all data that had been gathered and reduced were analyzed. 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.

5.2 Regression Analysis

After the data had been reviewed and any possible changes or corrections made, the first of many regression analyses was performed. The analyses were performed using a General Linear Model Procedure (GLM) 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% chance of being of significant importance 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 provided an indication of any variables that may possibly be interrelated or interacting with each other. The Type I sums of squares indicates a variable's significance when considering removing the effects of the other variables, and the Type II sums of squares indicates 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 (Bednar, 1989). For example, a positive coefficient for the 18-kip ESAL's term indicates that higher ESAL's on the pavement section would generate higher PSI. Although the models may appear to fit the data well, people 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.

When the final set or sets of independent variables had been decided upon, another regression analysis was performed to develop a model or models which were verified against actual data that was not included in the original analyzed data sets.

In some cases there was more than one model that seemed to fit the observed data very well, and therefore multiple models were sometimes considered.

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 (ESAL's, 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 0 to 1 with the higher number indicating a better fit of the model to the actual data.

5.3 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. In order 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 was examined to assure that it met the required criteria for the model or models being considered. The independent variables were input into the developed regression models and the PSI's predicted by the models were plotted against the actual recorded PSI's. In most cases the fit was superb and often the two lines were indistinguishable. Figures 3 through 17 show examples of the model verification data. Based on the verification study it was determined which models were actually the best. The model that had the best fit was chosen as a final candidate for that project and district.

Since the PSI is an arbitrary scale and there can be a large variation in the initial PSI of a project, it was decided to keep the initial PSI value in the form of a user input and allow the models to predict the change in PSI over the years of service. This provides the user with a more accurate prediction by accounting for project variability. Tables 7 through 22 summarize the verified models for all techniques and all NDOT districts.

5.3.1 Definition of Variables

AC: Type of binder used in first the structural layer below the flush, sand and chip seal projects, located in as-built plans, identified as a type.

AGGR: Aggregate spread rate for chip and sand seal projects, found in maintenance records, lbs/yd^2.

data bases, the statistical relationships will be limited to applications which lie within the boundaries of realistic combinations of variables. Therefore, the statistically based models should only be used with realistic variables and combinations of variables. If unrealistic values or combinations are used in the models, the output of the models may prove to be highly unreliable. For example, if the model is used to predict the performance of a pavement section with a low structural number that is subjected to very high ESAL's, the output of the model may be very unrealistic. This results from the fact that pavements with low structural numbers are not built to carry high ESAL's and vise versa.

5.5 Sensitivity Analysis

Sensitivity analysis allows for the examination of the models in hypothetical situations in which each of the variables is tested over its entire range while holding all other variables constant. This indicates the strong and weak significance of variables in the models and allows for any final changes that may need to be considered, or limitations that may need to be placed on a model. In the analysis some of the variable were used in the models at their low, mean, and high levels and the output was analyzed. Figures 18 through 25 show typical sensitivity analysis curves. Figures 18 through 22 demonstrate sensitivity analysis that were performed using realistic variables and combinations of variables, these plots indicate realistic trends. Figures 23 through 25 demonstrate what could happen if unrealistic combinations of data are input to the model. All the values used in the development of the sensitivity analysis relationships are presented on the graphs for ease of reference.

6.0 SUMMARY AND RECOMMENDATIONS

Sixteen performance models were developed to cover all maintenance and rehabilitation techniques for all three NDOT districts.

The six techniques for which models were developed are.

Maintenance Techniques	Rehabilitation Techniques
Flush Seals	Flexible Overlays
Sand Seals	Roadbed Modifications
Chip Seals	Mill and Overlay

The majority of the models have R-squared values above seventy 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.

The research work summarized in this report represents a tremendous effort to correlate actual pavement performance to material properties, traffic loading, and environmental conditions. This effort represents a major step towards using PMS data in conjunction with structural and environmental information to develop relationships between PSI and pavement age. Advanced statistical analysis has proven to be a powerful tool in analyzing pavement performance data.

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-squared 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 sensitivity analysis has shown that in order to obtain the best results from the models, realistic values for variables and combinations of variables must be used as inputs.

• The models should not be used for situations which are outside the boundaries of the original data base. If a certain combination is desired which is outside the boundaries of the data base, an effort should be made to approximate the desired data with the closest variables that existed within the data base. For example, if a binder type is recommended for a flush seal project, and that binder is not available in the model's data base, then a binder which most closely resembles the desired binder, in performance characteristics, should be chosen.

• The developed models should undergo extensive implementation efforts and be updated on a yearly basis during the fist three to five years in order to accommodate the rapidly changing trends in material specifications (i.e. SHRP) and pavement performance monitoring.

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Matthews, James Mark and Pandey, B.B.. Performance of Flexible Pavements. Transportation Research Record 1307, 1991, pp. 51-62.

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TABLES

Table 1. State Force Flush Seal Projects

State Force Flush Seal Projects						
				Milepost		
Project	Contract	Route	County	Begin	End	Length
101	1988	IR015	CL	66.80	93.91	27.11
102	1989	SR264	ES	0.00	19.68	19.68
103	1989	SR266	ES	0.00	24.03	24.03
104	1987	SR317	LN	37.10	45.33	8.23
105	1989	SR361	NY	7.67	22.27	14.60
106	1989	SR373	NY	0.00	16.30	16.30
107	1989	SR844	NY	0.00	12.31	12.31
109	1988	US006	NY	98.00	112.00	14.00
111	1986	US093	LN	80.45	88.40	7.95
112	1987	US093	LN	148.00	157.48	9.48
113	1989	US095	CL	9.00	18.50	9.50
114	1986	US095	CL	26.00	46.50	20.50
115	1988	US095	CL	92.36	106.30	13.94
116	1990	US095	ES	20.00	43.55	23.55
117	1988	US095	ES	40.15	44.95	4.80
118	1990	US095	ES	86.43	94.20	7.77
119	1986	US095	NY	14.30	26.43	12.13
120	1988	US095	NY	72.00	86.56	14.56
121	1989	US095	NY	85.25	103.58	18.33
209	1983	SR121	CH	14	26.95	12.95
201	1989	SR671	WA	0.00	4.54	4.54
202	1990	SR827	LY	1.00	5.80	4.80
205	1990	US395	DO	0.00	4.00	4.00
206	1990	US395	DO	4.00	16.00	12.00
301	1986	IR080	EL	32.00	44.00	12.00
302	1987	IR080	EL	74.04	91.30	17.26
303	1986	IR080	EU	0.00	2.80	2.80
305	1984	IR080	HU	29.30	37.04	7.74
306	1988	IR080	HU	54.86	61.38	6.52
307	1987	IR080	LA	16.00	26.98	10.98
308	1990	SR225	EL	38.00	52.72	14.72
311	1984	SR227	EL	0.00	4.90	4.90
312	1986	SR305	LA	73.00	91.00	18.00
313	1986	SR318	NY	0.00	18.80	18.80
314	1986	SR318	NY	18.80	33.50	14.70
315	1986	US006	WP	19.00	29.63	10.63
317	1989	US095	HU	10.00	22.06	12.06

Table 2. State Force Sand Seal Projects

State Force Sand Seal Projects						
				Milepost		
Project	Contract	Route	County	Begin	End	Length
101	1989	SR160	CL	0.00	2.03	2.03
102	1989	SR376	NY	15.30	25.03	9.73
103	1987	SR376	NY	25.03	36.75	11.72
104	1988	US006	NY	1.80	7.44	5.64
105	1989	US006	NY	7.30	14.20	6.90
106	1988	US095	MI	0.00	16.56	16.56
107	1986	US095	MI	25.55	28.40	2.85
201	1990	SR121	CH	0.00	14.30	14.30
202	1990	SR121	CH	14.30	26.95	12.65
203	1989	SR341	ST	9.00	14.54	5.54
204	1989	SR341	WA	14.54	20.50	5.96
205	1988	SR342	ST	0.00	2.60	2.60
206	1987	SR396	PE	0.00	13.00	13.00
207	1988	SR396	PE	13.00	28.00	15.00
208	1990	SR397	PE	0.00	11.40	11.40
209	1987	SR398	PE	0.00	4.30	4.30
210	1988	SR431	WA	0.00	8.14	8.14
211	1988	SR431	WA	8.14	20.50	12.36
212	1989	SR431	WA	20.00	24.53	4.53
213	1989	SR445	WA	36.61	43.98	7.37
214	1989	SR446	WA	0.00	13.16	13.16
215	1990	SR839	CH	0.00	13.92	13.92
216	1990	SR839	MI	74.82	78.97	4.15
218	1990	US050	CH	43.71	53.70	9.99
219	1990	US050	CH	53.70	60.52	6.82
301	1988	IR080	HU	17.95	29.30	11.35
302	1988	SR140	HU	3.80	6.53	2.73
303	1988	SR140	HU	60.30	75.50	15.20
305	1986	SR305	LA	69.35	77.20	7.85
306	1988	SR305	LA	98.20	109.18	10.98
307	1987	SR306	EU	12.80	20.43	7.63
309	1989	SR794	HU	14.62	17.10	2.48
310	1986	SR892	WP	0.00	5.50	5.50
311	1986	SR892	WP	11.70	23.00	11.30
312	1988	US095	HU	10.00	22.09	12.09
313	1987	US095	HU	22.04	25.30	3.26
314	1986	US095	HU	45.70	60.20	14.50
315	1990	US095	HU	60.20	73.76	13.56

Table 3. State Force Chip Seal Projects

State Force Chip Seal Projects						
				Milepost		
Project	Contract	Route	County	Begin	End	Length
101	1983	US093	LN	89.00	92.00	3.00
102	1984	SR160	NY	22.00	34.00	12.00
103	1984	SR372	NY	0.00	7.77	7.77
104	1984	US095	CL	124.00	130.14	6.14
105	1984	US095	NY	8.98	15.00	6.02
106	1984	US093	LN	0.00	12.15	12.15
107	1985	US093	CL	52.18	63.31	11.13
108	2058	SR375	LN	0.00	40.00	40.00
109	1986	US050	CL	106.00	111.00	5.00
110	1986	SR160	NY	6.30	11.00	4.70
111	1987	SR160	NY	22.00	26.00	4.00
112	1987	US093	CL	13.30	16.62	3.32
113	1988	US095	NY	7.00	14.37	7.37
114	1989	US093	LN	39.70	46.46	6.76
115	1989	US093	LN	55.00	64.66	9.66
116	1989	SR319	LN	51.50	59.00	7.50
201	1985	US095A	MI	0.00	5.92	5.92
202	1985	IR080	PE	26.21	37.68	11.47
203	1986	SR088	DO	0.00	4.50	4.50
204	1986	US050	CC	0.70	7.60	6.90
205	1986	US050	CH	16.04	20.66	4.62
206	1986	US050	LY	8.32	18.37	10.05
207	1986	US395	DO	4.53	10.00	5.47
208	1986	US395	WA	1.03	9.15	8.12
209	2147	US050	CH	70.00	100.00	30.00
210	1987	SR208	LY	20.04	25.84	5.80
211	1987	US050	DO	0.66	7.02	6.36
212	2208	IR080	PE	12.00	16.48	4.48
213	2208	IR080	PE	37.70	43.55	5.85
214	2206	IR080	WA	41.70	4.11	7.50
215	1988	SR429	WA	1.51	3.50	1.99
216	1988	SR429	WA	3.50	7.38	3.88
217	1989	US050	LY	32.08	35.36	3.28
306	1985	US093	EL	0.00	15.00	15.00
307	1986	US093	EL	77.34	83.20	5.86
308	1986	US093	WP	56.65	60.80	4.15
309	1986	US006	WP	14.19	18.99	4.80
310	1986	US050	WP	61.81	66.06	4.25
311	1987	IR080	HU	36.00	42.19	6.19
312	1987	SR290	HU	0.63	4.00	3.37
313	1987	IR080	EL	95.20	102.79	7.59
314	1987	US093A	EL	9.03	12.38	3.35
316	1987	US006	WP	1.80	8.37	6.57
317	2255	US050	EU	2.33	7.00	4.67
318	2255	US050	LA	35.59	40.00	4.41
320	1988	IRO80	EL	43.90	51.00	7.10
321	1988	IR080	HU	29.51	33.00	3.49

Table 4. Contract AC Overlay Projects

Contract AC Overlay Projects						
				Milepost		
Project	Contract	Route	County	Begin	End	Length
102	1837	IR015	CL	51.12	66.73	15.61
105	2155	SR360	MI	0.00	23.24	23.24
106	2155	SR361	MI	6.00	22.00	16.00
107	1963	US006	ES	19.98	26.00	6.02
109	2122	US093	CL	17.62	24.99	7.37
110	1964	US093	LN	147.90	161.31	13.41
112	2005	US095	CL	35.41	46.63	11.22
201	2033	SR207	DO	0.03	3.14	3.11
202	2151	SR341	ST	9.20	14.00	4.80
203	2146	SR431	WA	8.14	20.00	11.86
204	2150	SR447	WA	0.00	16.00	16.00
205	2151	SR661	WA	27.55	30.46	2.91
206	2151	SR671	WA	0.00	4.54	4.54
208	2150	SR828	LY	0.11	7.75	7.64
209	1844	US050A	CH	0.00	3.14	3.14
210	2145	US050A	CH	3.06	9.29	6.23
211	1844	US050A	LY	70.41	78.00	7.59
212	1971	US095A	LY	44.24	58.36	14.12
301	2124	IR080	EL	0.00	1.12	1.12
304	1969	IR080	EL	91.30	93.36	2.06
305	2017	IR080	EU	0.00	2.88	2.88
306	2124	IR080	EU	15.73	25.70	9.97
307	2017	IR080	LA	21.23	26.98	5.75
308	2158	SR233	EL	11.14	22.70	11.56
311	2159	SR226	EL	17.42	32.85	15.43
313	2080	SR489	WP	0.00	8.24	8.24
314	2085	US006	WP	30.10	34.00	3.90
315	1974	US093	WP	53.45	64.84	11.39
316	2080	US093	WP	67.00	76.35	9.35
319	1962	US095	HU	0.02	10.00	9.98
321	1950	SR318	NY	0.00	7.04	7.04

Table 5. Contract Roadbed Modification Projects

Roadbed Modification Projects with CTB						
				Milepost		
Project	Contract	Route	County	Begin	End	Length
101	1930	US093	LN	80.67	88.31	7.640
102	1936	US006	NY	0.82	14.00	13.180
104	1960	US095	MI	11.48	16.38	4.900
105	2265	US095	ES	26.00	43.95	17.950
107	2322	SR376	LA	0.00	18.06	18.060
108	2330	US006	NY	117.99	132.02	14.030
109	2331	US006	NY	83.26	98.00	14.740
110	2344	IR015	CL	118.45	123.79	5.340
201	1973	US050	CH	11.56	15.91	4.350
203	2045	US095A	LY	13.65	24.63	10.980
204	2094	SR117	CH	4.22	6.95	2.730
205	2094	US095	CH	15.68	25.07	9.390
206	2149	US050	CH	43.71	60.05	16.340
207	2170	SR116	CH	0.00	10.49	10.490
208	2209	US095	CH	28.23	50.31	22.080
212	2317	US050	CH	30.03	43.71	13.680
213	2319	US095	MI	27.98	39.68	11.700
301	1929	SR225	EL	76.37	87.23	10.860
302	1943	US006	WP	19.00	36.00	17.000
303	1982	SR225	EL	94.00	112.78	18.780
304	2030	US006	WP	38.03	52.46	14.430
305	2038	SR318	NY	18.54	33.56	15.020
306	2068	SR318	WP	1.00	10.00	9.000
307	2141	SR766	EU	2.50	4.40	1.900
308	2207	US006	WP	64.85	75.10	10.250
309	2225	US093	WP	1.36	11.00	9.640
310	2258	SR225	EL	30.54	38.11	7.570
311	2264	US093	EL	54.56	64.87	10.310
312	2271	US095	HU	60.32	73.79	13.470
322	2141	SR766	EU	0.00	6.32	6.32
323	2068	SR318	WP	33.56	38.79	5.230

Table 6. Contract Milling and Overlay Projects

Contract Milling and Overlay Projects						
				Milepost		
Project	Contract	Route	County	Begin	End	Length
101	2416	IR015	CL	0.00	16.30	16.30
102	2431	SR589	CL	26.38	29.38	3.00
103	1945	SR601	CL	0.00	3.17	3.17
104	1934	SR604	CL	44.54	50.75	6.21
202	2261	US050	CC	10.81	12.81	2.00
203	2329	US050	CC	0.00	7.60	7.60
204	2382	US050	CC	9.61	10.78	1.17
206	2353	IR080	CH	3.08	12.00	8.92
207	2449	IR080	CH	0.00	2.21	2.21
209	2353	IR080	PE	26.20	51.33	25.13
210	2409	IR080	PE	0.00	16.47	16.47
211	2424	IR080	PE	26.21	37.68	11.47
212	2060	SR341	ST	8.15	9.22	1.07
213	2353	IR080	WA	0.00	6.30	6.30
214	2353	IR080	WA	7.10	12.00	4.90
215	1940	SR647	WA	12.75	14.59	1.84
217	1977	SR663	WA	0.01	2.48	2.47
218	1946	US395	WA	22.53	26.68	4.15
301	2037	IR080	EL	52.70	62.10	9.40
303	2352	IR080	EL	43.84	62.10	18.26
304	1969	IR080	EL	91.30	95.26	3.96
306	2124	IR080	EU	15.73	25.70	9.97
309	2352	IR080	LA	0.00	3.21	3.21
311	2353	IR080	PE	55.80	63.30	7.50

Table 7: 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 8: 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 9: Verified Flush Seal District 3 Model

Flush Seal District 3 Model	Number of Observations	R-Squared
$PSI = 11.96 + C1 + C2*BDR - 7.00e\text{-}7ESALS - 5.62SN - 0.34YEAR - 1.79e\text{-}13ESALS^2 + 0.92SN^2$	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 10: 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 11: Verified Sand Seal District 2 Model

Sand Seal District 2 Model	Number of Observations	R-Squared
$PSI = 6.23 + C1 - 0.51BDR + 3.95e\text{-}6ESALS + 0.24SN - 0.045TMAX - 9.8e\text{-}4CFT - 0.50YEAR + 3.50e\text{-}10ESALS^2 + 0.12YEAR^2 - 8.93e\text{-}6ESALS*SN$	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 12: Verified Sand Seal District 3 Model

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

Table 13: Verified Chip Seal District 1 Model

Chip Seal District 1 Model	Number of Observations	R-Squared
PSI = 1.20 + C1 + C2 + C3 - 2.89e-7ESALS + 0.027AGGR - 0.013TMAX - 8.6e-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 14: 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-4ESALS - 0.015AGGR + 0.075TMAX - 2.98e-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 15: 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	

Table 16: Verified AC Overlay District 1 Model

AC Overlay District 1 Model	Number of Observations	R-Squared
PSI = 2.50 + 0.37DPT + 0.60SN - 0.96PMF + 0.0098TMAX - 2.23e-7ESALS - 0.13YEAR - 0.22DPT*SN + 0.29DPT*PMF	182	0.80
Variables	**Range**	
DPT	2.25 - 4.50	
SN	0.90 - 3.78	
PMF	0.00 - 1.50	
TMAX	63 - 83	
ESALS	6205 - 1558703	
YEAR	1 - 9	

Table 17: Verified AC Overlay District 2 Model

AC Overlay District 2 Model	Number of Observations	R-Squared
PSI = -0.83 + 0.23DPT + 0.19PMF +0.27SN + 0.078TMIN + 0.0037FT - 7.10e-7ESALS - 0.14YEAR	154	0.87
Variables	**Range**	
DPT	2.00 - 5.00	
SN	1.05 - 4.45	
PMF	0.00 - 1.50	
TMIN	29 - 38	
ESALS	365 - 942430	
YEAR	1 - 7	
FT	95 - 183	

Table 18: Verified AC Overlay District 3 Model

AC Overlay District 3 Model	Number of Observations	R-Squared
PSI = 3.63 + C1 - 0.18PMF + 0.004SN - 0.10DPT - 3.5e-8ESALS + 0.007TMAX - 0.10YEAR + C2*ESALS + C3*DPT + C4*PMF	184	0.57
Variables	**Range**	
DPT	1.50 - 6.00	
SN	1.15 - 3.88	
PMF	0.00 - 2.00	
TMAX	57 - 67	
ESALS	365 - 2861053	
YEAR	1 - 9	
Binder Type	**Constant (C1)**	**Constant (C2)**
AC-10	-2.710076935	8.0e-9
AC-20	-0.489746182	6.8e-5
AR-8000	-0.418984145	-3.95e-7
AR-4000	0.00	0.00
Binder Type	**Constant (C3)**	**Constant (C4)**
AC-10	0.215717430	1.429517326
AC-20	0.00	0.00
AR-8000	0.196309621	0.00
AR-4000	0.00	0.00

Table 19: Verified Roadbed Modification District 1 Model

Roadbed Modification District 1 Model	Number of Observations	R-Squared
$PSI = -165.05 + C1 - 1.3e\text{-}6ESALS + 182.14SN + 1.79TMAX - 4.20TMIN - 0.24FT - 0.11WETD + 0.16YEAR + 2.99e\text{-}12ESALS^2 - 34.79SN^2 - 0.035YEAR^2$	184	0.73

Variables	Range
YEAR	1 - 9
ESALS	365 - 1880000
SN	2.29 - 3.54
TMAX	62 - 83
TMIN	30 - 52
FT	43 - 189
WETD	18 - 63

Binder Type	Constant (C1)
AC-20P	41.3844649
AR-4000	0.00

Table 20: Verified Roadbed Modification District 2 Model

Roadbed Modification District 2 Model	Number of Observations	R-Squared
$PSI = -5.77 - 8.33e\text{-}6ESALS - 0.44SN + 1.61TMAX - 2.48TMIN - 0.053FT - 0.18YEAR - 1.50e\text{-}12ESALS^2 + 3.30e\text{-}6ESALS*SN$	194	0.79

Variables	Range
YEAR	1 - 9
ESALS	4745 - 1440000
SN	2.01 - 3.39
TMAX	65 - 73
TMIN	33 - 41
FT	100 - 176

Table 21: Verified Roadbed Modification District 3 Model

Roadbed Modification District 3 Model	Number of Observations	R-Squared
$PSI = 305.08 + C1 + 5.53e\text{-}5ESALS + 8.58SN - 0.74TMAX - 14.30TMIN - 0.022FT - 0.29WETD - 0.19YEAR - 2.03e\text{-}10ESALS^2 + 0.20TMIN^2 - 1.38SN^2 - 1.0e\text{-}7ESALS*FT - 1.1e\text{-}6ESALS*TMIN$	288	0.58

Variables	Range
YEAR	1 - 10
ESALS	365 - 470000
SN	2.21 - 3.81
TMAX	54 - 68
TMIN	30 - 37
FT	128 - 216
WETD	37 - 77

Binder Type	Constant (C1)
AC-20P	-0.8430558
AR-4000	0.00

Table 22: Verified Statewide Milling Model

Statewide Milling Model	Number of Observations	R-Squared
$PSI = -7.89 + C1 - 8.4e\text{-}8ESALS - 0.22DPT + 0.75MILL + 0.12TMAX + 0.07WETD - 0.007FT - 0.16YEAR - 1.3e\text{-}12ESALS^2$	86	0.65

Variables	Range
YEAR	1 - 6
ESALS	1095 - 4671270
DPT	1.50 - 4.00
TMAX	57 - 83
MILL	1.50 - 3.00
FT	43 - 230
WETD	18 - 73

Binder Type	Constant (C1)
AC-20	-0.231224614
AR-4000	0.00

FIGURES

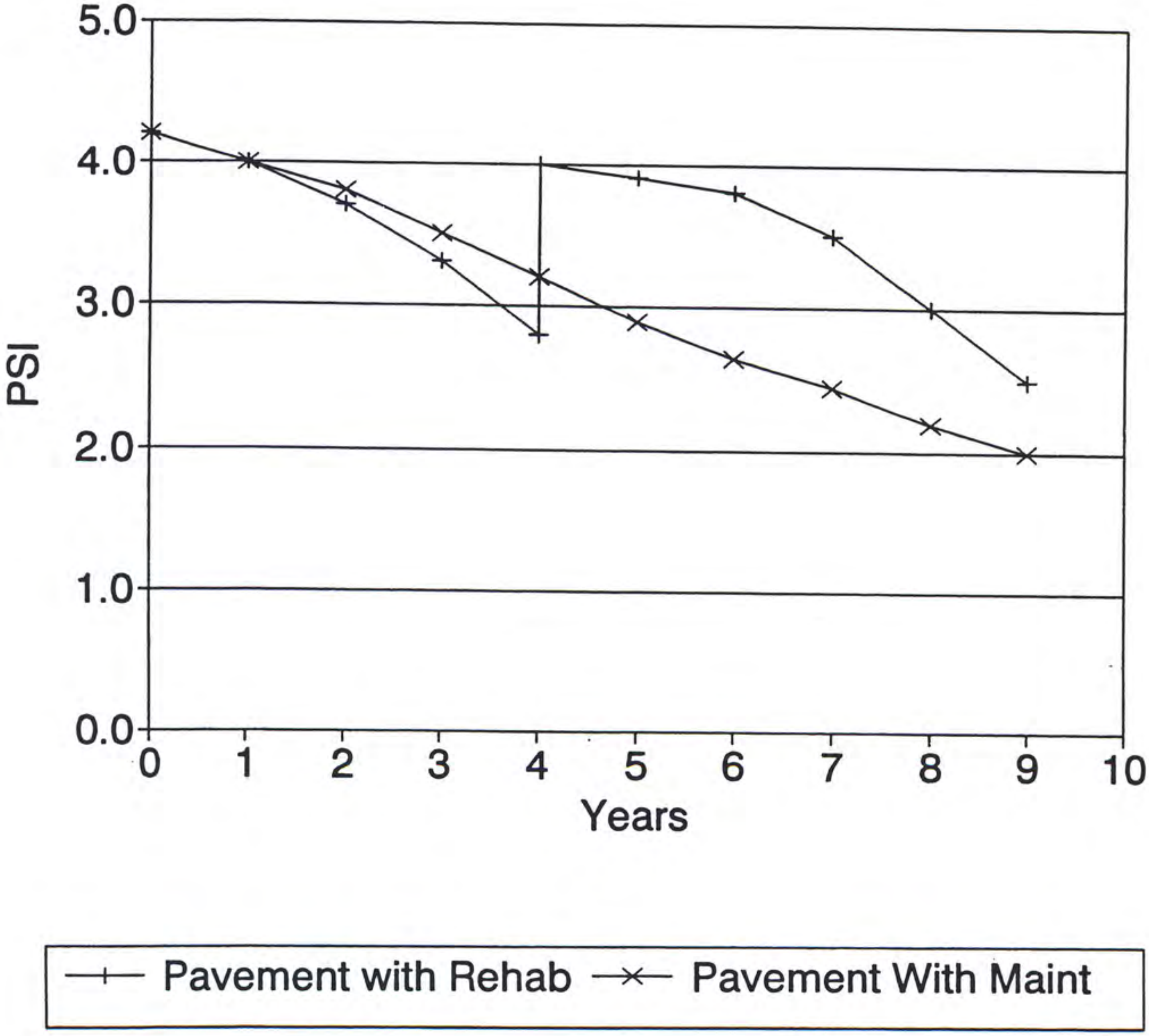

Figure 1. Typical PSI vs Pavement Life for Maintenance and Rehabilitation Activities

PROJECT:_______________

FLUSH SEALS OVER FLEXIBLE PAVEMENTS

Date:_/_/_

Location:____________________

Begining Milepost:_____._____ Ending Milepost:______.___

MATERIALS / MIXTURES OF FLUSH SEAL

Binder Type:_______________ Residue by Distillation:_________

Viscosity/Temp:______/______ L.A. Abr:________

Penetration/Temp:______/______ Ductility/Temp:_______________

Binder Rate (gal/yd2):____________

Curing Time (hrs):__________ Cracks Sealed Prior to Construction: (Y / N)

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Flushseal & During Project Life)
-FWD (Prior to Flushseal & During Project Life)

PMS:	Alligator cracking	Long. cracking
	Transv. cracking	Rut Depths
	Rideability (Roughness)	Slope Variance
	PSI	Raveling
	Flushing	Skid Number (normalized)

Figure 2. Standard Data Collection Forms

PROJECT: ______________

LYR.	YEAR COMPL	THICK	STABL VALUE	% FRCT	BINDER GRADE/SOURCE	% A.C	Mr dry	Mr wet	RATIO	Ts dry	Ts wet	RATIO	% STABIL.	L.A. ABRASION

Figure 2. Standard Data Collection Forms (Continued)

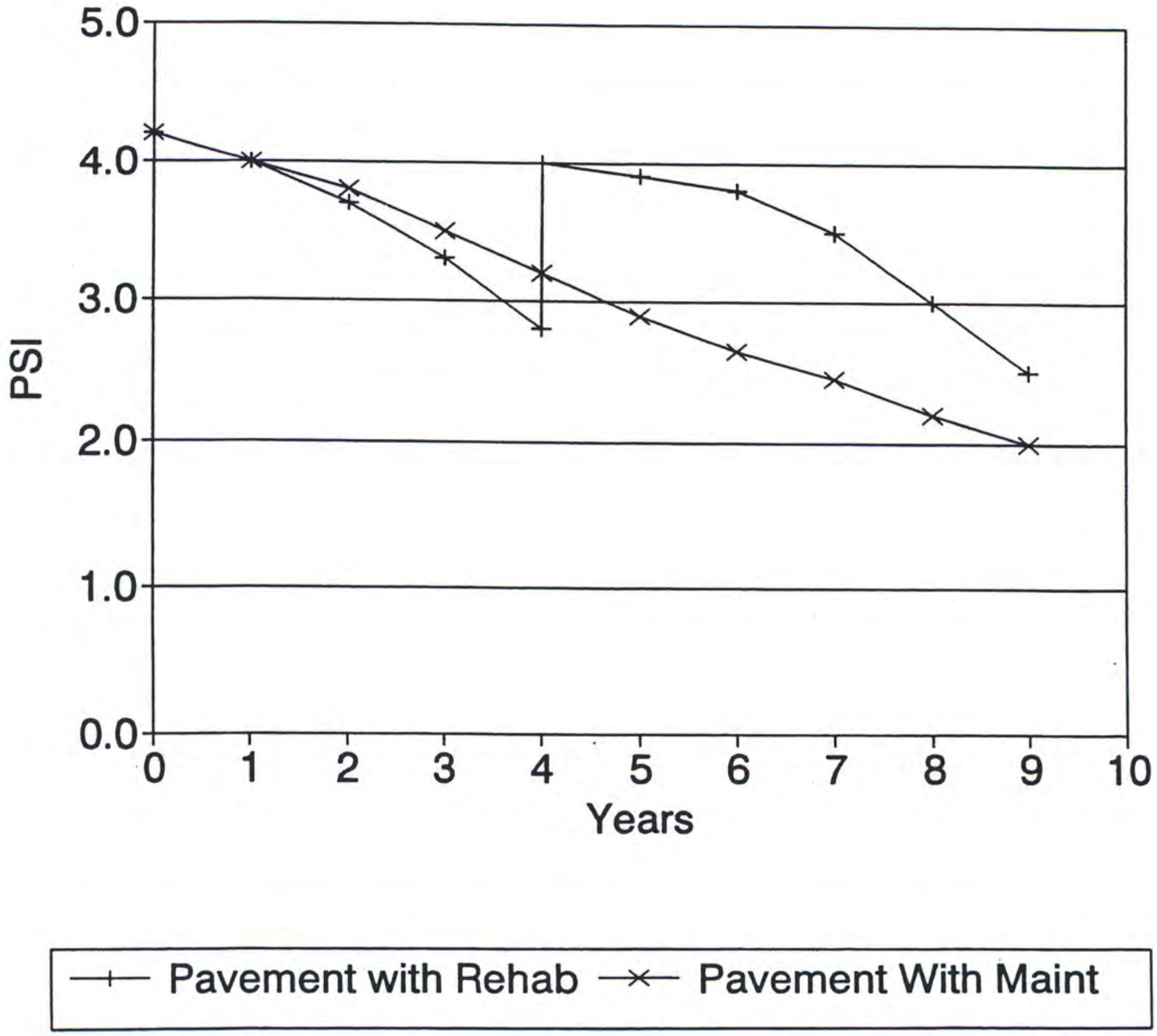

Figure 1. Typical PSI vs Pavement Life for Maintenance and Rehabilitation Activities

PROJECT:______________

FLUSH SEALS OVER FLEXIBLE PAVEMENTS

Date:__/__/__

Location:____________________

Begining Milepost:_____.___ Ending Milepost:_____.___

MATERIALS / MIXTURES OF FLUSH SEAL

Binder Type:_______________ Residue by Distillation:_________

Viscosity/Temp:_____/_____ L.A. Abr:________

Penetration/Temp:_____/_____ Ductility/Temp:________________

Binder Rate (gal/yd2):___________

Curing Time (hrs):__________ Cracks Sealed Prior to Construction: (Y / N)

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Flushseal & During Project Life)
-FWD (Prior to Flushseal & During Project Life)

PMS:	Alligator cracking	Long. cracking
	Transv. cracking	Rut Depths
	Rideability (Roughness)	Slope Variance
	PSI	Raveling
	Flushing	Skid Number (normalized)

Figure 2. Standard Data Collection Forms

PROJECT: ______________

FLUSH SEALS OVER FLEXIBLE PAVEMENTS

Date:_/_/_

Location:____________________

Begining Milepost:_____.___ Ending Milepost:_____.___

MATERIALS / MIXTURES OF FLUSH SEAL

Binder Type:______________ Residue by Distillation:_________

Viscosity/Temp:_____/_____ L.A. Abr:________

Penetration/Temp:_____/_____ Ductility/Temp:________________

Binder Rate (gal/yd2):__________

Curing Time (hrs):_________ Cracks Sealed Prior to Construction: (Y / N)

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Flushseal & During Project Life)
-FWD (Prior to Flushseal & During Project Life)

PMS:		
	Alligator cracking	Long. cracking
	Transv. cracking	Rut Depths
	Rideability (Roughness)	Slope Variance
	PSI	Raveling
	Flushing	Skid Number (normalized)

PROJECT:______________

SAND SEALS OVER FLEXIBLE PAVEMENTS

Date:__/__/__

Location:____________________

Begining Milepost:_____.__ Ending Milepost:_____.__

MATERIALS / MIXTURES OF CHIP SEAL

Binder Type:________________ Residue by Distillation:_________

Viscosity/Temp:______/_____ L.A. Abr:________

Penetration/Temp:______/_____ Ductility/Temp:________________

Aggr Gradation:

1/2"-___ # 16-___
4-___ #200-___

Aggregate Rate (lb/yd2):__________ Binder Rate (gal/yd2):___________

Curing Time (hrs):__________ Cracks Sealed Prior to Construction: (Y / N)

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Sandseal & During Project Life)
-FWD (Prior to Sandseal & During Project Life)

PMS:
Alligator cracking
Transv. cracking
Rideability (Roughness)
PSI
Flushing
Long. cracking
Rut Depths
Slope Variance
Raveling
Skid Number (normalized)

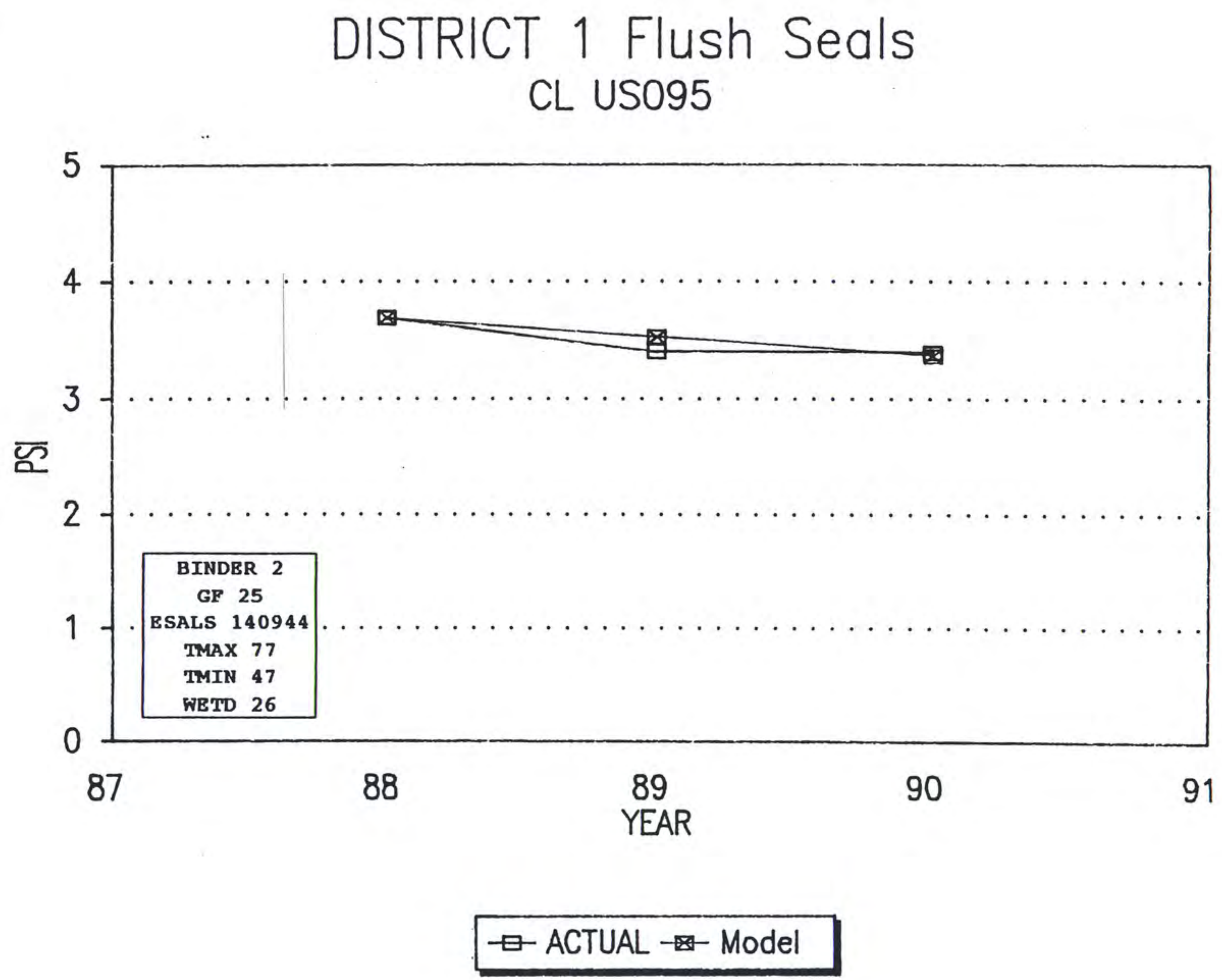

Figure 3. Actual and Predicted PSI for Flush Seals Model, District 1.

PROJECT: ______________

LYR.	YEAR COMPL	THICK	STABL VALUE	% FRCT	BINDER GRADE/SOURCE	% A.C	Mr dry	Mr wet	RATIO	Ts dry	Ts wet	RATIO	% STABIL.	L.A. ABRASION

Figure 2. Standard Data Collection Forms (Continued)

PROJECT:______________

CHIP SEALS OVER FLEXIBLE PAVEMENTS

Date:__/__/__

Location:____________________

Begining Milepost:_____.__ Ending Milepost:_____.__

MATERIALS / MIXTURES OF CHIP SEAL

Binder Type:________________ Residue by Distillation:_________

Viscosity/Temp:______/_____ L.A. Abr:________

Penetration/Temp:______/_____ Ductility/Temp:_________________

Aggr Gradation:

3/4"-____	# 4-___
1/2"-____	# 16-___
3/8"-____	#200-___

Aggregate Rate (lb/yd2):___________ Binder Rate (gal/yd2):____________

Curing Time (hrs):__________ Cracks Sealed Prior to Construction: (Y / N)

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Chipseal & During Project Life)
-FWD (Prior to Chipseal & During Project Life)

PMS:

Alligator cracking	Long. cracking
Transv. cracking	Rut Depths
Rideability (Roughness)	Slope Variance
PSI	Raveling
Flushing	Skid Number (normalized)

PROJECT:______________

FLEXIBLE PAVEMENT OVERLAYS OVER FLEXIBLE PAVEMENTS

Date:__/__/__

Location:____________________

Begining Milepost:_____.___

Ending Milepost:_____.___

MATERIALS / MIXTURES OF OVERLAY

Mix Type:______________

AC Grade:________

% Fractured:____________

Viscosity/Temp:______/_____

Penetration/Temp:______/_____

Ductility/Temp:_________/_______

Sabilometer Value:____________

Mix Design Data:

Voids:__________

VMA:____________

Stability:______

Mr/temp/moisture:_____/_____/_____

%AC:__________

Field Density:__________

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Flexible Pavement Overlay & During Project Life)
-FWD (Prior to Flexible Pavement Overlay & During Project Life)

PMS:

Alligator cracking	Long. cracking
Transv. cracking	Rut Depths
Rideability (Roughness)	Slope Variance
PSI	Raveling
Flushing	Skid Number (normalized)

PROJECT:________________

FLEXIBLE PAVEMENT OVERLAYS OVER ROADBED MODIFICATION

Date:__/__/__

Location:____________________

Begining Milepost:_____.___ Ending Milepost:_____.____

MATERIALS / MIXTURES OF OVERLAY

Mix Type:______________ AC Grade:________

% Fractured:____________ Viscosity/Temp:______/_____

Penetration/Temp:______/_____ Ductility/Temp:__________/_______

Sabilometer Value:___________

Mix Design Data:

Voids:__________ VMA:___________

Stability:______ Mr/temp/moisture:_____/____/_____

%AC:__________ Field Density:___________

MATERIALS / MIXTURES OF MODIFIED PAVEMENTS

Depth of Pulverization:________ Compressive Strength/Days:______/_____

Cement Type:___________ % Cement:____________

Virgin Agg: (Y / N) %__________ Type:_________

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)
-ESALS will be used if LEF are site specific

PMS DATA

-FWD (Prior to Roadbed Modificaiton & During Project Life)
-PMS (During Project Life)

PMS:				
	Alligator Cracking	Long. Cracking	PSI	Skid Number
	Transv. Cracking	Rut Depths	Raveling	
	Rideability	Slope Variance	Flushing	

PROJECT:_______________

MILLING AND OVERLAY OF FLEXIBLE PAVEMENTS

Date:__/__/__ Contract:________

Location:____________________

Begining Milepost:_____.___ Ending Milepost:_____.___

MATERIALS / MIXTURES OF OVERLAY

Type of Milling:(Hot / Cold / ___________)

Depth of Milling:________ Overlay Depth:_______

Mix Type:_______________ AC Grade:________

SAMI Used:(Yes / No) Type:__________

Mix Design Data:

Voids:__________ VMA:____________

Stability:______ Mr/temp/moisture:_____/_____/_____

%AC:__________ Field Density:__________

TRAFFIC HISTORY

-Traffic Composition By Classes (6-13) (as extensive as possible)

-ESALS will be used if LEF are site specific

PMS DATA

-PMS (Prior to Milling Pavement & Overlay & During Project Life)
-FWD (Prior to Milling Pavement & Overlay & During Project Life)

PMS:
- Alligator cracking
- Transv. cracking
- Rideability (Roughness)
- PSI
- Flushing
- Long. cracking
- Rut Depths
- Slope Variance
- Raveling
- Skid Number (normalized)

PROJECT: ____________

LYR.	YEAR COMPL	THICK	STABL VALUE	% FRCT	BINDER GRADE/SOURCE	% A.C	Mr dry	Mr wet	RATIO	Ts dry	Ts wet	RATIO	% STABIL.	L.A. ABRASION

APPENDIX B

COEFFICIENTS USED IN STRUCTURAL NUMBER CALCULATIONS

Coefficients Used in Structural Number Calculations

MATERIAL	COEFFICIENT (a)
Base (all types)	0.1
Borrow	0.07
PBS (Plantmix Bituminous Surface)	0.35
RBS (Roadmix Bituminous Surface)	0.25
RBM/CTB	0.12
PCC (Portland Cement Concrete)	0.42
Old PBS (PBS older than 8 years)	0.25
Old RBS (RBS older than 8 years)	0.20

Example of Structural Number (SN) Calculation

A given flexible pavement section was constructed in 1983 consisting of 4 inches of Plantmix Bituminous Surface (PBS) over 8 inches of Crushed Aggregate Base. In 1993, the section was overlaid with 3 inches of PBS. The SN calculation for this section is given below. Note that the original construction is older than 8 years.

$$SN = \sum a_i t_i$$

where: SN = Structural Number

a = Layer Coefficient

t = Layer Thickness

SN = (0.35*3") + (0.25*4") + (0.1*8") = 2.85

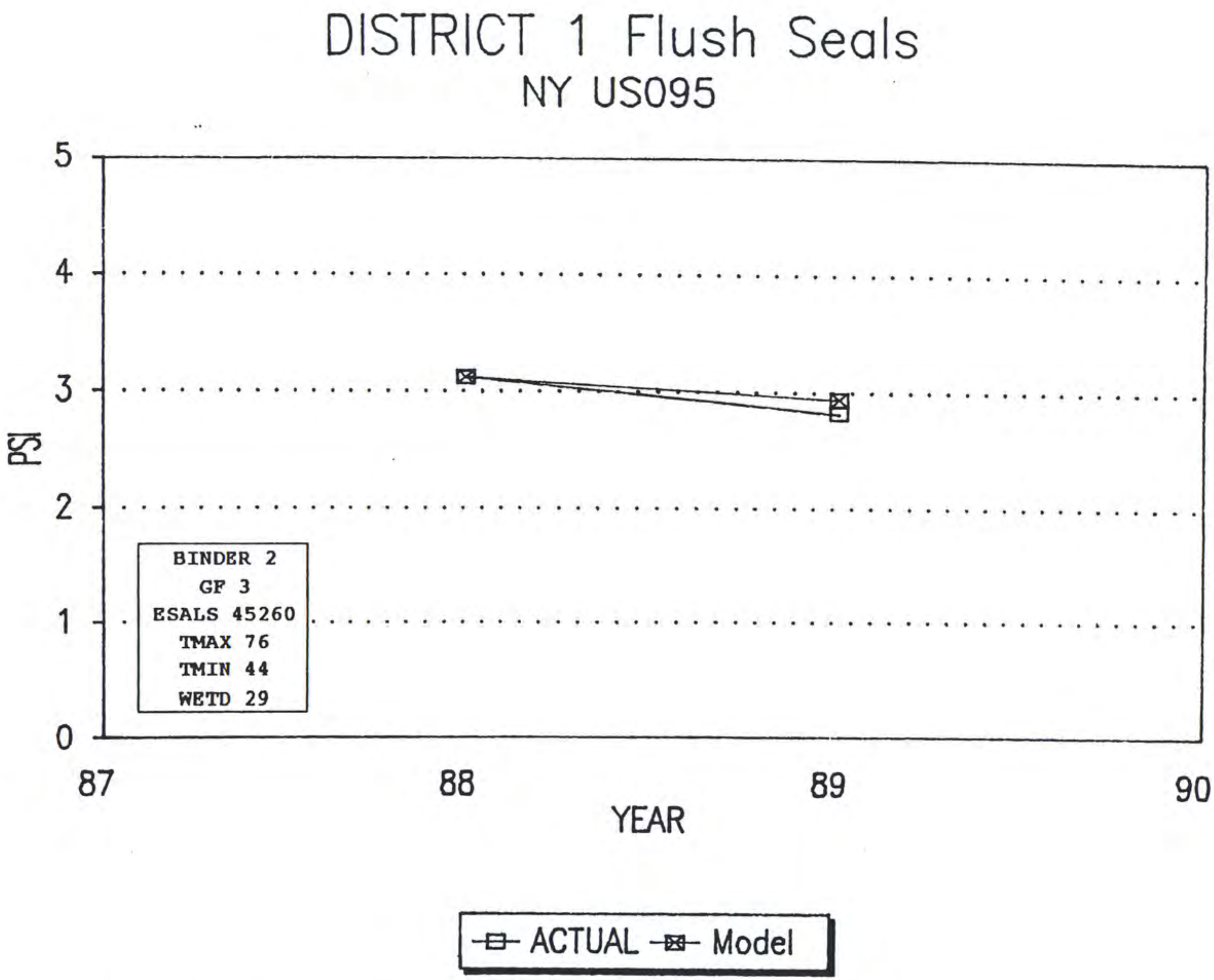

Figure 4. Actual and Predicted PSI for Flush Seals Models, District 1.

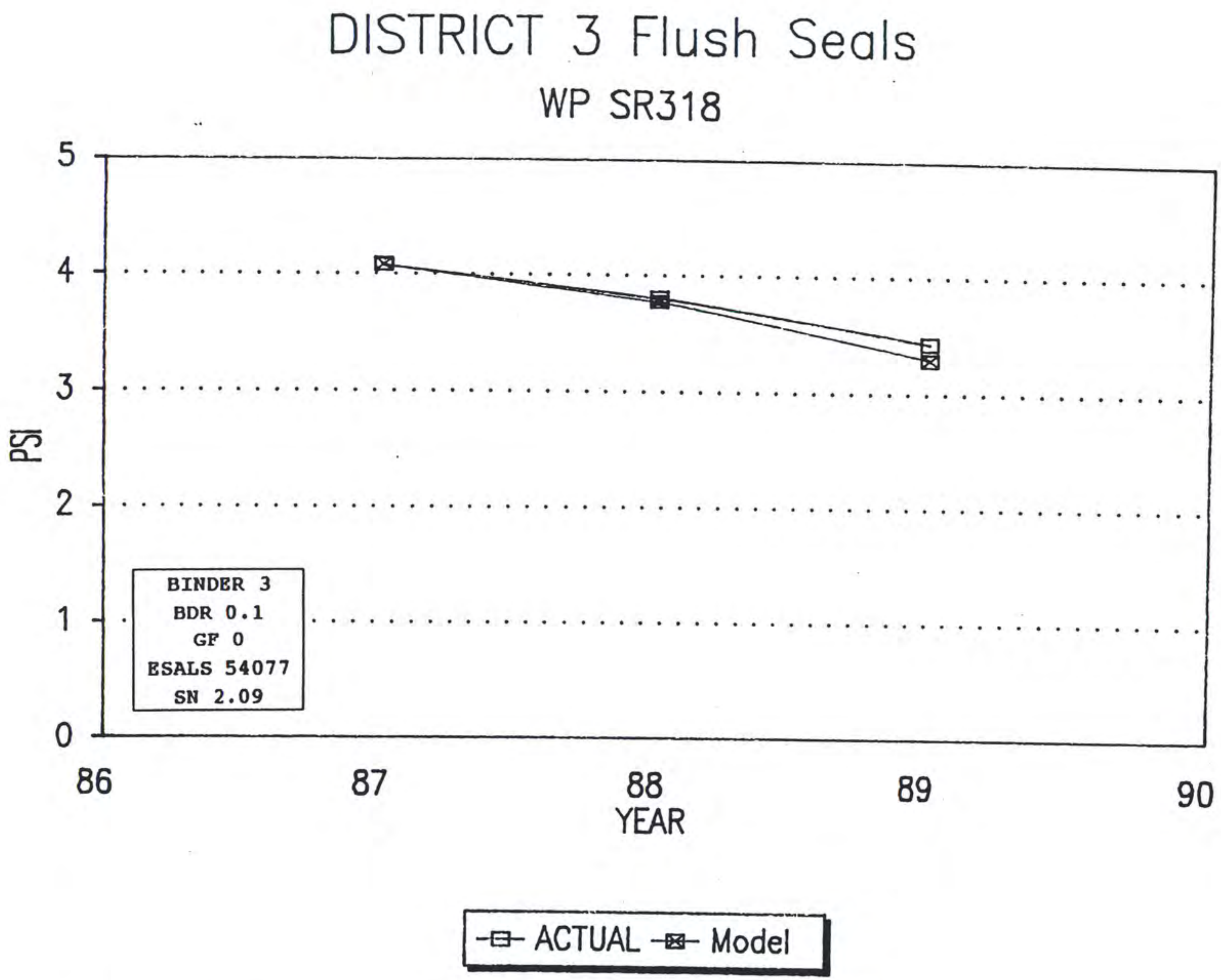

Figure 5. Actual and Predicted PSI for Flush Seals Models, District 3.

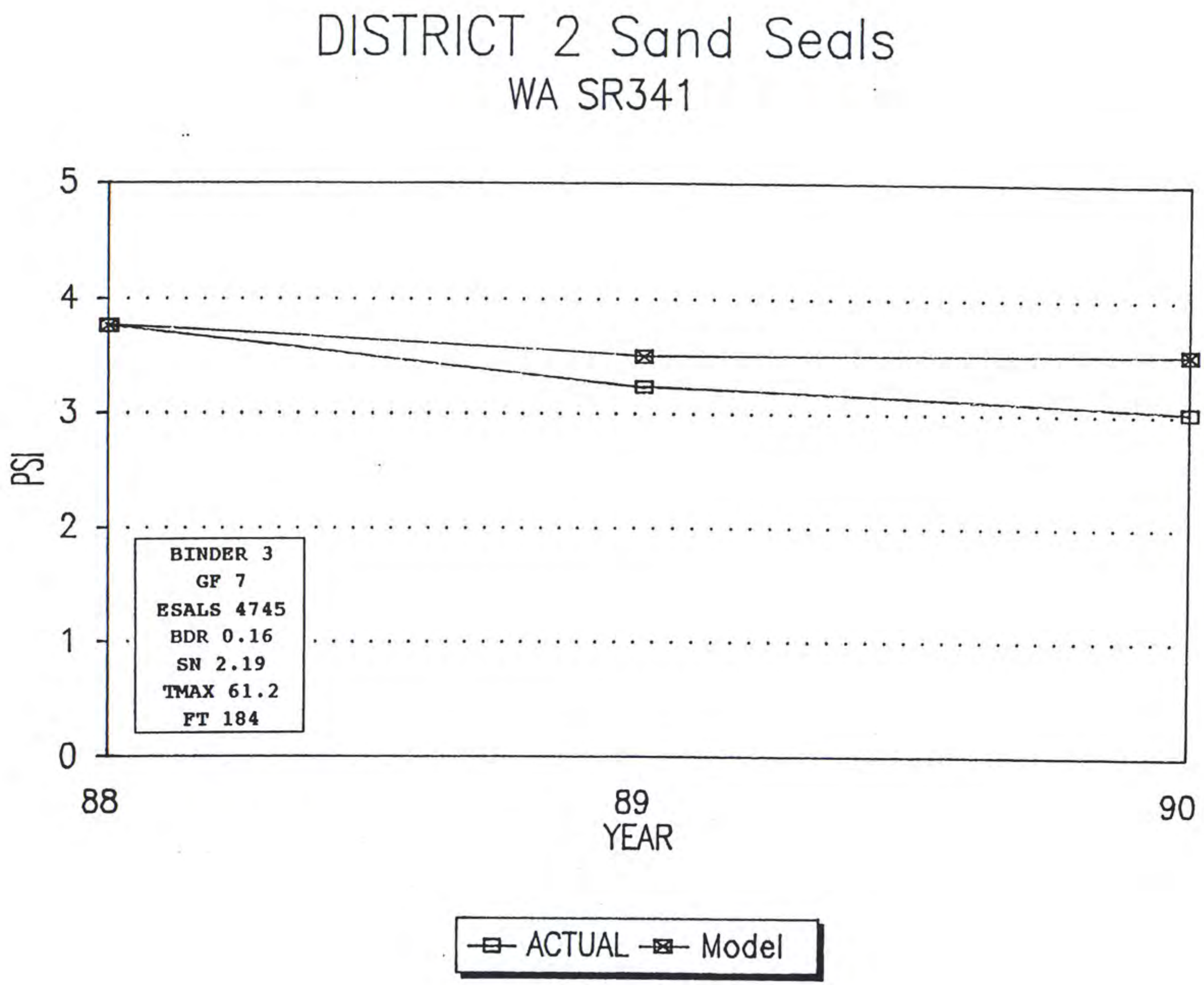

Figure 6. Actual and Predicted PSI for Sand Seals Models, District 2.

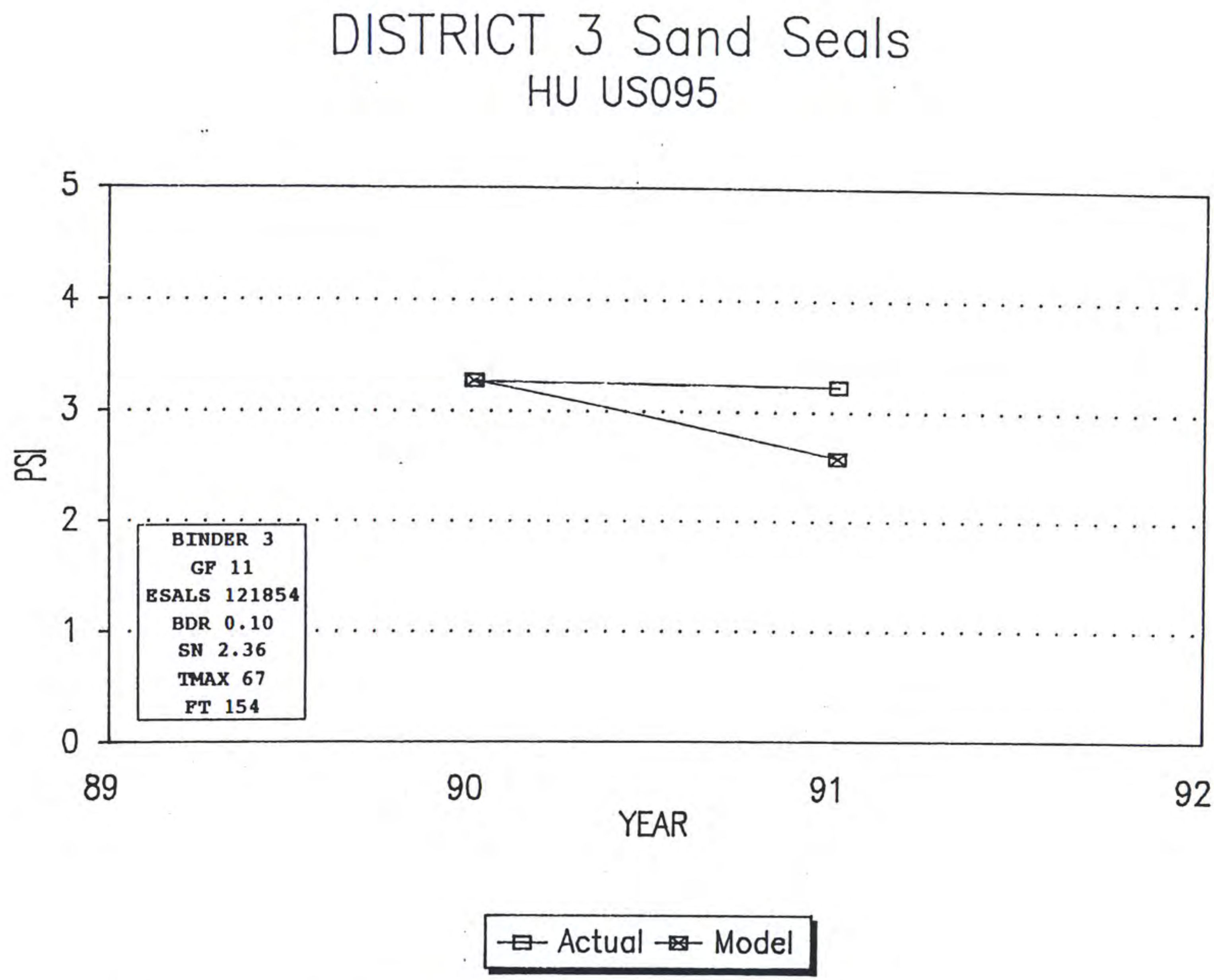

Figure 7. Actual and Predicted PSI for Sand Seals Model, District 3.

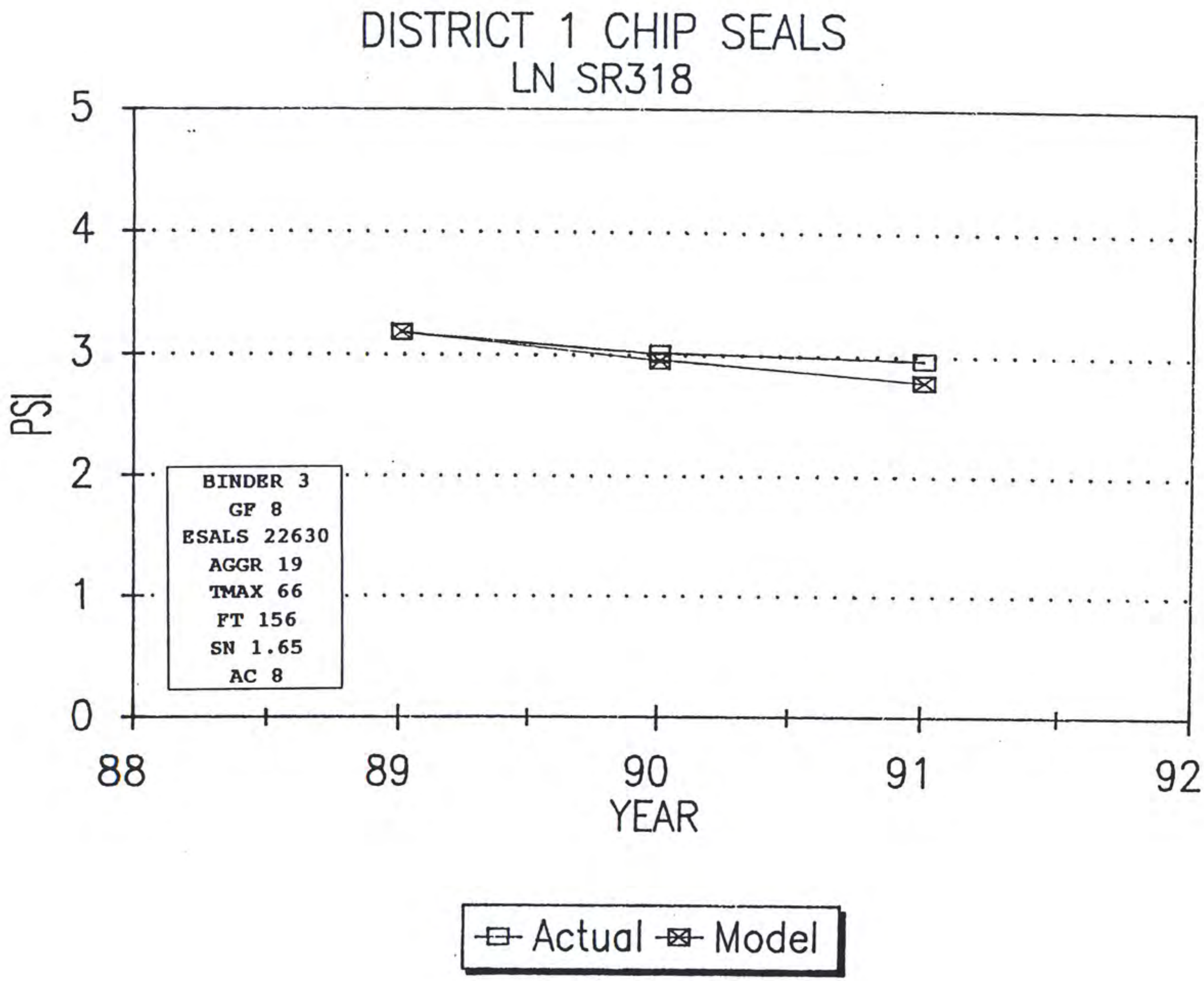

Figure 8. Actual and Predicted PSI for Chip Seals, District 1.

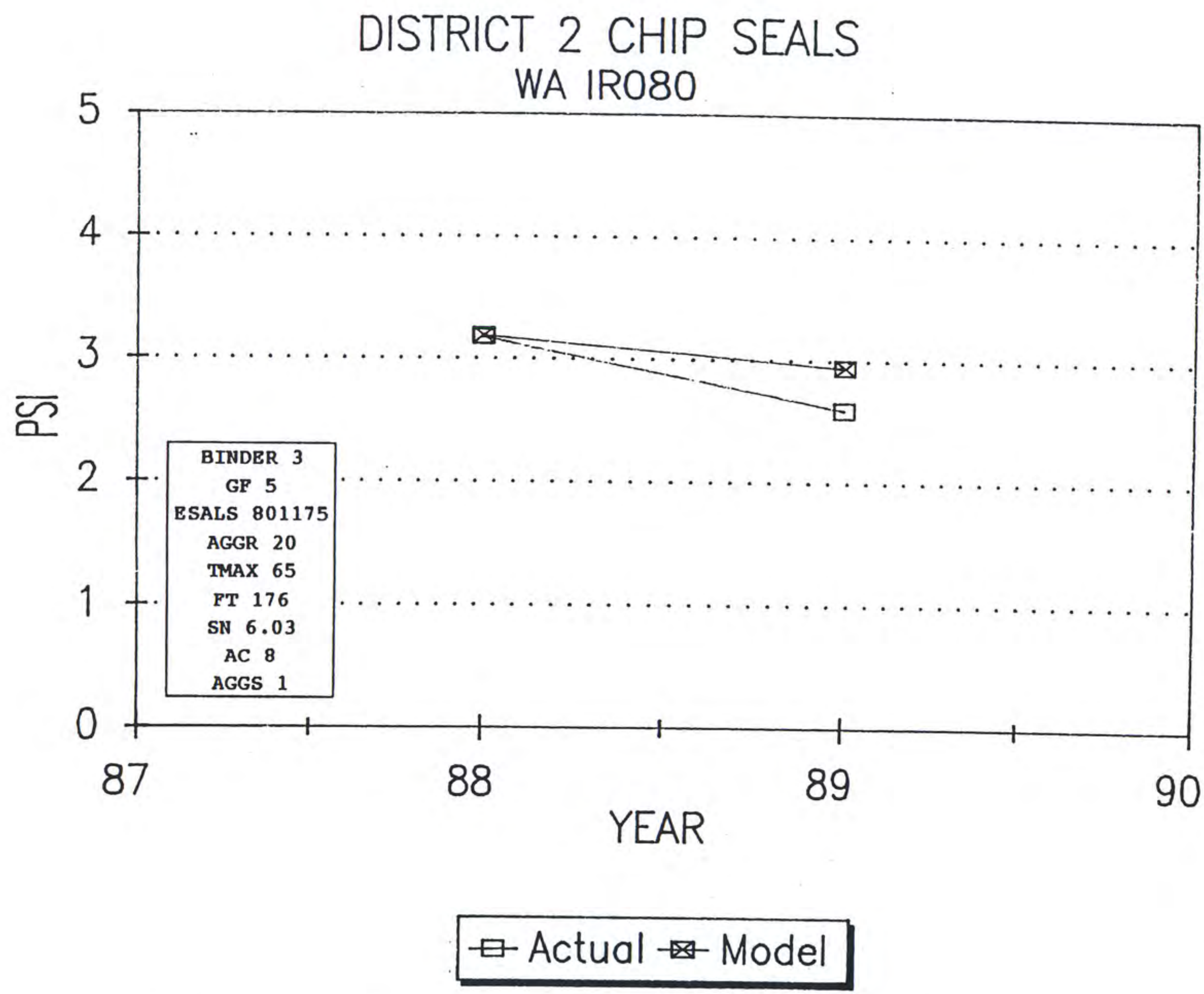

Figure 9. Actual and Predicted PSI for Chip Seals Model, District 2.

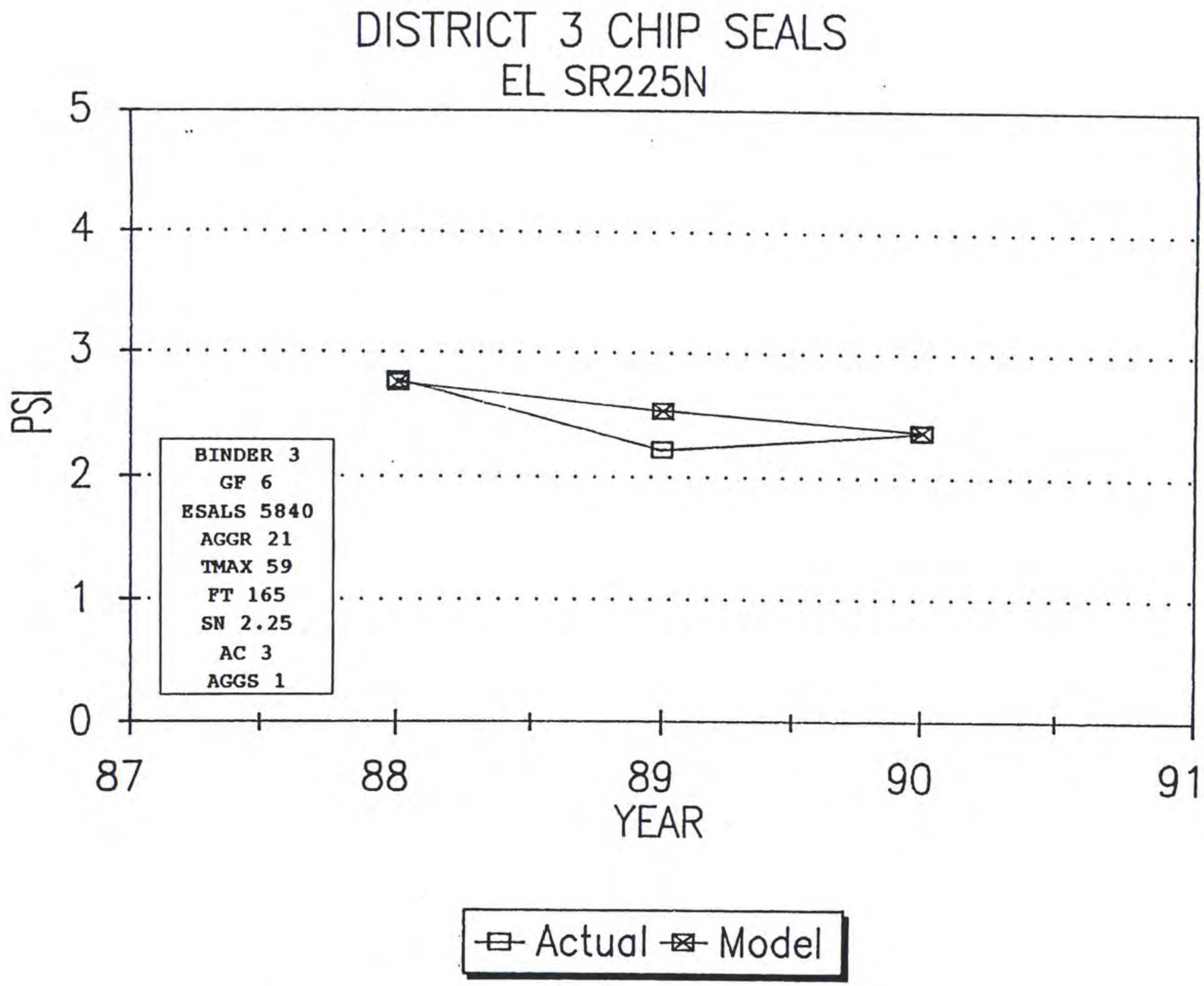

Figure 10. Actual and Predicted PSI for Chip Seals Model, District 3.

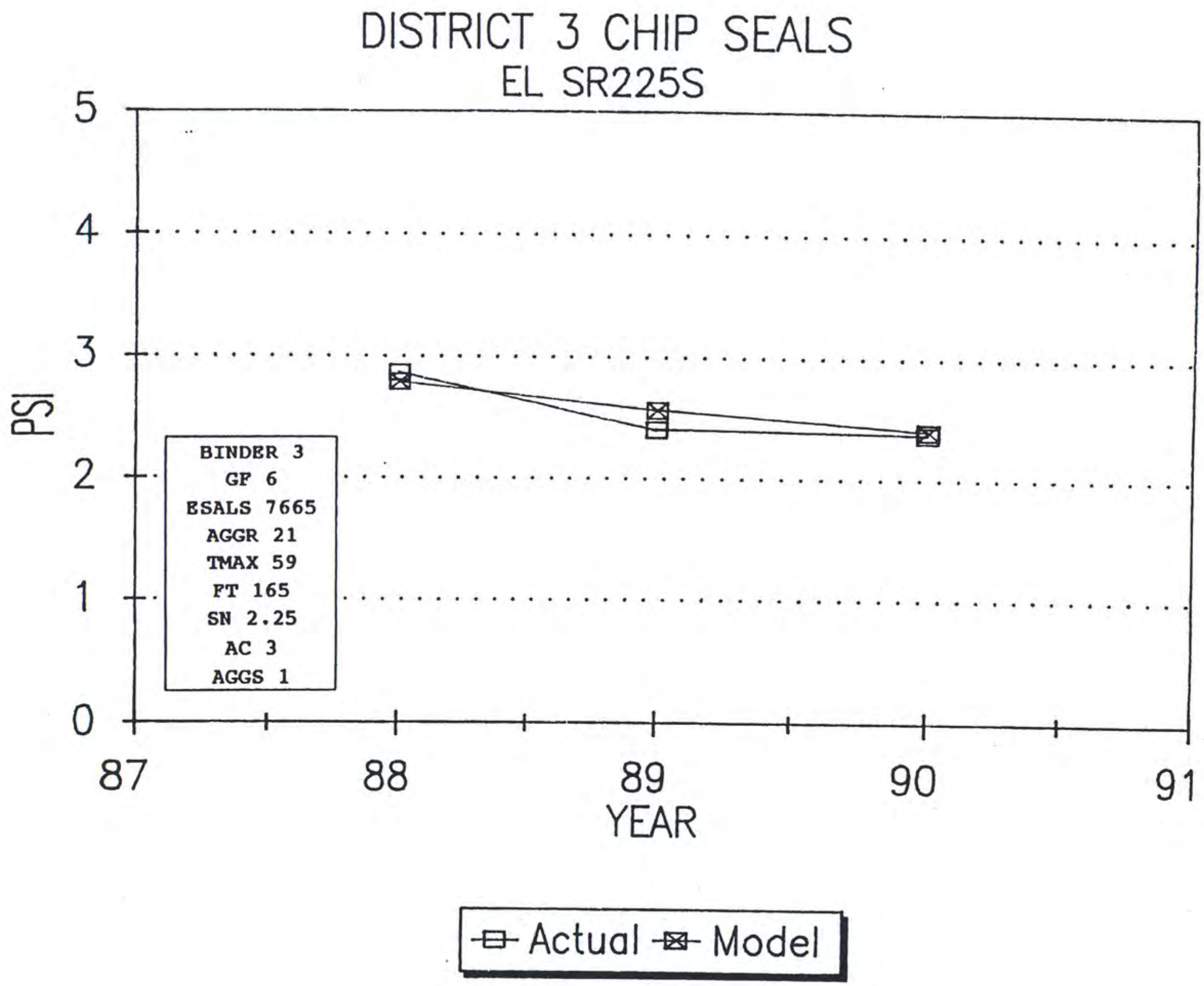

Figure 11. Actual and Predicted PSI for Chip Seals Model, District 3.

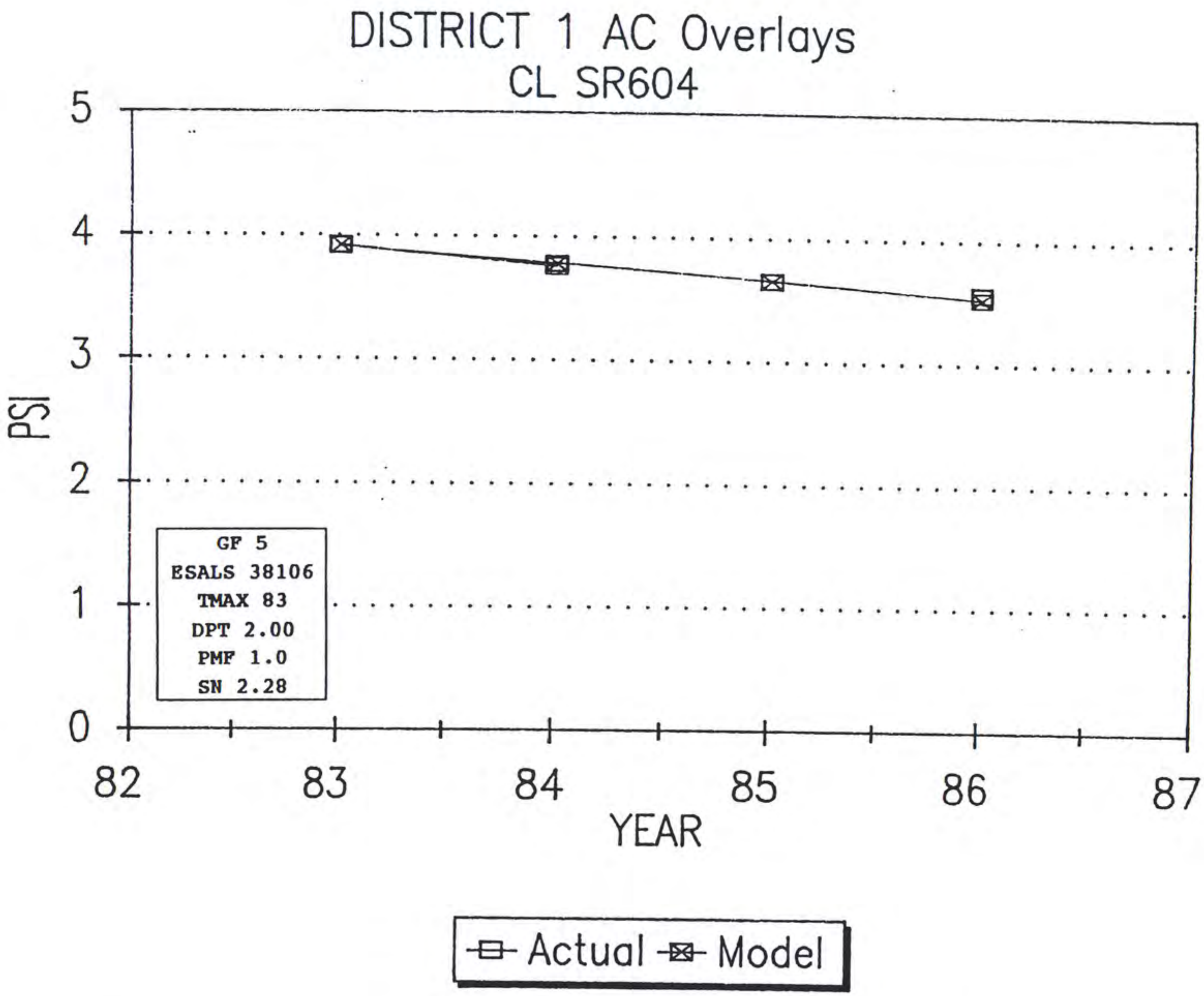

Figure 12. Actual and Predicted PSI for AC Overlays Model, District 1.

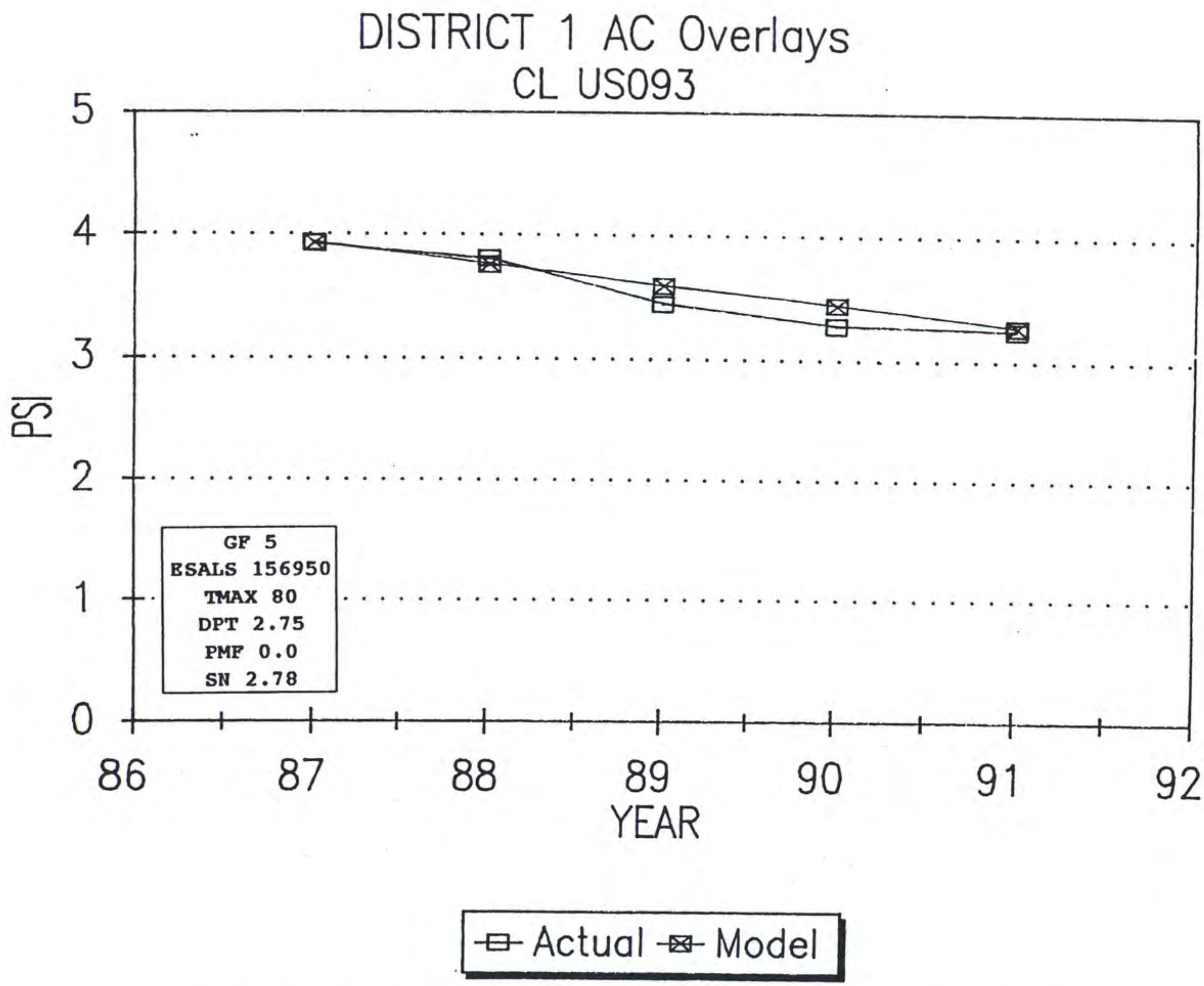

Figure 13. Actual and Predicted PSI for AC Overlays Model, District 1.

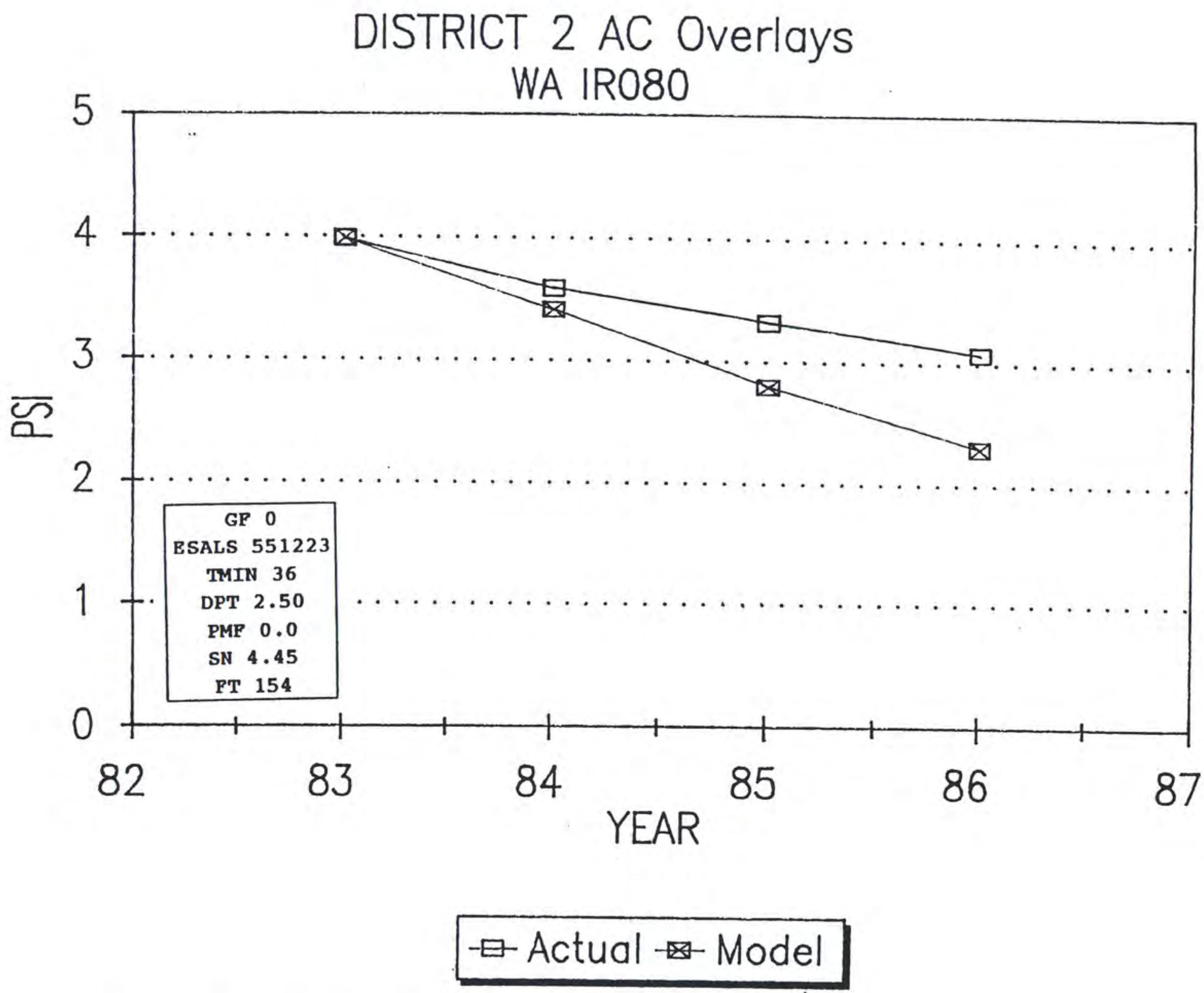

Figure 14. Actual and Predicted PSI for AC Overlays Model, District 2.

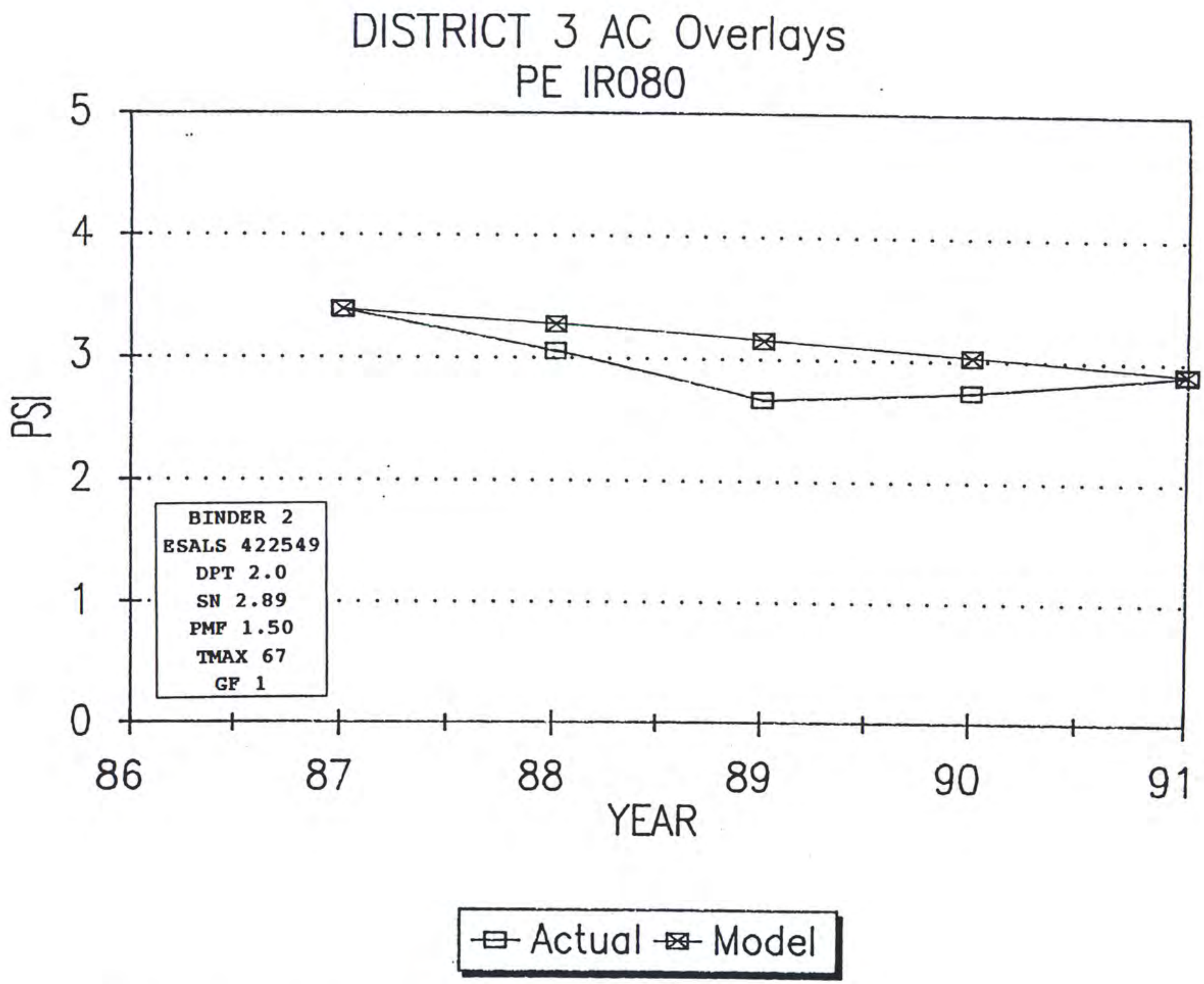

Figure 15. Actual and Predicted PSI for AC Overlays Model, District 3.

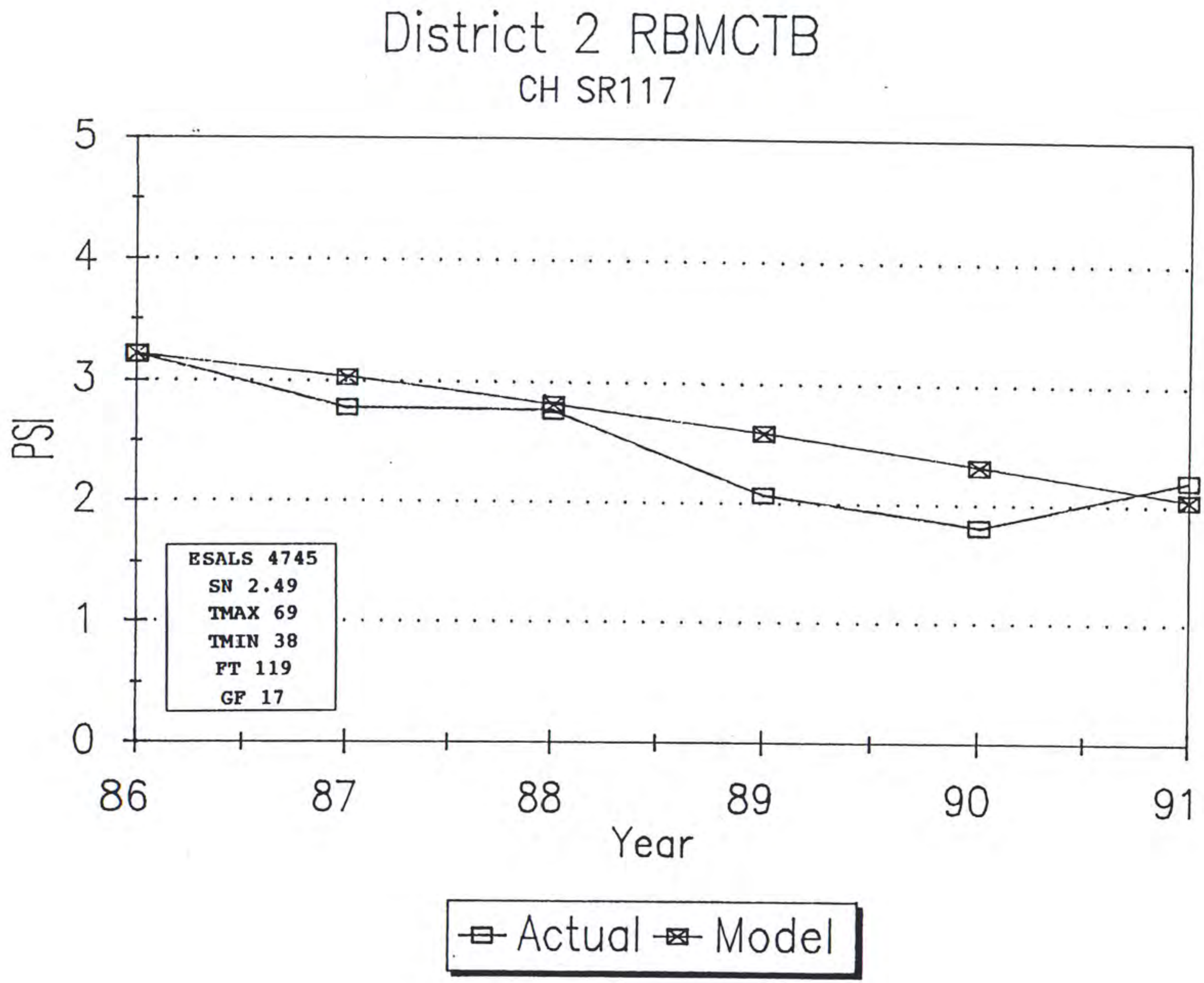

Figure 16. Actual and Predicted PSI for Roadbed Modification Model, District 2.

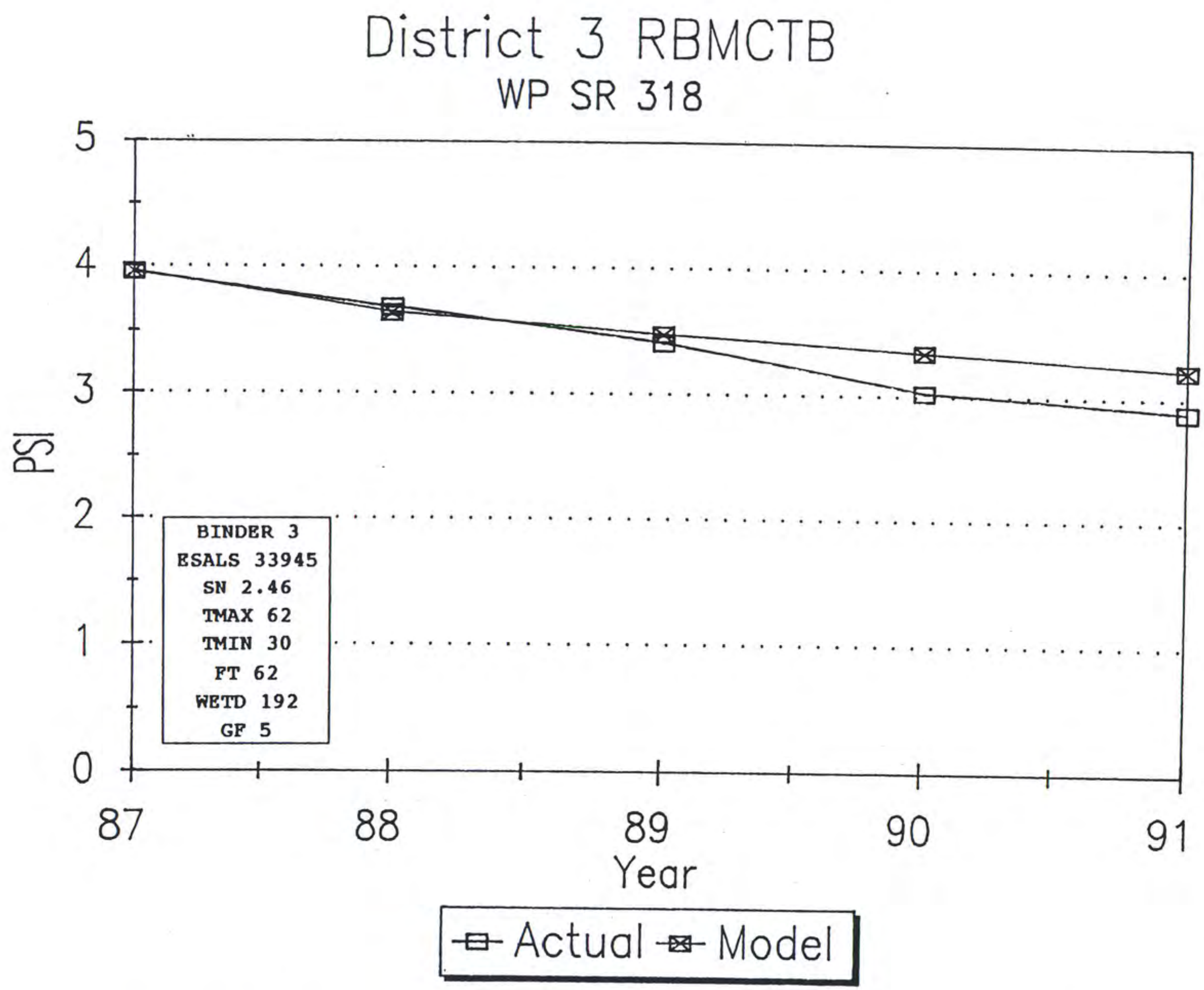

Figure 17. Actual and Predicted PSI for Roadbed Modification Model, District 3.

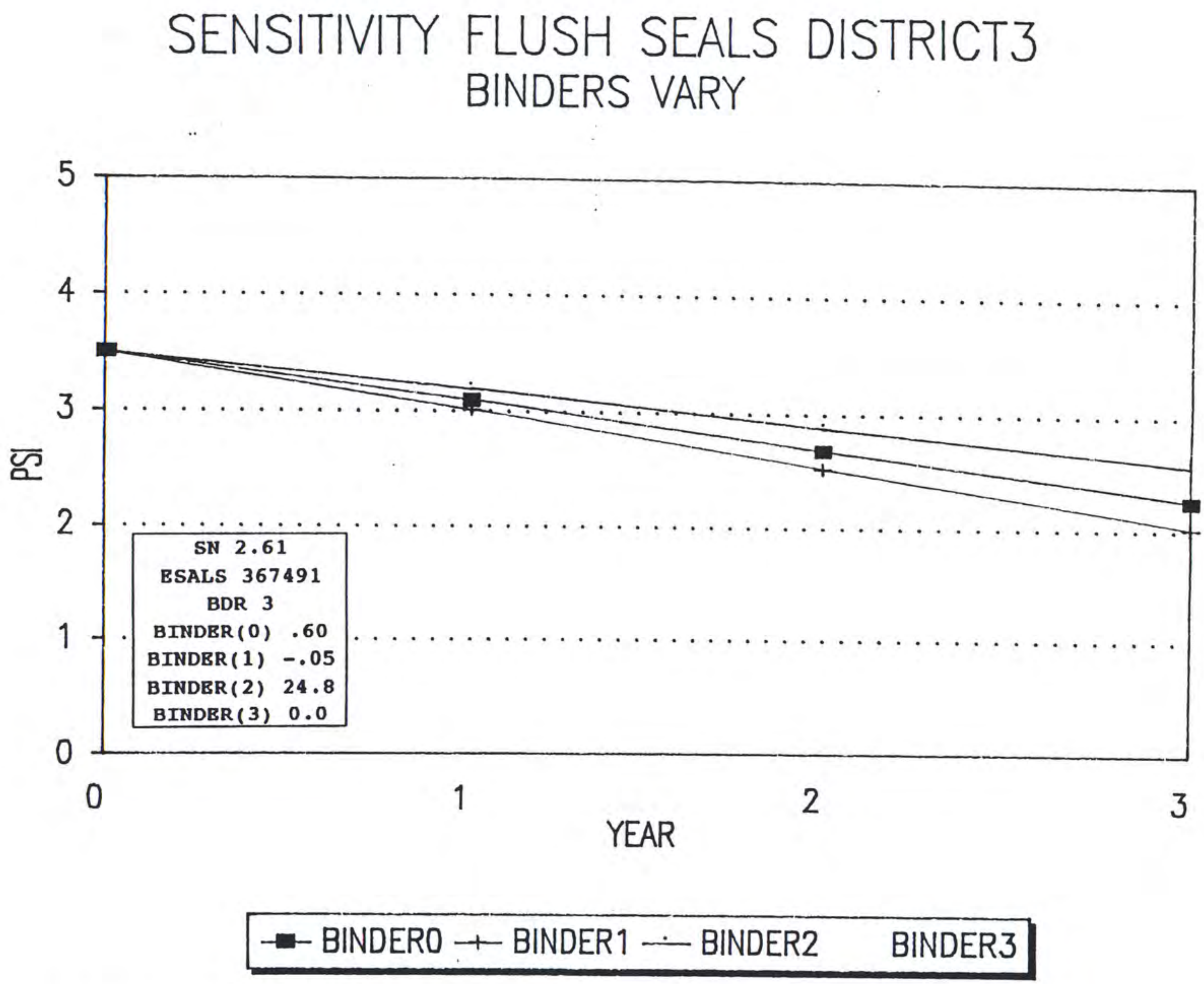

Figure 18. PSI vs Pavement Life, Flush Seals District 3, Binders Vary

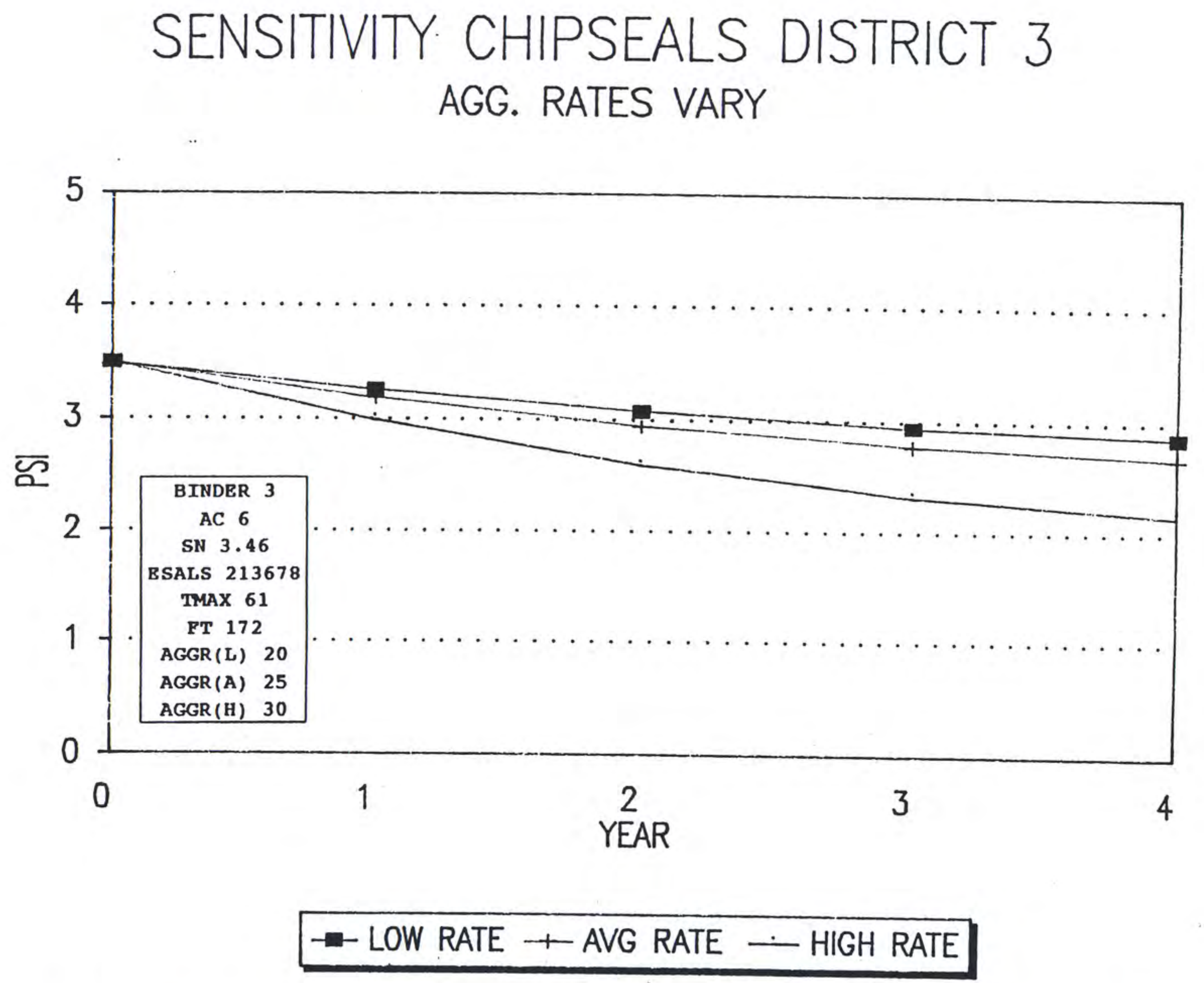

Figure 19. PSI vs Pavement Life, Sand Seals District 3, Aggregate Spread Rates Vary

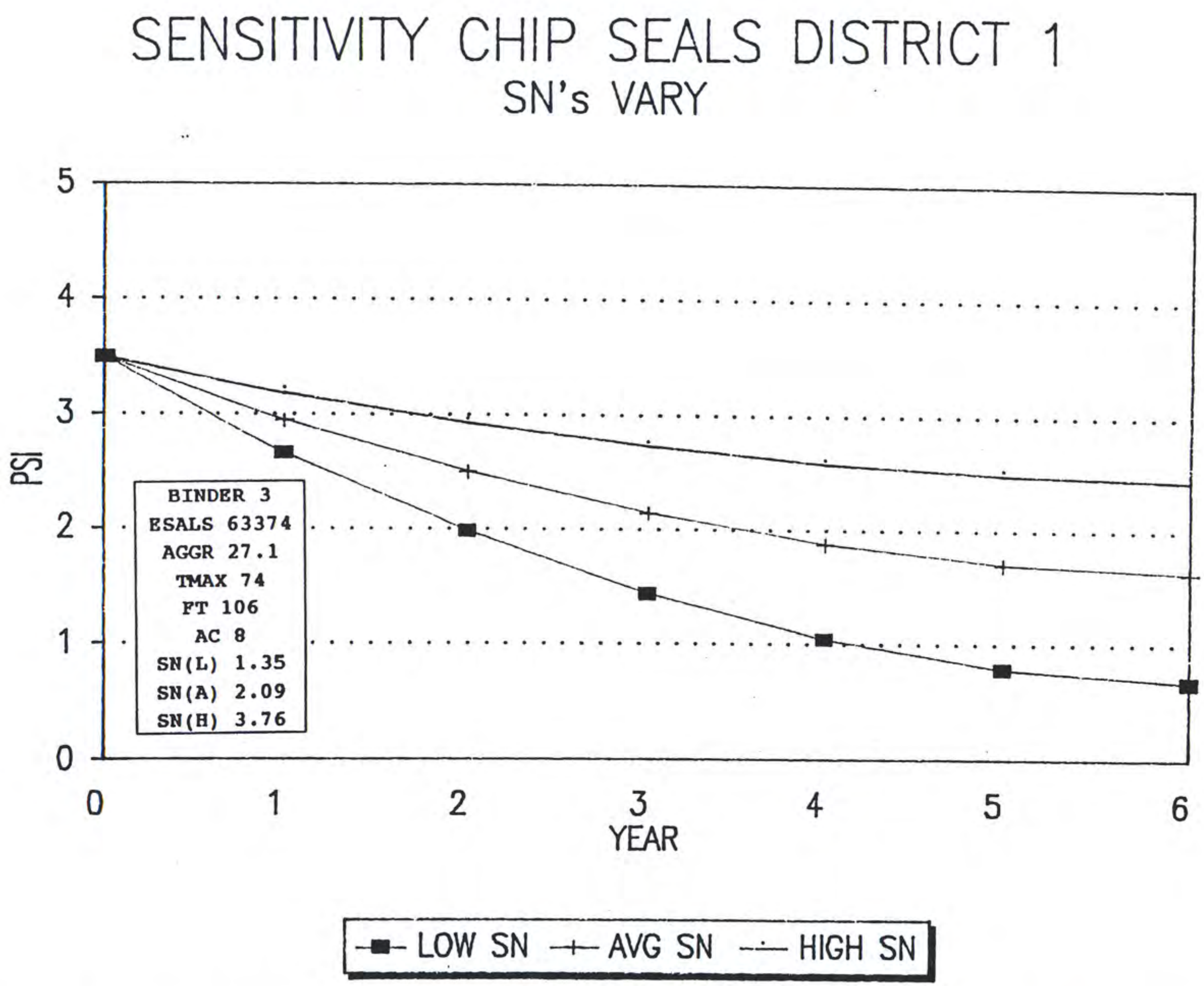

Figure 20. PSI vs Pavement Life, Chip Seals District 1, Structural Numbers Vary

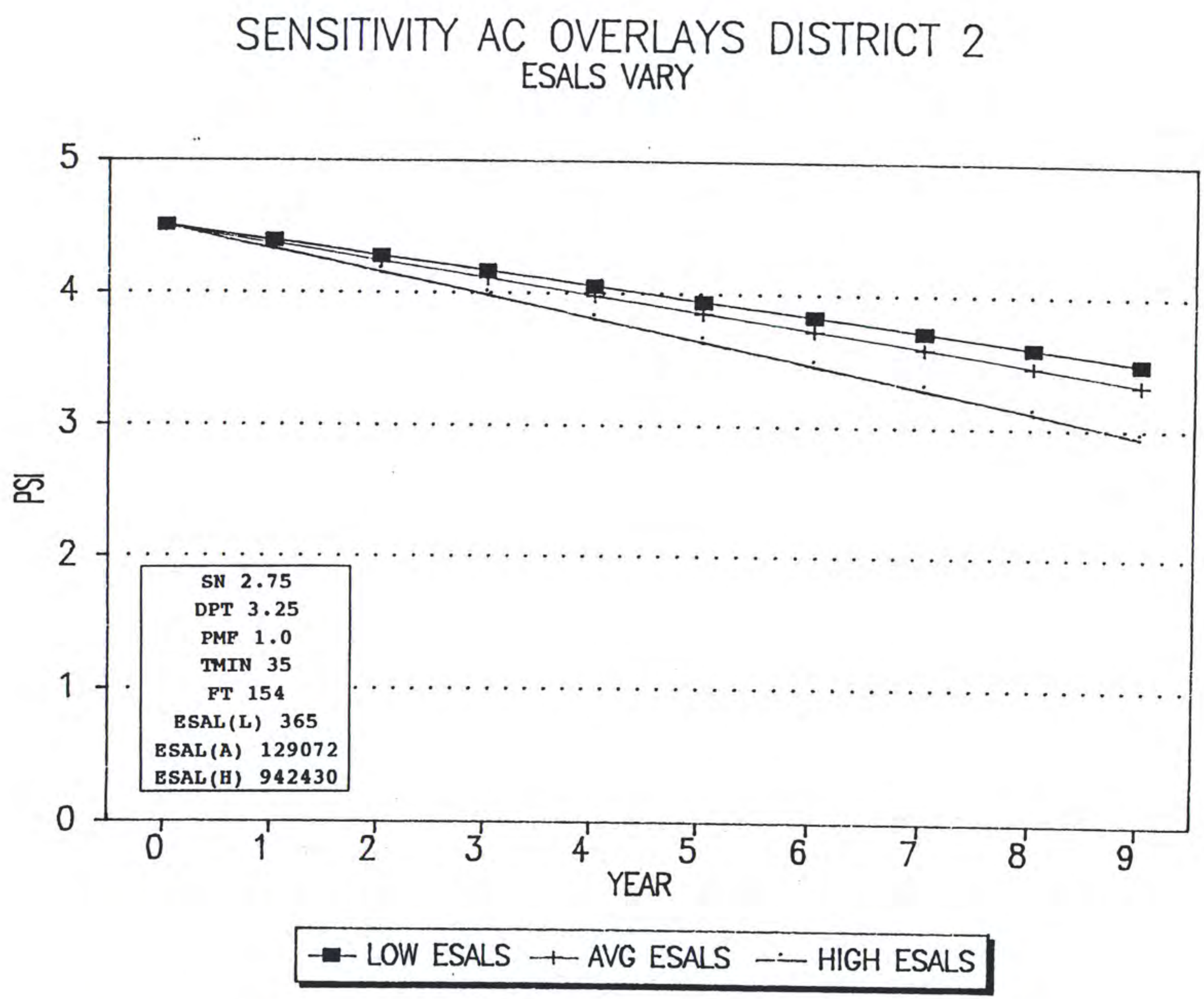

Figure 21. PSI vs Pavement Life, AC Overlays District 2, ESALS Vary

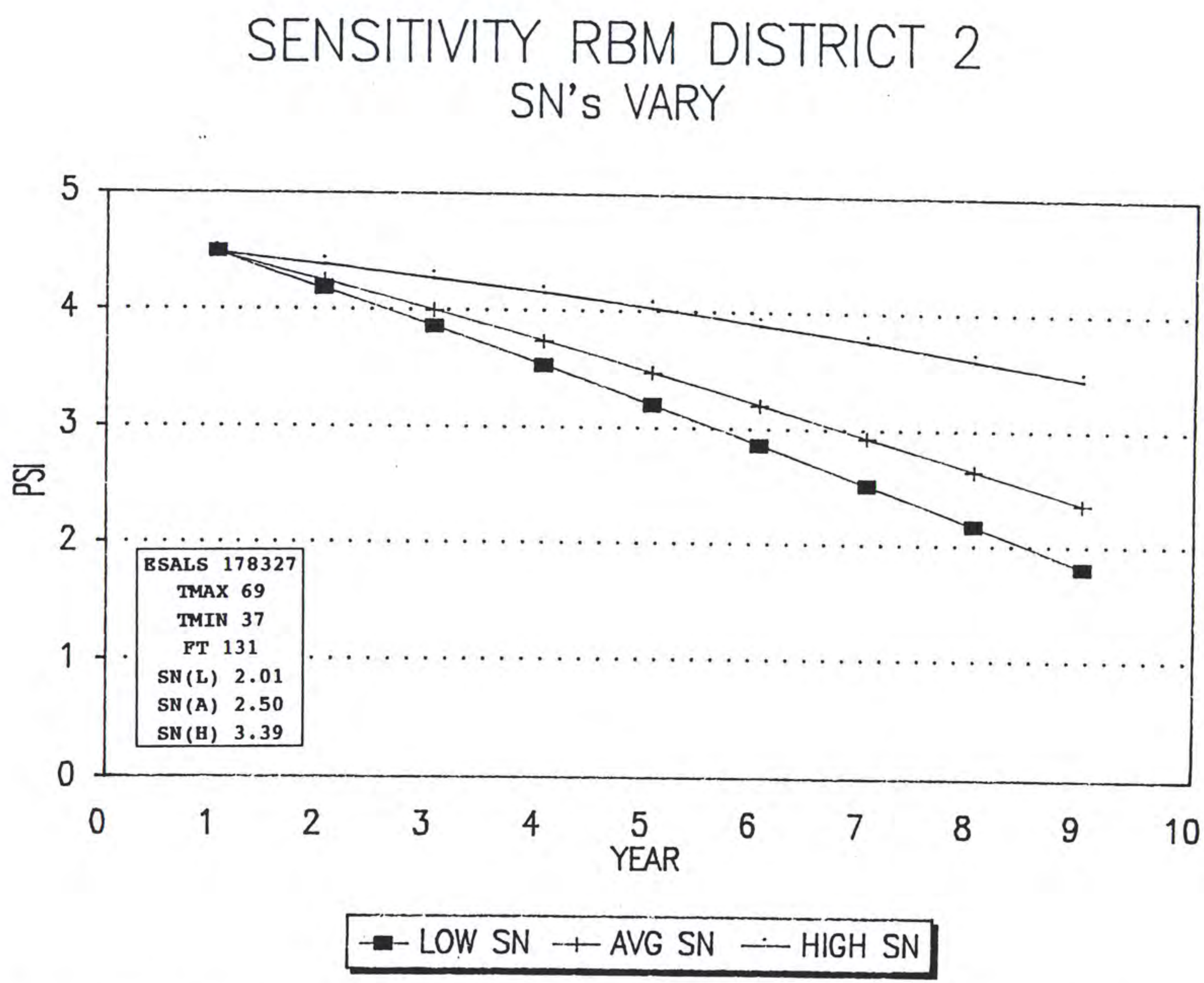

Figure 22. PSI vs Pavement Life, Roadbed Modification District 2, Structural Numbers Vary

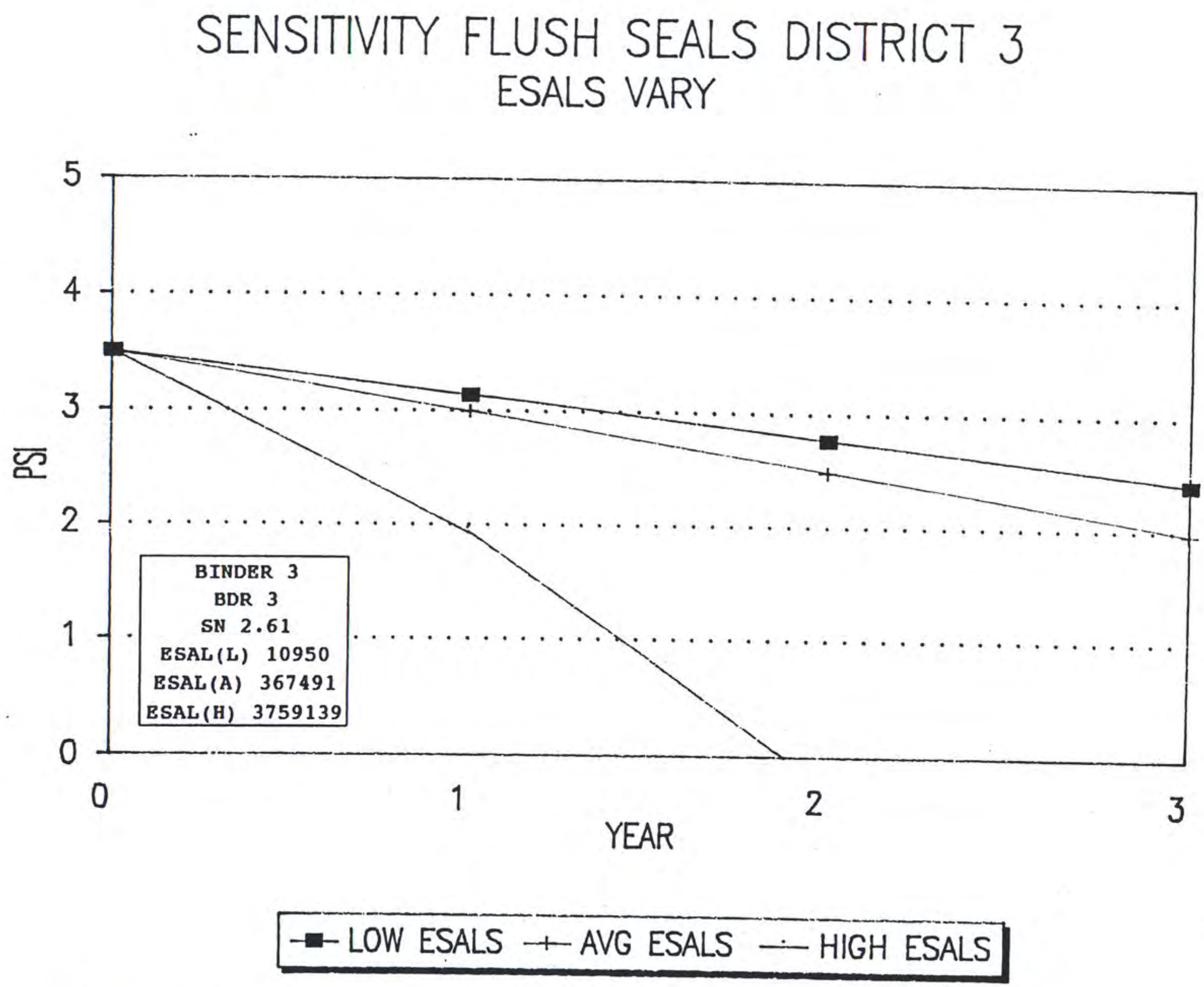

Figure 23. PSI vs Pavement Life, Flush Seals District 3, ESALS Vary

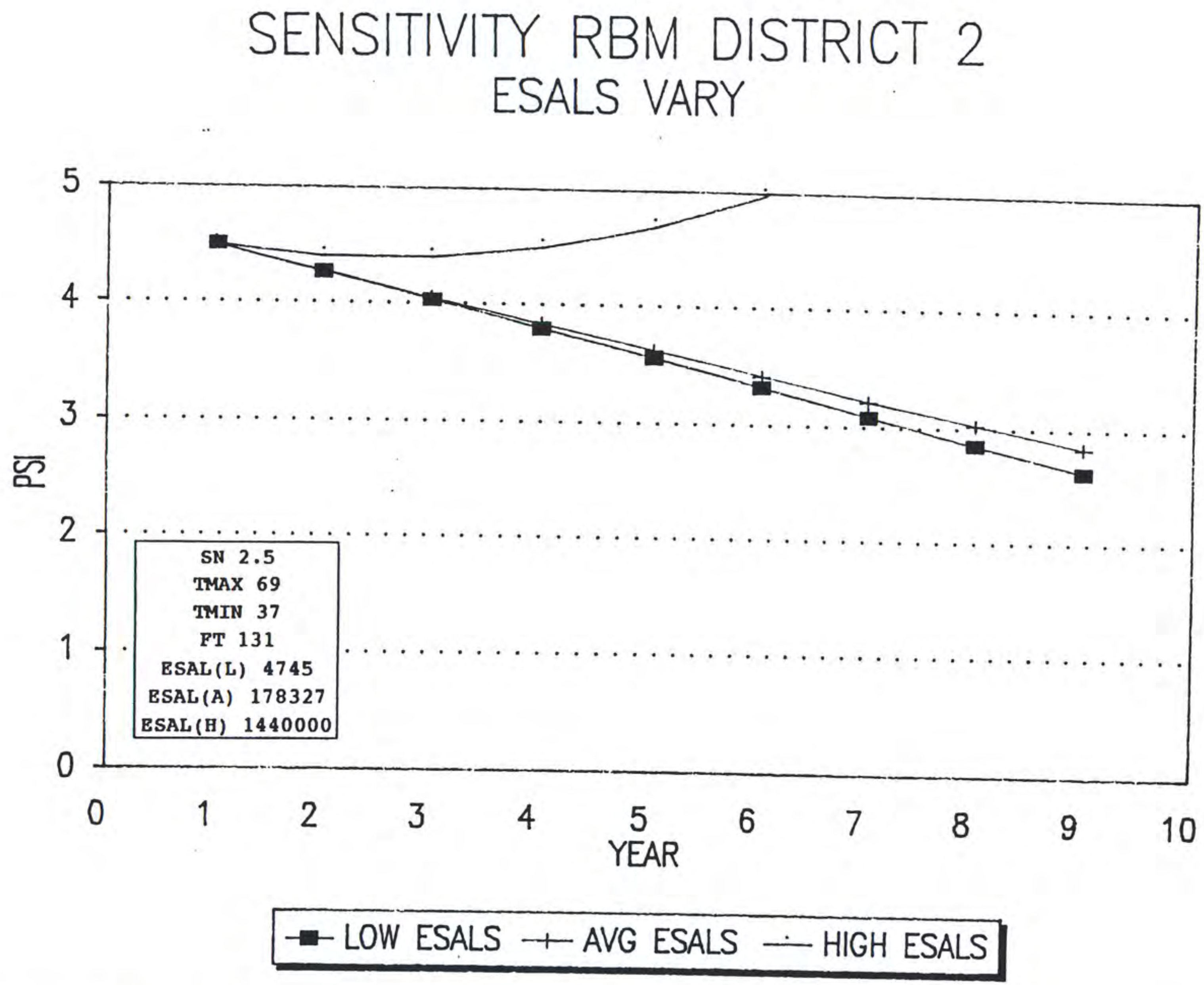

Figure 24. PSI vs Pavement Life, Roadbed Modifications District 2, ESALS Vary

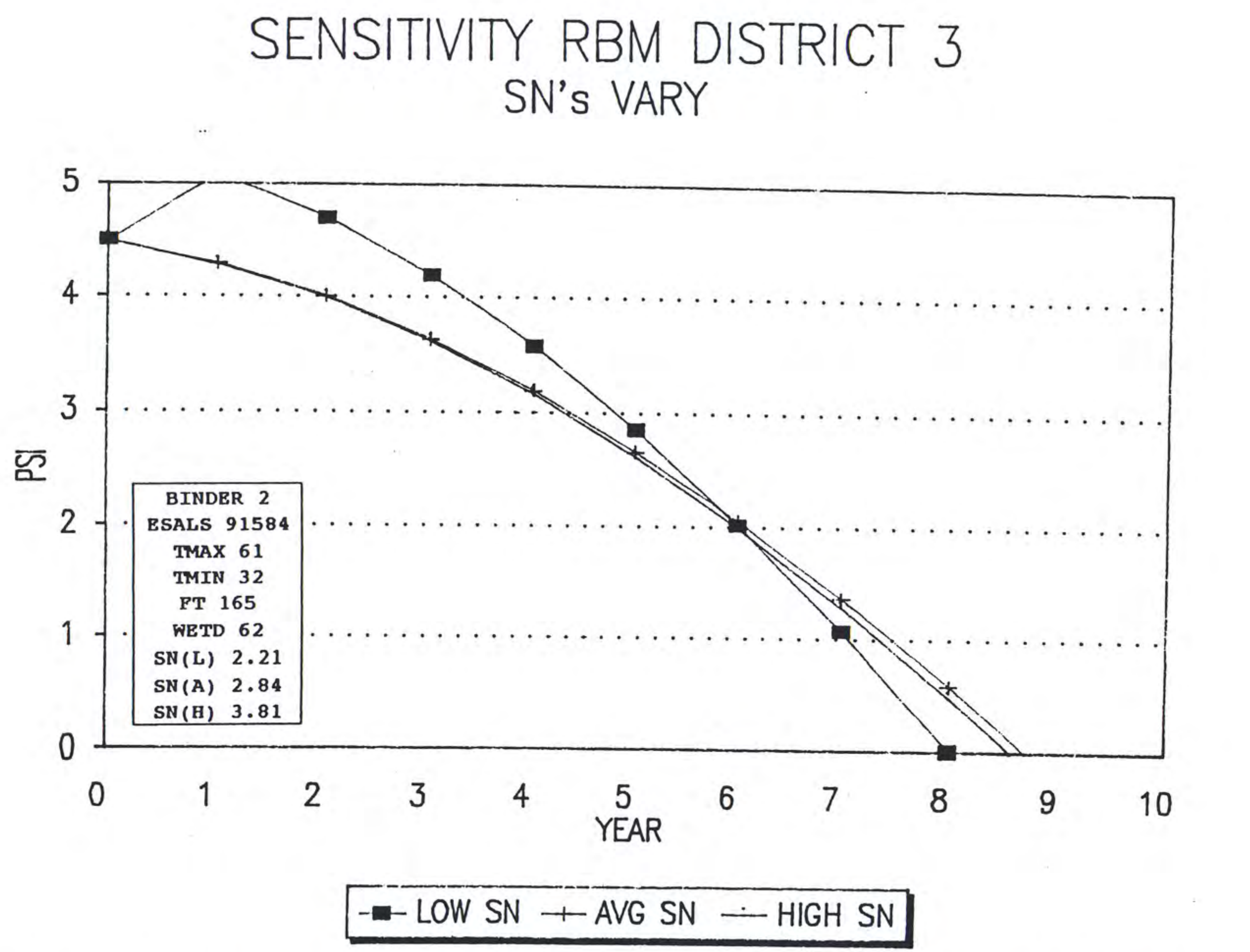

Figure 25. PSI vs Pavement Life, Roadbed Modifications District 3, Structural Numbers Vary

APPENDIX A

STANDARD DATA COLLECTION FORMS

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