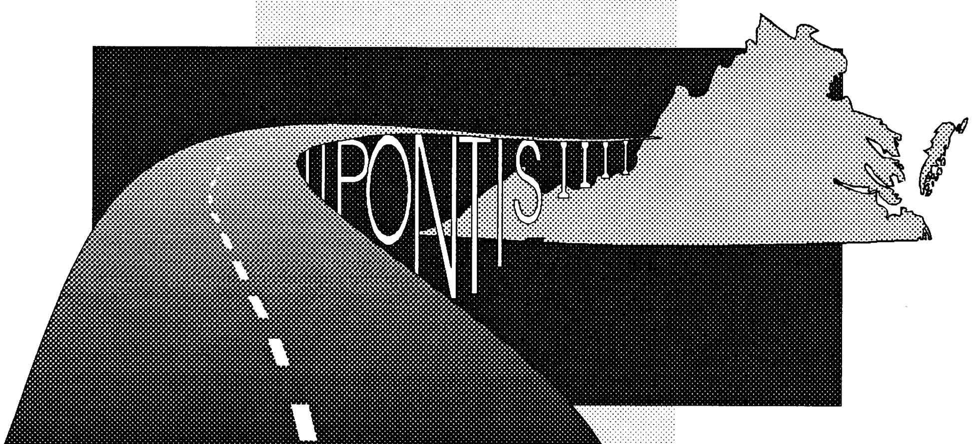
FINAL REPORT

ENVIRONMENTAL CLASSIFICATION SCHEME FOR PONTIS



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Abstract

In an effort to comply with the federal mandate for bridge management systems, many states have chosen to implement an existing system rather than develop their own. One such system is Pontis, the network-level bridge management system developed through the Federal Highway Administration's Demonstration Project 71. Although this system is intended for general application, the actual implementation process must be tailored to meet the needs of each state. One component of this implementation process involves assigning the bridge elements to one of four environments, each of which has a unique stochastic model associated with it. The environments used in Pontis—benign, low, moderate, and severe—are not explicitly defined. They represent relative distinctions between rates of deterioration resulting from operating practices and climatic exposure. This research presents a systematic strategy for developing a definition of these environments suitable to the needs of individual states. Instructions are included for data collection, and various classification methods are presented and compared. A step-by-step procedure for collecting the necessary data using easily constructed surveys is explained. Regression analysis can then be used to analyze the data, thereby providing a way of defining the environments. The strategy is demonstrated by applying it to concrete bridge decks.

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

In an effort to comply with the federal mandate for bridge management systems, many states have chosen to implement an existing system rather than develop their own. One such system is Pontis, the network-level bridge management system developed through the Federal Highway Administration's Demonstration Project 71. Although this system is intended for general application, the actual implementation process must be tailored to meet the needs of each state. One component of this implementation process involves assigning the bridge elements to one of four environments, each of which has a unique stochastic model associated with it. The environments used in Pontis—benign, low, moderate, and severe—are not explicitly defined. They represent relative distinctions between rates of deterioration resulting from operating practices and climatic exposure. This research presents a systematic strategy for developing a definition of these environments suitable to the needs of individual states. Instructions are included for data collection, and various classification methods are presented and compared. A step-by-step procedure for collecting the necessary data using easily constructed surveys is explained. Regression analysis can then be used to analyze the data, thereby providing a way of defining the environments. The strategy is demonstrated by applying it to concrete bridge decks.

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INTRODUCTION

The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) has mandated the use of bridge management systems (BMSs) to predict the future condition of bridge networks (Department of Transportation, 1993), and to do this, it is necessary to model the deterioration of the bridges. One frequently used method to model deterioration is the Markov Process. It captures the dynamic and probabilistic, i.e., stochastic, nature of deterioration. A stochastic process is considered a Markov Process if the conditional probability distribution depends only on the current state of the system. In other words, the Markov Process is memoryless (for a more formal definition, see Appendix A). In order to predict the future state of the system, it is only necessary to know the current state of the system.

One-step transition probabilities depict the probability of the system deteriorating from its current state to its next state. These represent the probability that the transition at any given time is from the current state to a future state. When all of the one-step transition probabilities for a specific time are grouped, the result is a transition probability matrix. Since some parts of a bridge deteriorate more rapidly than other parts, multiple transition matrices are needed to capture the distinct rates of deterioration. Modelling at this level of detail provides the information needed to specify the corrective actions that should be taken. This method of modelling deterioration is used by Pontis, the network-level optimization and planning program developed through the Federal Highway Administration Demonstration Project 71 (Cambridge Systematics, Inc. & Optima, Inc., 1991). Pontis uses the Markov Process to capture the uncertain, changing nature of bridge deterioration. When the modelling began on Pontis, it was recognized that the component condition ratings required as part of the National Bridge Inspection Standards (NBIS) program were inadequate if the Markov Process was to be used. Because component ratings of the deck, superstructure, and substructure are required as part of the National Bridge Inventory (NBI), previous BMSs had used these condition ratings as the primary data. However, these components are a collection of various elements that have distinct deterioration patterns (see Figure 1). In this figure, the deterioration of the substructure is represented by a single curve. However, the substructure is

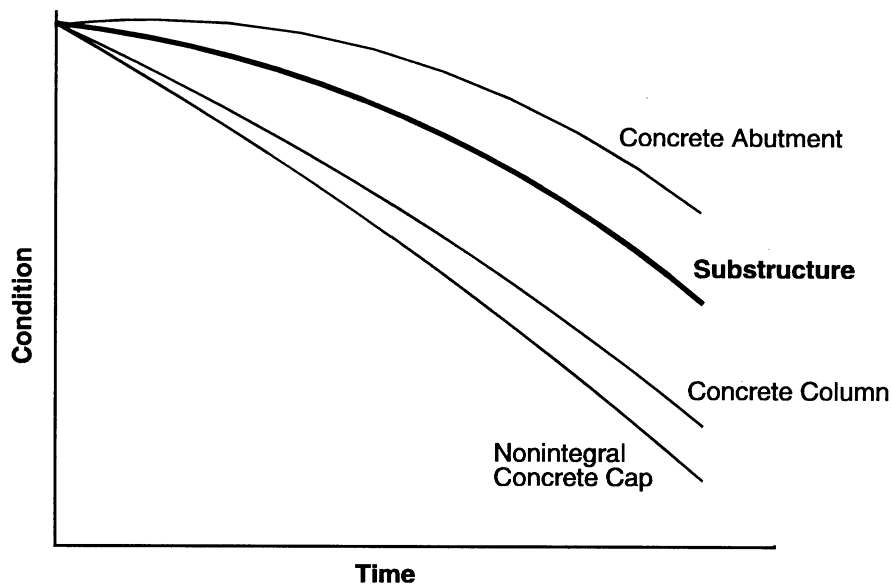

Figure 1. Rates of deterioration of the elements of the NBI substructure component.

actually composed of the three distinct elements, each of which has its individual rate of deterioration as shown (concrete abutment, concrete column, and nonintegral concrete cap). To enable better predictive modelling, Pontis uses individual elements of the bridge with clearly defined condition states.

To refine the predictive model further, it is necessary to examine a single element. Consider, for example, two identically constructed concrete bridge decks, one of which is on a seldom traveled secondary road and the other on a heavily traveled interstate highway, and the need for a further distinction is obvious. To allow for the difference in deterioration rates because of climatic exposure and operating practices (e.g., average daily traffic or annual chloride applications), Pontis requires the elements to be classified in one of four environments—essentially, these are deterioration classes. These four environments—benign, low, moderate, and severe—are left to individual agencies to define. Figure 2 illustrates how the four environments are used to model the deterioration rates of a single element.

PURPOSE AND SCOPE

This research develops a method to be used to determine how to assign bridge elements to one of the four environments—benign, low, moderate, or severe—within Pontis. The method allows the agency to develop quantitative

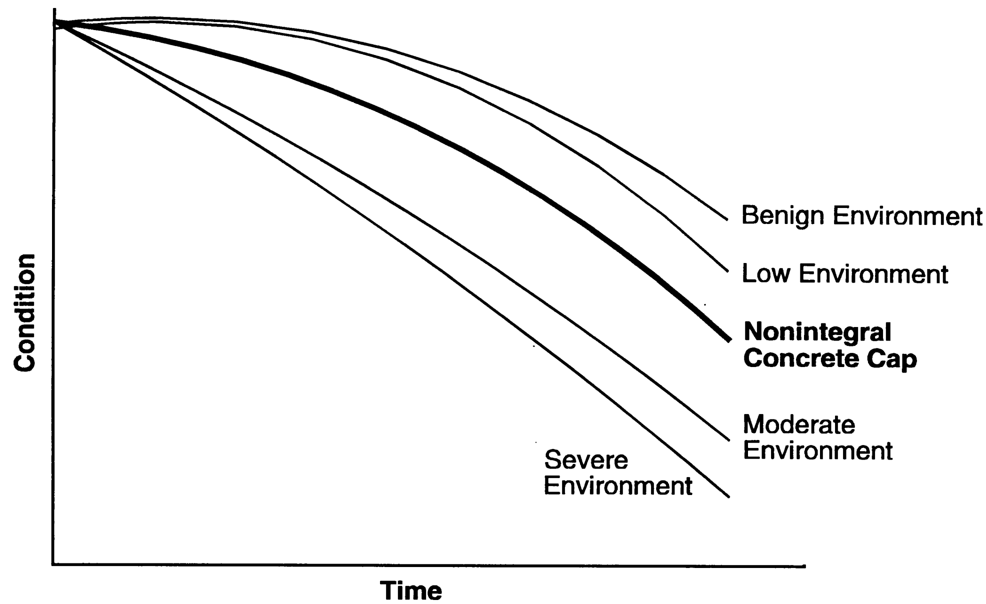

Figure 2. The impact of environment on the deterioration of a specific element.

definitions of the environments based on the appropriate operating practices and climatic exposure for every element in the agency's bridge population. For the purpose of illustrating the method, an application is developed for concrete bridge decks using operating practices and climatic exposures specific to Virginia.

It is possible to implement Pontis without differentiating between the four environments. However, if this were done, the result would be a less representative model of an agency's bridge population. By developing an easily implemented strategy for the quantitative definition of the four environments, every agency using Pontis will be able to receive the full benefits of the deterioration modelling provided by the system.

APPROACH

Studies have been conducted in the past to determine the factors that affect the deterioration rates of bridges. The new problem posed by Pontis is that every element of the bridge must be assigned to an environment. Since most of the previous studies address the deterioration of individual bridges, the results cannot be used to generate environmental categories at this level. The level of specificity required has not been documented, and the available data is not appropriate for a quantitative analysis of this nature. In addition, a previous study done in the state of Virginia found that the historical inspection and maintenance data was very incomplete (see McGhee, Allen, & McKeel, 1993; Allen & McKeel, 1989).

Because the definition of the environments needs to be tied to realistic situations anticipated within the agency's bridge population, the definition of the environments needs to be tailored to each state. For these reasons, it was decided to create a survey to collect the data for the initial environmental classification. Even though information obtained from surveys contains biases, it was decided that a review of the classification after several cycles of use would determine the method's effectiveness. If the scheme performed unsatisfactorily, the historical data collected in the intervening time could be used to reformulate the model. The result of using the surveys would be an easily implemented methodology that would allow quick assignment of the elements of the environments.

Once an acceptable survey was developed, a process had to be devised for creating the definitions of the four environments from the collected data. Steps included the organization of the data, the selection of the appropriate sample of the data, and the classification method to be used to develop the definitions. The method that emerged appears in the following section. In many ways, this method is a result of trial and error. The application used in this developmental process is described in detail later in the report. The emphasis of this research is on the development of a suitable methodology to define the four environments for any Pontis element.

FINDINGS AND INTERPRETATION

The general methodology to be used to develop the quantitative definitions for the environments is as follows:

1. *Determine the element or group of elements of a structure for which the survey is to be developed.* Pontis includes over 100 elements. To develop surveys for all of these elements, to distribute them, to have them completed and returned, and to analyze the results is prohibitively time consuming. Instead, elements affected by the same operating practices and climatic conditions can be grouped. For example, all decks and slabs can be covered in one survey for the purpose of environmental classification. Expert elicitation and historical records can be used to distinguish between the deterioration behavior resulting from different materials or structural properties. Also, as another example, many studies have found that the deterioration of decks is dependent on traffic, but that the deterioration of the substructure elements is not. Therefore, the deck and the substructure elements should not be grouped together.

2. *Gather climatic information and information about operating practices that may affect the deterioration of the specified element(s).* One source is previous research studies. Factors that might affect deterioration include average daily traffic, average annual snow fall, or the angle of skew of the bridge. A second source is what experts in the field believe affects deterioration rates. If the surveyor is still unsure what factors actually affect the deterioration of a particular element, a preliminary survey can be distributed with instructions to note any relevant factors that were omitted. This was done in Virginia with satisfactory results. It is important to ensure that the factors determined to affect the rate of deterioration are not included as separate Pontis elements. For example, in the Virginia study, several respondents commented that the presence of epoxy-coated reinforcing steel affected the rate of deterioration of concrete decks. However, a concrete deck with epoxy-coated reinforcing steel is a separate Pontis element; thus, it should not be included as climatic information or as an operating practice.

3. *Determine the applicable, state-specific, quantitative ranges over which the factors selected in step 2 may vary.* For general survey construction, it is important that the ranges of the variables include all of the possible responses for bridges located in the particular agency's Pontis database. For example, if average daily traffic is found to be a factor in the deterioration of a particular element, a range of 10-900 average vehicles per day might be selected. This would indicate that no bridge in the state that is included in the Pontis database is expected to have an average daily traffic of less than 10 vehicles per day or more than 900 vehicles per day.

4. *Using the information collected in steps 2 and 3, create a survey for the element(s) selected in step 1.* The purpose of this survey is to relate those factors determined to affect the deterioration of an element with their impact on the rate of deterioration. During the course of this research, it was determined that a graphical format is the easiest method to adapt to various elements and the easiest format for the respondent. The recommended format for the survey instrument is shown in Figure 3. In this figure, an example is used from the application to bridge decks in Virginia, which will be discussed in detail in a later section of this report. In this example, the element chosen in step 1 was a concrete bridge deck. The climatic and operating practices determined in step 2 were average daily truck traffic (ADTT), annual freeze thaw cycles (F/T), and annual chloride applications (Cl.). The ranges for each of these factors as determined in step 3 are indicated. For example, the range for ADTT was determined to be 0 to 800.

The lines on each graph depict the scenario that the respondent is asked to consider. In the graph in the top left corner, the respondent is asked to evaluate the rate of deterioration of the concrete bridge deck with high values of ADTT, F/T, and Cl., as compared with all the other concrete bridge decks within the agency. In this example, three factors are being tested for their impact.

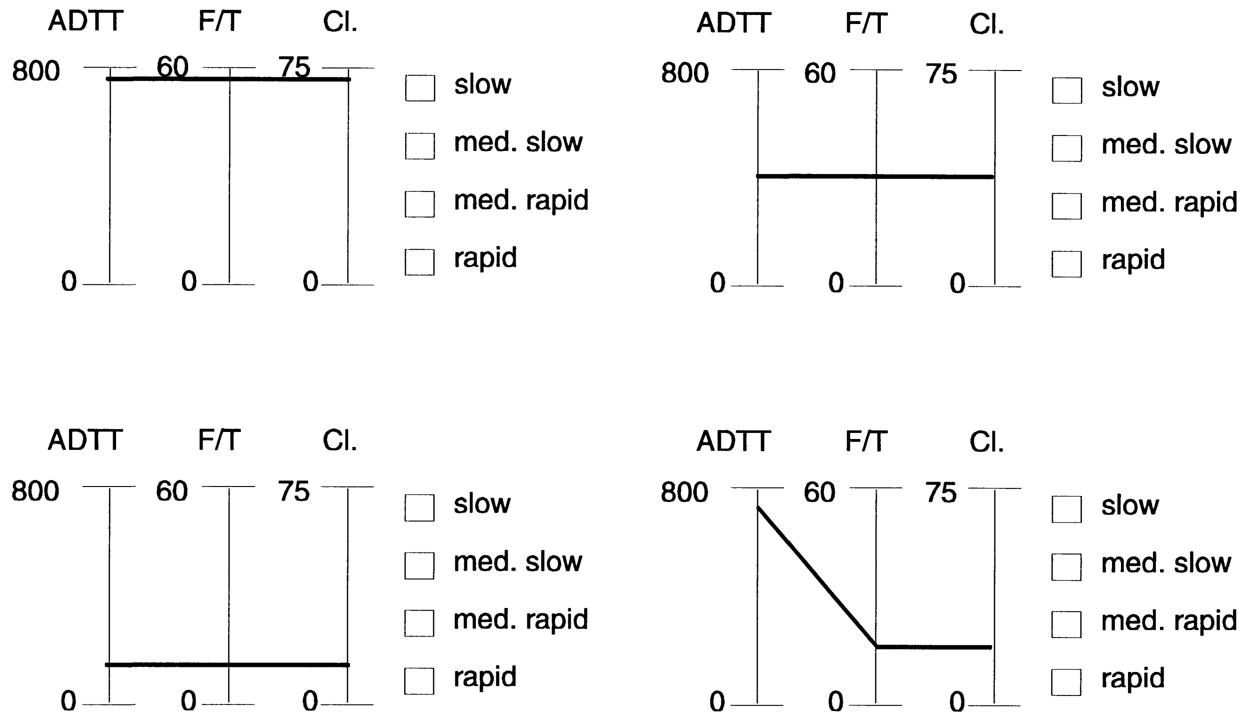

Figure 3. Format for survey.

Ensure that enough graphs are depicted to allow subsequent analysis. One suggestion is that the user be given 3^f graphs, where f is the number of factors determined in step 2. In the example shown in Figure 3, there are three factors; therefore, there should be a total of 3^3=27 graphs. This allows a high, medium, and low range for each variable. Empty graphs should also be provided in which the respondent depicts an average case in each class (see Figure 4). The dotted lines in the figure demonstrate the lines that one respondent drew to indicate a typical combination of influences leading to the rate of deterioration indicated to the right of each graph.

This helps ensure that the user understands the survey method. Using the various combinations in the survey, many different combinations of variables can be surveyed. Other methods that can survey this wide range of possible responses were found to take much longer to answer. As the survey was developed, the following assumptions were made:

- First, it was assumed that the person surveyed at the local level had a good understanding of how specific elements behave under certain conditions throughout the area, which would include the relative behavior of identical elements under different use and treatment patterns and the general causes of the deterioration.

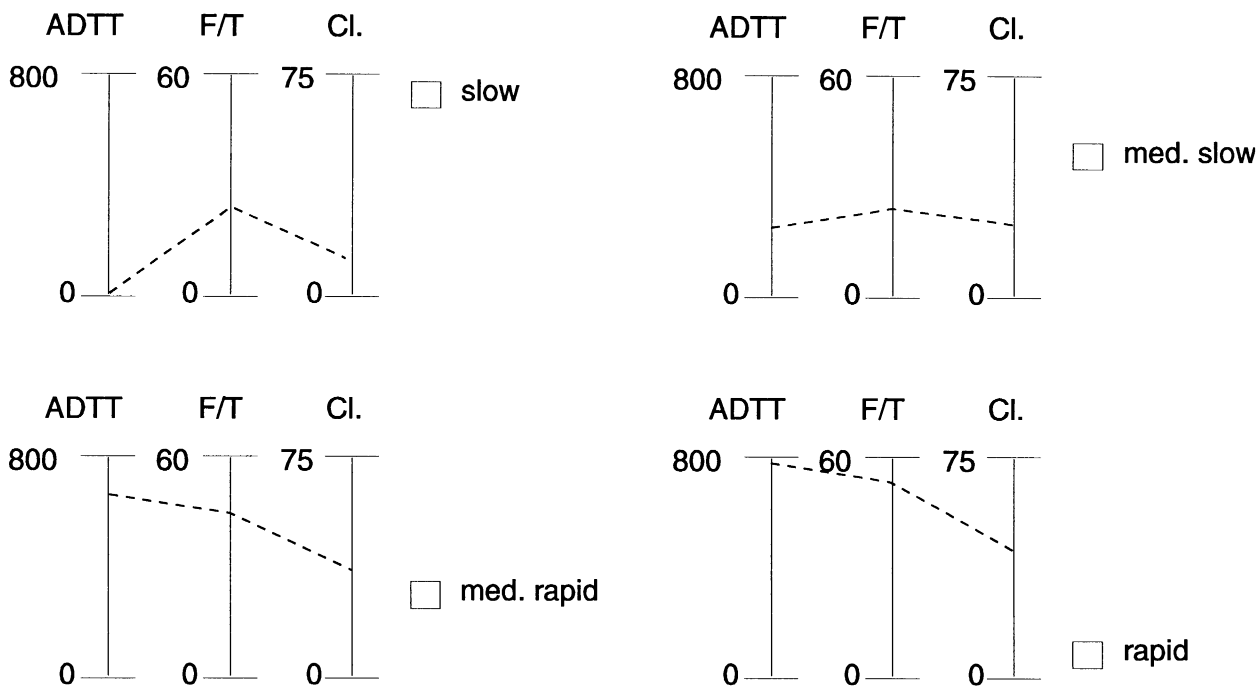

Figure 4. User-drawn survey graphs.

- A second assumption was that similar conditions would cause like elements to deteriorate similarly across the state.

- A third assumption was that the Markov property is valid for bridge deterioration. That is, it is only necessary to survey and consider the current condition of the element to predict future behavior. If past behavior would affect future behavior, then the survey that was developed would be inadequate. This assumption also underlies the fundamental modelling of Pontis, so it is a consistent assumption.

5. *Collect and review the surveys.* If there are a significant number of responses stating that a particular relevant factor was initially disregarded, then the survey should be reformulated. By administering the survey again, the factors determined originally to influence the rate of deterioration as well as the other factors can be included in the new survey.

6. *Create a database of the results.* One suggestion is to use a spreadsheet. It is recommended that the high and low responses to the pre-constructed graphs be deleted if enough respondents participated. This partially controls for outliers. Another way of treating the data is to split the samples. If the data set is split, then part of the data can be used to "train" the model, and the other part can be reserved to "test" the model. One way of estimating the error of the various approaches is to divide the sample data ($\mathcal{L}$) into two sets ($\mathcal{L}_1$, $\mathcal{L}_2$). The data in $\mathcal{L}_1$ is used to "train" or to construct the model. The data in $\mathcal{L}_2$

is then used to validate the model. In many instances, $\mathcal{L}_2$ is taken to be 1/3 of $\mathcal{L}$, and $\mathcal{L}_1$ to be 2/3 of $\mathcal{L}$ (Breiman, Friedman, Olshen, & Stone, 1984). This method is only useful when the sample size is considered large enough for $\mathcal{L}_1$ to be statistically meaningful. Because of the size of the data set, this approach was not used in the application described later in this report.

7. *Classify the elements into environmental categories.* This classification will use the data collected from the surveys to create a definition of the four environments for a particular element within the agency. If there is enough data, the training data can be used to form the model. The testing data, which was separated originally, can then be used to validate or test the model for its ability to assign the described cases to the appropriate environment. In this case, the appropriate environment would be the one to which the experts in the survey assigned the described element. Such a classification procedure builds a model through which specific characteristics describing the element can be used to assign the element to one of the four environments.

There are two primary methods of approaching the classification problem.

- The first is to use a knowledge-based approach. Essentially, this method uses rules that are developed from the training data to classify future data sets. A strength of this method is that a set of descriptive characteristics will map directly to one of the four environmental classes. Classification and Regression Trees (CART) (California Statistical Software, 1988) is a software package that is used to assist in this process.

- The second method is statistical analysis, which involves fitting a function to the data to produce a function that characterizes future data. To use this method, the environmental classes must be treated as numerical values. By specifying applicable ranges, the values can be massaged to depict the four environmental classes. Some of the software packages compared in this process were CART, Abductory Induction Mechanism (AIM) (Abtech Corporation, 1989), and Data-Desk. The different methods tested did not yield significantly different results, and most state agencies already have multiple regression software. In the case of multiple regression, the output is an equation that can be used to classify future elements.

8. *Analyze the results of the environmental assignments based on the definitions developed using the various modelling approaches.* In general, there are several desirable criteria that should be met.

- The method should be easy to use and easy to understand.

- The method should be familiar to transportation agencies. Many sophisticated computer packages are available, and many of these are quite expensive. Unless the results are significantly better, it is more appropriate to select an inexpensive package that is currently in use or one that has multiple applications within the agency.

- The method should have a high rate of accurate classification.

- If the method misclassifies the data, it should not be off more than one class.

- The trade-off between accuracy and complexity must be considered. When using statistical analysis as a predictive method, it is important that the model not overfit or underfit the data. In types of regression analysis, this is often considered by adjusting for complexity. In general, as parameters are added, the method increasingly better fits the data on which the method was trained. However, the model with a high degree of complexity will generally not perform well on new data, that is, the data used to test, or validate, the model. The simpler the model is, the higher the chance of accurately classifying the variables that are introduced into the model (Elder & Brown, 1992) (see Figure 5).

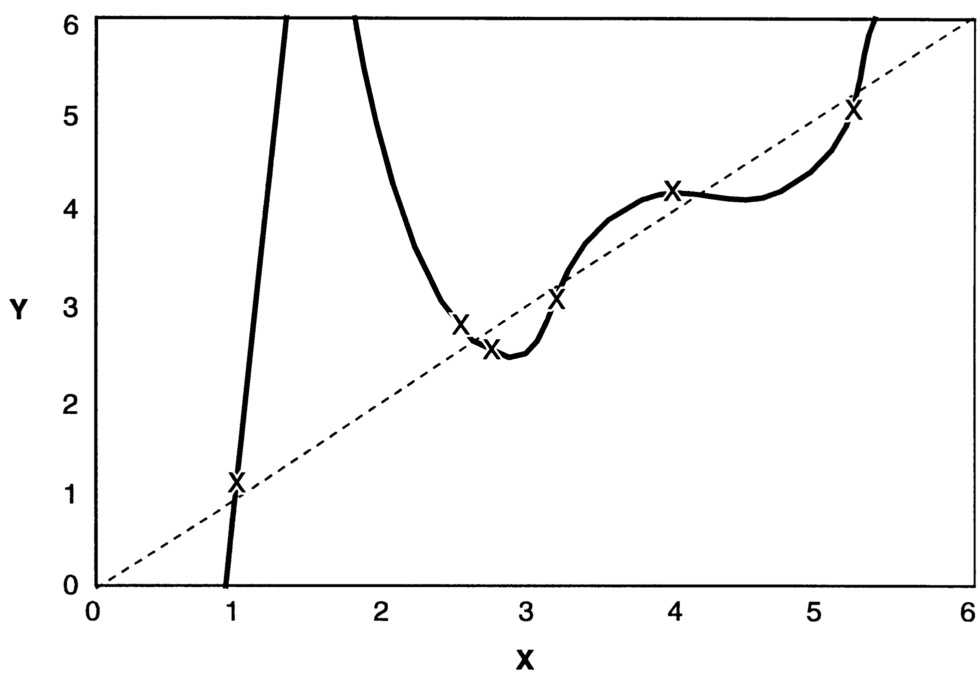

Figure 5. Example of model overfit.
Source: Adapted from Elder and Brown, 1992.

In Figure 5, a polynomial produces the curve that fits the data points exactly, however, the likelihood of future points falling on this curve is small. This example could demonstrate a model that is to predict the value of y, given the variable x. The polynomial shows a predictive model that was constructed with no control on complexity. The model fits the data with which it was built very well. There is no error in the data that was used to construct the model, that is, the training data. However, the general form of the data points suggests that if situations in which both x and y were known were tested on this model, a simple line would be a much better estimate (Elder & Brown, 1992). When constructing the model, the error of the training data on the simple line would be greater, but in general, the error on the testing data would be much less than if the polynomial was used.

As the various modelling approaches are analyzed, it is important to consider how they meet the listed criteria. The construction of a cross-validation probability matrix is one way to evaluate how well the method classifies the data (see Table 1). The values in the cross-validation probability matrix display the results predicted from the model versus the respondents' answers from the survey. A strong diagonal with zeros in the upper and lower diagonals is desirable. Consider the following matrix of environments:

Table 1
TRUE CLASS

Predicted Class	Benign	Low	Moderate	Severe
Benign	1.0	.25	0	0
Low	0	.60	.25	.03
Moderate	0	.13	.65	.14
Severe	0	.02	.10	.83

Ideally, the underlined values along the diagonal would equal 1.0 or 100%, but in most cases, since the opinions of experts vary, the "true" classes are not that uniform. In general, the values along the diagonal should be maximized, whereas those values outside the diagonal should be minimized. Preferably, the more extreme triangular regions are equal to zero. However, the results must be examined outside of these restrictions. For example, if nine experts predict severe and one expert predicts benign, it is preferable for the model to predict severe and have one prediction three classes off than for it to predict moderate and have nine predictions one class off and one prediction two classes off.

9. *Distribute the results to survey respondents for verification.*

10. *Use the results to assign defined elements to the appropriate environment.*

Application of Approach

The survey method described above was applied to define quantitatively the correct environment for various concrete bridge decks in Virginia. The first step was to isolate the climatic and operating practices that affect the deterioration of the bridge decks.

Historical Review

After reviewing various studies of deck deterioration (O'Connor & Hyman, 1989; Allen & McKeel, 1989; Fitzpatrick, Law, & Dixon, 1981), the following were found to be significant factors influencing the deterioration rates of concrete decks:

- type of span (e.g., simple vs. continuous)
- age
- average daily traffic
- chloride applications
- average daily truck traffic
- construction and maintenance procedures.

In addition to a literature search, various experts at the Virginia Transportation Research Council were asked what factors they thought affected the deterioration of concrete. In addition to those factors listed, they mentioned freeze/thaw cycles.

Survey Development

A survey that focused on decks was developed and conducted for the state of Virginia. There were three main purposes of this survey:

1. to evaluate the technique used to elicit information
2. to begin to educate the district employees about Pontis and the changes that Pontis will require in the inspection process
3. to determine the criteria required to define the four environments for bridge decks in Virginia.

Three variables were used in the survey: ADTT, Cl, and F/T. Figure 6 shows one component of the survey. Every possible combination of a high, medium, and low range for each variable was included in the survey (see Figure

3). Therefore, this is one of 27 graphs (3^3). The ranges shown on each factor reflect the ranges that were anticipated for Virginia's network. The heavy line represents the particular characteristics of an individual deck. For the deck in question, ADTT was almost 800, there were about 60 F/T cycles, and there were roughly 75 Cl applications. The survey respondent determined that under these conditions in Virginia, deterioration would be "rapid" relative to other bridge decks in the agency's database. For a copy of the complete survey see Appendix B.

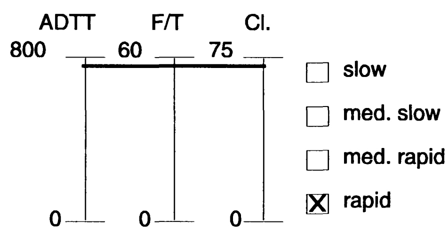

Figure 6. Sample survey question.

Every district bridge engineer in Virginia was given a survey to test the simplicity and accuracy of the technique. The size of the statistical sample was not the primary concern. The surveys were returned and the answers compiled (see Appendix C). To control for outliers, the high and low responses for each specified data set were not used in the analysis. The data set was not divided into training and testing sets.

Survey Analysis

Feedback about the format of the survey was favorable. The information was considered to be easy to understand and could be completed in about fifteen minutes. Since the following affect overall deterioration rates, the respondents suggested that they be included in future surveys:

- the depth of the concrete cover over the reinforcing steel (Because the depth of the cover is indicative of evolving practices, it is highly correlated with the age of the bridge deck; therefore, it might be easier to use age as opposed to cover depth.)
- the type of span (continuous or simple)
- the type of reinforcing steel (e.g., epoxy-coated)
- the original quality of deck concrete and construction
- the amount of live load deflection
- the exposure to extreme heat

- the waterproofing treatments
- the class of the road
- the speed of the traffic on the road
- the grade of the bridge
- the orientation of the bridge (e.g., north-south, east-west, etc.).

All of these factors affect the deterioration rate of a concrete deck, and some of these should be used in subsequent deck surveys. Many of these concerns are addressed in Pontis by differentiating between types of elements. For example, a deck with epoxy-coated reinforcing steel is a separate element from a deck with traditional reinforcing steel. The type of span and the class of road or the speed of the traffic on the road should be considered in subsequent deck surveys.

Discussion of Modelling Approaches

Several different classification methods were used to build the model, which could then be used to assign the bridge decks to one of the four environments when certain characteristics were known about the deck. In constructing the model, the environments that the experts assigned to the decks were used. The ability of the model to produce results similar to those produced by the surveyed experts was compared to select the most appropriate method. The software packages that were used were selected because of their availability and because they used modelling methods that were of interest. Because the Pontis environments are categorical variables, the modelling options for classification are limited. However, because the environments can be mathematically manipulated into real, ordered variables, more models become available.

To perform this manipulation, let the ordered measurement vector (x_1, x_2, x_3, x_4, . . .) be represented by the vector $\underline{\mathbf{x}}$, where $\underline{\mathbf{x}}$ contains all relevant factors that affect the deterioration of the specified bridge element. The measurement space X contains all of the possible measurement vectors. Let C be the set of classes such that any $\underline{\mathbf{x}}$ contained in X will belong to one of the classes in C:

$$C = \{\text{benign, low, moderate, severe}\}.$$

To avoid the prejudice that the use of the words benign, low, moderate, and severe has generated, let the four classes be defined as

$$C = \{1, 2, 3, 4\},$$

where 1 represents the class with the slowest deterioration rate for the area of use. Let A_1, A_2, A_3, A_4 be the subsets of X which belong to each of the four respective classes. The sets $A_1, \ldots A_4$ must be disjoint, and $X = \cup A_j \; \forall j$. That is, every element must belong to one and only one of the sets A_1, A_2, A_3, and A_4. This research suggests a formal approach that can be used to define A_1, A_2, A_3, and A_4 for any BMS element.

CART: Classification Tree

CART is a computer algorithm that generates binary decision trees through an inductive process. From the data that is supplied, the user can select the construction of either a classification or regression tree. The classification tree option in CART uses a process that inherently controls for the problem of simplicity versus complexity discussed earlier. Decision trees are recursively constructed in search of the tree that best classifies the problem, without overfitting or underfitting the data.

The decision tree is "grown" using a one-step optimal procedure, frequently called a greedy process. (In a greedy process, the splits are successively on the best single variables.) For this reason, a word of caution at this point is appropriate. Since CART uses a greedy approach, the final tree may be suboptimal, because, where a combination of variables produces a more accurate model, CART fails to produce the best fit.

Table 2 demonstrates a weakness of the approach used by CART. In this example, a greedy approach would build a model to predict Y from the variables, X_1, X_2, and X_3, using a single variable. In this case X_1 is the best single variable. A nongreedy approach would build a model to predict Y from the variables X_1, X_2, and X_3 using the model $X_2 + X_3$ since this predicts Y in every case. See Elder and Brown (1992) for a more complete discussion.

One strength of CART is its ability to handle different types of variables. These include ordered or numerical variables, which are real, measured values, and categorical variables (Breiman, et al., 1984). A second advantage of CART is the simplicity of the graph produced (see Figure 7). The terminal nodes of the tree clearly identify which environment the deck should be assigned.

Table 2
GREEDY PROCESS EXAMPLE[a]

Case	Y	X_1	X_2	X_3
1	3	3	2	1
2	3	3	1	2
3	3	3	2	1
4	3	1	1	2

[a]Adapted from Elder and Brown (1992).

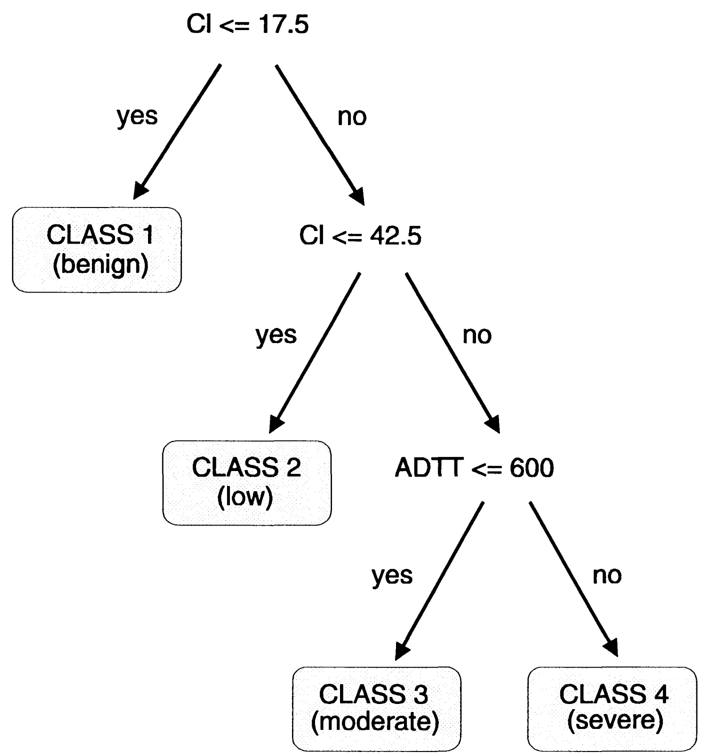

Figure 7. Classification tree.

A closer analysis of the graph shows a major problem. Consider two identically constructed bridge decks with the characteristics listed in Table 3.

Table 3
BORDER PROBLEM WITH CART

	ADTT	F/T	Cl	Class
Deck 1	700	45	42	Low
Deck 2	700	45	43	Severe

At some point, there must be an edge between classes, but changing the number of chloride applications by one per year, with everything else remaining constant, does not intuitively suggest a distinction of two classes. A clearer example of this problem occurs when ADTT increases by one vehicle with F/T and Cl remaining constant. In this case, a two-class distinction is even more unacceptable. It was first thought that this problem resulted from the size of the data set, but further research revealed that this problem with borders is a typical problem with CART (Safavian & Landgrebe, 1991). Attempts to rectify this problem have been proposed using a "fuzzy logic search," but this was not used in this research (see Wang and Suen, 1987).

When CART is run, a cross-validation matrix is supplied (see Tables 4 and 5). This is a way of representing how CART predicts its model will behave in the future. The true classification, in this case the responses of the bridge engineers, is compared with the class predicted by the decision tree generated by CART. For the CART run, the cross-validation matrix is given. Again, 1 is the benign environment, 2 the low, 3 the moderate, and 4 the severe.

Table 4
CROSS-VALIDATION CLASSIFICATION MATRIX FOR CART

	True Class			
Predicted Class	1	2	3	4
1	36	12	0	0
2	0	29	14	1
3	0	6	37	5
4	0	1	6	29

Table 5
CROSS-VALIDATION CLASSIFICATION PROBABILITY MATRIX FOR CART

	True Class			
Predicted Class	1	2	3	4
1	1.0	.25	0	0
2	0	.60	.25	.03
3	0	.13	.65	.14
4	0	.02	.10	.83

An examination of the diagonal shows that the model predicts class 1 very well and class 4 well; the prediction of classes 2 and 3 is a little uncertain. Another concern is the magnitude of the model's inaccuracy. There are instances when the model may predict a class that is two classes away from the class predicted by the survey respondents.

CART: Regression Tree

Regression analysis assumes continuous, real variables. This problem was forced into the regression model by allowing the environments to be assigned numerical values. That is, 1 was assigned the benign environment, 2 the low, 3 the moderate, and 4 the severe. CART was allowed to assume that the values were continuous. The tree produced gave a value at the terminal node as shown by the boxes in Figure 8. It was then necessary to translate this value to the appropriate environment by rounding to the nearest integer value. (For example, 3 has meaning. It is the moderate environment. On the other hand, 3.7 has no meaning. It is an environmental class between moderate and severe, but since only four environments are allowed, 3.7 can be addressed by rounding to 4.) Because this method assumes that the environmental classifications are continuous values between 1 and 4, some rounding errors gave

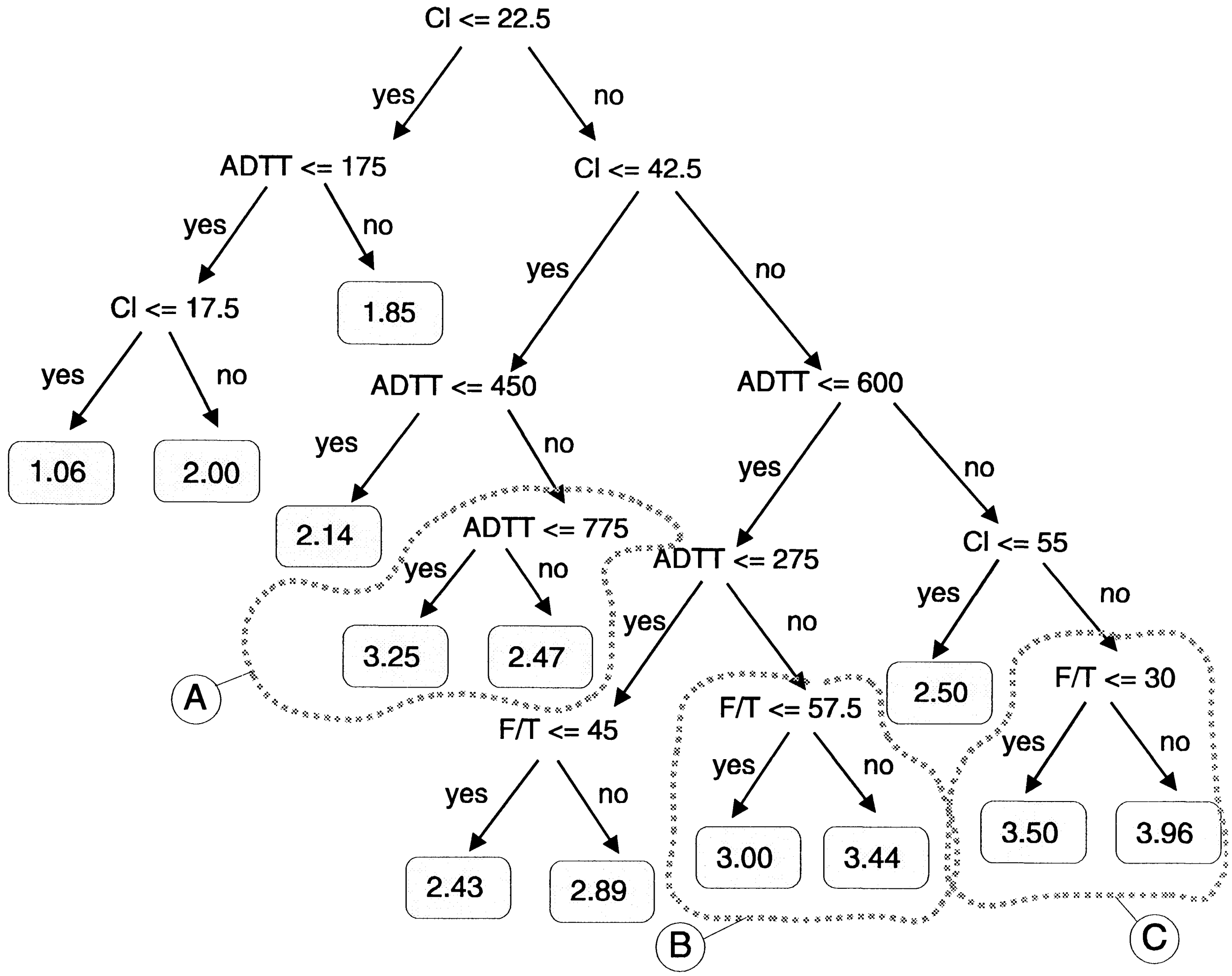

Figure 8. CART regression tree as produced.

counterintuitive results. For example, at the node that splits on the no branch of ADTT ≤ 450 labelled A and circled in Figure 8, the tree shows a split. If ADTT ≤ 775 the class assignment is 3; if ADTT > 775 the assignment is 2. This is counterintuitive since we know that as traffic increases the rate of deterioration increases. Problems such as this indicate that this is not a good method to use for this particular problem. Other problems are noted by B and C in the figure. Since CART assumes that the environmental classes are continuous in order to perform regression analysis, the original tree split at both of these nodes. However, the split assigned both nodes to the same class. Figure 9 shows the regression tree with these problems corrected. This is the tree that is discussed in the comparative analysis. The cross-validation matrices indicate that the model is a good classifier (see Tables 6 and 7). The upper and lower extreme

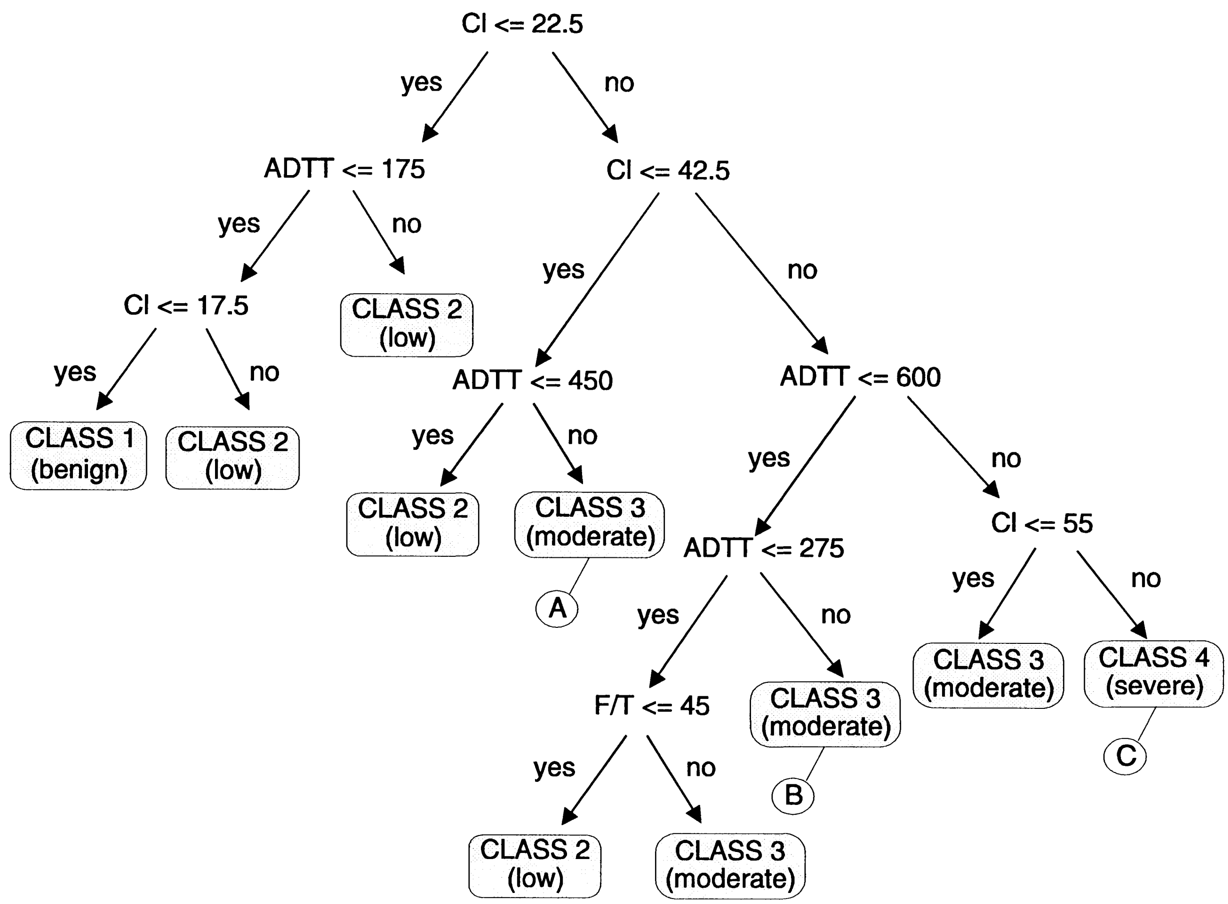

Figure 9. Modified CART regression tree.

Table 6
CROSS VALIDATION CLASSIFICATION MATRIX FOR CART REGRESSION

	True Class			
Predicted Class	1	2	3	4
1	38	4	0	0
2	4	37	9	0
3	0	18	47	11
4	0	0	7	33

Table 7
CROSS VALIDATION CLASSIFICATION PROBABILITY MATRIX FOR CART REGRESSION

	True Class			
Predicted Class	1	2	3	4
1	.90	.07	0	0
2	.10	.63	.14	0
3	0	.30	.75	.25
4	0	0	.11	.75

diagonals are 0. The regression tree results are better than the classification tree in some ways. The problem is that the model was counterintuitive without the adjustments that were made, and it would not have been usable otherwise.

AIM

Unlike the classification tree option in CART, AIM is designed to predict response using statistical methods. Like the regression tree in CART, AIM can be tricked into performing a classification if the output classes are ordered values.

AIM combines nonlinear regression techniques with a tree mechanism and builds a tree of regression equations to form a plane. AIM is based on the Algorithm for Synthesis of Polynomial Networks (ASPN). Both models use a sequence of incomplete third order polynomials to construct the networks; they use up to three variables in each polynomial (Elder & Brown, 1992). This method prevents the problems of the one-step greedy procedures, since combinations of variables can be considered.

Minimizing the error of the training sample introduces complexity that may result in a poor predictive model. AIM addresses this trade-off between accuracy and complexity through a complexity multiplier. When the user sets a low complexity penalty multiplier (CPM), the error on the training data is minimized. On the other hand, a high CPM increases the impact of the complexity penalty, thereby resulting in a less complex network. The error term of the testing data is the predicted squared error (PSE) and is defined as follows:

$$\text{PSE} = \text{MSE} + \text{KP},$$

where KP is the complexity penalty, and MSE is mean squared error, i.e., the actual error of the model using the training data. KP is defined as:

$$KP = CPM\left(2\frac{KS_p^2}{N}\right),$$

where CPM is the complexity penalty multiplier set by the user, K is the total number of coefficients, N is the number of training data, and S_p^2 is the a priori estimate of the true model error variance (AbTech Corporation, 1989). To determine the best model, networks were constructed using various complexity multipliers, and from these, the best representatives without overfit or underfit were selected. The mean square error and the predicted square error for this data set are plotted in Figure 10.

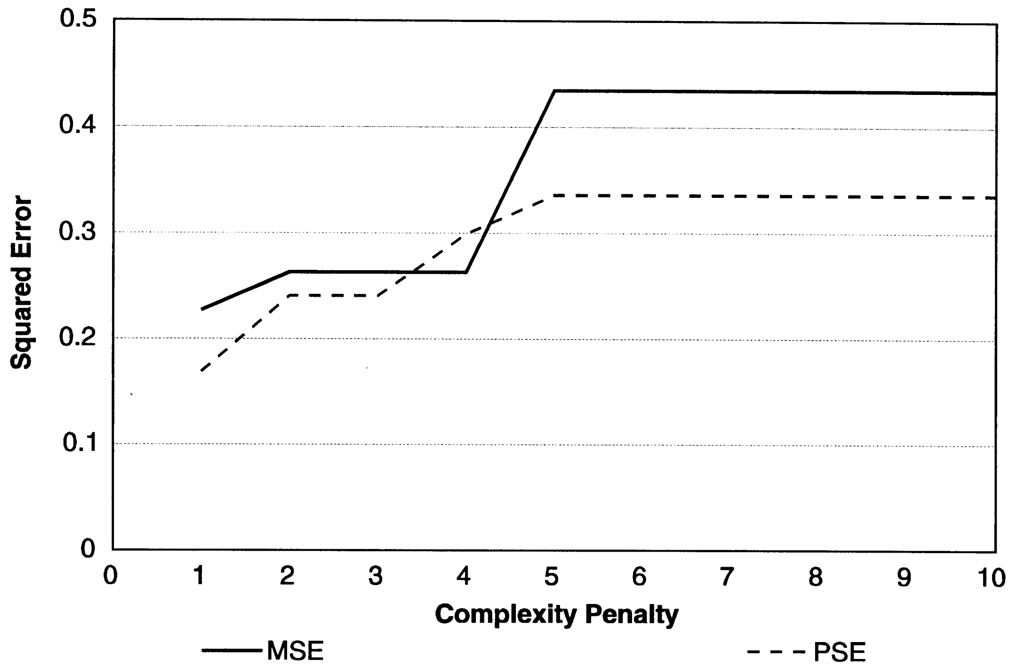

Figure 10. AIM graph: Complexity penalty versus squared error.

To demonstrate the impact of the user-selected CPM on the resulting analysis, two cases are discussed. In the first case, the CPM is 3, and in the second it is 5.

Complexity Penalty of 3. Two of the constructed networks are shown. The network for the complexity penalty of three is shown in Figure 11. For the purposes of this report, the box labelled white is only important in that it is a label for the function shown. Through algebraic manipulation of the equations, this can also be represented by the equation

$$En = 0.769 + 0.00143(ADTT) + 0.0265(Cl),$$

where En is environment, ADTT is average daily truck traffic, and Cl is the number of chloride applications per year.

Some concern is raised about the misclassification of class 2 (see Tables 8 and 9), but the high percentages in the other positions along the diagonal show that this is a good predictor. Comparison with the complexity penalty of 5 shows the problem raised by oversimplification.

Complexity Penalty of 5. The network shown in Figure 12 may also be represented by the equation

$$En = 0.7922 + 0.039491(Cl).$$

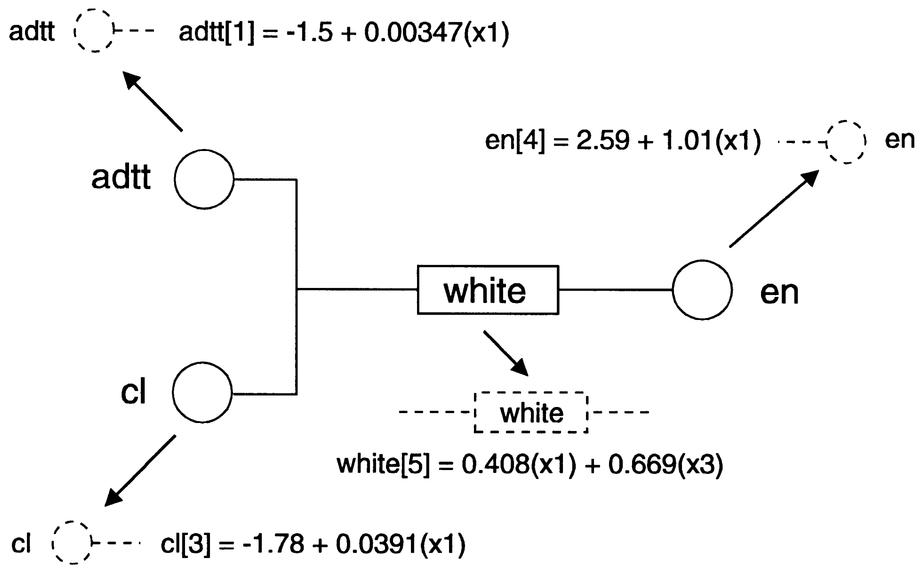

Figure 11. AIM network with complexity penalty of 3.

Table 8
CROSS VALIDATION CLASSIFICATION MATRIX FOR AIM (CPM = 3)

	True Class			
Predicted Class	1	2	3	4
1	39	6	0	0
2	3	31	5	0
3	0	22	51	11
4	0	0	7	33

Table 9
CROSS VALIDATION CLASSIFICATION PROBABILITY MATRIX FOR AIM (CPM = 3)

	True Class			
Predicted Class	1	2	3	4
1	.93	.10	0	0
2	.07	.53	.08	0
3	0	.37	.81	.25
4	0	0	.11	.75

The spread of the predictor is unacceptable as can been seen from the cross-validation matrices. In one case, the model predicted class 1, and the expert classified the case as class 4. This range is unacceptable.

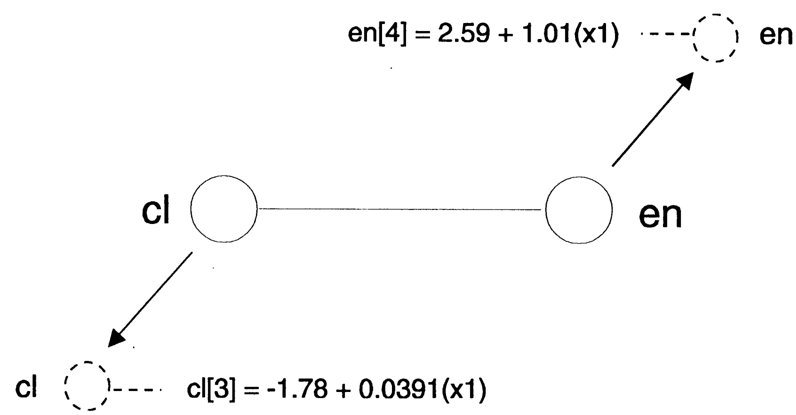

Figure 12. AIM network with complexity penalty of 5.

A complexity penalty of 5 is unacceptable because of the range of the misclassification (see Tables 10 and 11). The strong diagonal nature of the matrix shows that a complexity penalty of 3 is more acceptable. In spite of the results, this is a very complicated package to use because of the balance between complexity and accuracy that is left to the user. Multiple regression analysis produces a comparable model without the difficulty of this package. However, if a variable is not considered to have a significant impact on the classification, it will not appear in the construction. This is an important asset of both CART and AIM, particularly if some doubt exists about the relevance of one or more of the variables.

Table 10
CROSS VALIDATION CLASSIFICATION MATRIX FOR AIM (CPM = 5)

	True Class			
Predicted Class	1	2	3	4
1	41	13	0	1
2	3	32	16	3
3	0	1	15	1
4	0	10	32	39

Table 11
CROSS VALIDATION CLASSIFICATION MATRIX FOR AIM (CPM = 5)

	True Class			
Predicted Class	1	2	3	4
1	.93	.23	0	.02
2	.07	.57	.25	.07
3	0	.02	.24	.02
4	0	.18	.51	.89

Multiple Regression Analysis

Regression analysis is not a rule-based system in the way that CART is. Instead, a statistical representation of the data is provided. By fitting a line for a single independent variable or a plane for multiple independent variables to the data, an equation is generated that can be used to estimate the output for future variable sets. The value produced using the equation is rounded to the nearest integer to determine the appropriate environmental assignment (where 1 is benign, and 4 is severe). If 176 observations are used, then the following model is given:

$$En = 0.001347(ADTT) + 0.005533(F/T) + 0.024999(Cl) + 0.677581,$$

where En is the environment, ADTT is average daily truck traffic, F/T is freeze/thaw cycles, and Cl is the number of chloride applications per year.

The cross-validation classification matrices (see Tables 12 and 13) show the relation between the class predicted by the regression model and the class assigned by the expert. Multiple regression provides a good model of the data. Regression analysis is a common statistical method, and most agencies have software available for regression analysis. Another positive sign is that the spread in the data is relatively small in this particular example. This is illustrated by the fact that the upper and lower diagonal extremes are zero. Regression analysis did not predict any class that was more than one off the actual class.

Table 12
CROSS-VALIDATION CLASSIFICATION MATRIX FOR MULTIPLE REGRESSION ANALYSIS

	True Class			
Predicted Class	1	2	3	4
1	29	0	0	0
2	9	32	5	0
3	0	14	49	7
4	0	0	5	28

Table 13
CROSS-VALIDATION CLASSIFICATION PROBABILITY MATRIX
FOR MULTIPLE REGRESSION ANALYSIS

	True Class			
Predicted Class	1	2	3	4
1	.75	.23	0	0
2	.25	.70	.08	0
3	0	.30	.84	.20
4	0	0	.08	.80

A weakness of the regression analysis used is that all of the input variables will appear in the output equation with some weight. If a variable was found to have no impact on the environmental classification, then neither CART nor AIM use it in the model. Another way of ensuring that variables that do not substantially contribute to the environmental classification are not considered is to use step-wise regression. In this method, only variables that have significant impact are used in the model (Devore, 1991). The inclusion of all of the variables in the resulting model is a tolerable weakness if all of the factors impact the deterioration to some degree. If sufficient previous research exists, as was the case with bridge decks, then the factors can be verified.

The equation produced by AIM has a strong similarity with the complexity penalty of 3 and the multiple regression equation. The presence of freeze/thaw in the regression equation is the significant difference.

Discussion of Results

As the survey method is developed and later used, it is important to note that there are two major sources of error. The first is in the classification scheme itself. The second is that the information used to train and then evaluate the model was gathered from a survey of people who may have different frames of reference, experience, and exposure. Since the responses from the survey will be used to determine to which environment the elements are assigned, it is important that careful consideration be given to the selection of those people to be surveyed. It is important that these people have experience in the field. It is also important that they be willing to spend the time to complete the survey as accurately as possible.

In this application, the environmental assignments were subjective assessments. The opinion of experts was used to generate data to train the model; but as can be seen from the table in Appendix C, these results vary. To address this issue, it is best to perform and then analyze various classification methods.

If an element is assigned an environment that is not a true representation, then the penalty is that the predictions of the future condition of the element will be off because the element will deteriorate either slower or faster than anticipated. Any critical deterioration should be noticed on the two-year inspection cycles, and the problem should be flagged. If the element is deteriorating at a slower rate than expected, the condition assigned during the bridge inspection will reflect this, and no action will be taken. For this reason, the errors indicated by the various methods are all acceptable, and the methods are reasonable for this particular problem.

In addition, as the system is used, the deterioration of the elements of particular bridges can be tracked using the Pontis database. If the rate of deterioration is not consistent with the class assignment, the element can be reassigned. If this occurs often, then the deterioration rates tracked historically can be used to redefine the environments.

The survey method itself works well as long as enough information is available to produce representative scenarios. One caution is that the surveys should focus on information that is easily available for the bridge elements. For example, in the case described, average daily truck traffic is measured easily, and the information generally can be found on record. Chloride applications are not recorded in Virginia. Since it is uncertain where the chloride is actually applied and how frequently it is applied, chloride is a measurement that the inspector will have to estimate, which will add inaccuracy and complexity. Freeze/thaw data is available through climatological information and can be analyzed to determine relatively accurate historical records, and most states are divided into climatological regions. However, this is not information that is recorded on bridge records.

Regardless of the modelling approach used to develop the environmental definitions, the data sample should be split into training and testing sets. In retrospect, it would have been easier to evaluate the modelling approaches had the data been split in this application. At the time of the research, it was decided that the size of the sample was inadequate for this approach. When this method is used to define the environments, a larger survey sample would be advisable, and then the data set could be split without worry about the size of the training set.

CONCLUSIONS

As Pontis is implemented, the development of the cost data, which is the critical component necessary to ensure usable results, will require extensive labor. This survey method of defining environments will give a good environmental class without sacrificing manpower that should be devoted to these cost models.

To facilitate the transfer of the method among states, it is advised that regression analysis be used. This method was found to be as good as the other methods tried for this case. Most agencies have regression software available and have personnel already familiar with its use.

Though CART produced satisfactory results, the border problem generated enough concern to eliminate this method from consideration. If there is sufficient doubt about the effects of the factors on deterioration, then the use of AIM or step-wise regression should be strongly considered. Otherwise, it is recommended that multiple regression analysis be used, since it is quick and easily understood.

The guidelines detail the process taken for quantitatively defining the environmental classes. Use of this method will assist in the successful implementation of Pontis, and it will ensure that all of the available environments will be used when needed.

RECOMMENDATIONS

The classification of the bridge population into the four environments instead of one will improve the accuracy of the model. The end result will be a more realistic representation of the actual system and more accurate projections of where limited resources are best expended. Whether this method for developing environment definitions or another is used, the environmental assignments should not be sacrificed for a slight initial savings in time. The method presented in this report is easily adaptable to any Pontis element or group of elements, and it was found in our application to yield reasonable results.

Once Pontis has been in use for four cycles (8 years), it is recommended that the environments be evaluated. At that time, it may be found that the transition matrices for the different environments are not distinct. Only after a review like this is made, should the number of environments used by a state be reduced.

The successful implementation of a BMS such as Pontis will necessitate future research in a variety of different areas. Mention has been made several times of the problem of the costs that will be used in the Pontis database. Since Pontis addresses bridges at the network level, developing costs that are appropriate at the network level and significant at the project level is a major issue that must be confronted in the near future. It is possible that the environmental definition can be tied in with the cost model in such a way that the environments serve a two-fold purpose. First, the environments would function as deterioration classes representing operation practices and climatic exposure as has been emphasized throughout this report. Second, the definition of the environments might be expanded to include factors that lead to significant cost differences. Such a possibility was beyond the scope of this research but should be explored in future research.

Another topic that should be considered for future research is the development of a self-correcting environmental assignment procedure that could be incorporated into the Pontis computer code. The motivation for using a survey in this research was that historical data did not exist at the element level. Once the Pontis system has been in place for several inspection cycles, sufficient data will exist so that the system could automatically partition the elements into the appropriate four environments based on actual inspection data. Such a mechanism would increase the accuracy of the prediction of deterioration and subsequently improve the cost projections of the model.

ACKNOWLEDGMENTS

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APPENDIX A

MARKOV PROCESS

MARKOV PROCESS

A stochastic process $\{X(t)\ t \in T\}$ is a Markov Process if it possesses the Markov property. That is, if for any set of indices, $t_0 < t_1 < t_2 < \ldots t_n < t$, and any set of states, $X(t) \in A \subset S$, the conditional probability distribution of $X(t)$ given all its prior values $x_0, x_1, x_2, \ldots x_n$, depends only on its last value x_n:

$$P\{X(t) \in A \mid X(t_0)=x_0, X(t_1)=x_1, X(t_2)=x_2 \ldots X(t_n)=x_n\} = P\{X(t) \in A \mid X(t_n)=x_n\}$$

For a discrete parameter Markov Process with a discrete state space, the Markov property can be restated as

$$\begin{aligned} P\{X_{n+1}=j \mid X_0=i_0, X_1=i_1, X_2=i_2 \ldots X_n=i\} &= P\{X_{n+1}=j \mid X_n=i\} \\ &= P_{ij}(n) \end{aligned}$$

for all times n and states i and j. The $P_{ij}(n) = P\{X_{n+1}=j \mid X_n=i\}$ are called the (one-step) transition probabilities (White, 1991).

APPENDIX B

SAMPLE SURVEY

Name______________________________ District______________________________
Position____________________________ Total District Bridge Population________

Pontis and Bridge Management

Recent legislation has mandated that by October 1, 1995, all states have an operational bridge management system. With this in mind, the Federal Highway Administration has sponsored the development of Pontis, a network-level bridge management system, that will aid in the prioritization of maintenance, rehabilitation, repair, and improvement projects statewide.

In its analysis, Pontis considers the future condition of the bridge network. By comparing the cost of an action in the current year with the cost of the action in the next year, Pontis allows the more efficient allocation of funds. It also has the capability to predict future conditions given various (current) funding levels. This allows decision makers to see the impact of their decisions on the future. This is expected to provide a clear justification for budget requests to the General Assembly.

Elements and Need for Environments

With the adoption of Pontis, some changes will occur in the inspection process. In order to predict the future conditions of the bridges, each bridge is broken down into its elements. Using probabilistic methods based on the opinion of experts and historical data, the future condition of the elements is predicted. Since different climatic and operating practices cause identical elements to deteriorate at different rates, Pontis assigns every type of element on an individual bridge to one of four environmental classes. These classes can also be thought of as groupings of deterioration rates.

The purpose of this survey is to determine the factors which affect the deterioration of different elements. To do this, we wish to isolate four deterioration classes for a concrete bridge deck. Then we ask your expertise to determine the important factors behind this deterioration. The current condition of the element is not important, but rather the rate at which the element deteriorates to a worse condition state when left alone.

This is a preliminary survey with several purposes. First, we want to gather information about the concrete decks so that we can develop very objective criteria for assigning the decks to environments. Second, we want to evaluate the technique for getting this information. We would appreciate any comments you have about the survey, including whether it is clear what we are attempting, if you like the format, approximately how long the survey took you, etc.

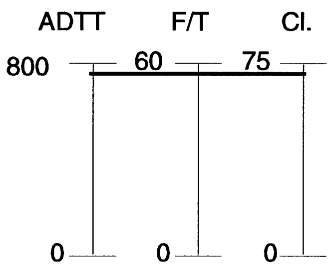
Instructions

The first two pages of the survey attempt to isolate four deterioration classes of bridge decks for Virginia. Try to divide the bridge decks into four groups based on their rate of decay, not their current condition. Once you have done this, each graph shows 3 characteristics. For example, the first shows an average daily truck traffic of 800, 60 freeze/thaw cycles per year (a freeze/thaw cycle is considered a drop in air temperature below 28 F with a subsequent rise to 32 F or above), and 75 chloride applications per year. For these characteristics, which deterioration rate would a deck exposed to these factors belong in? If you disagree with the range of numbers, please write a note to this effect.

Thank you very much for taking the time to complete this. Your input is valuable to the successful implementation of Pontis. The results will be available to you once they have been compiled. Please return this to us by February 25 and call if you have any questions.

Dixie Wells or Jose Gomez (804)-293-1936
VTRC
Box 3817 University Station
Charlottesville, VA 22903

For the concrete bridge decks in Virginia, please check the box which represents the deterioration rate of the deck subjected to the graphed condition. If you feel that there are no bridge decks in Virginia that experience the shown conditions, please write *not applicable* (na) by the graph. ADTT is Average Daily Truck Traffic, F/T is the number of freeze thaw cycles per year, and Cl is the number of chloride applications to the deck or the approaching road way per year.



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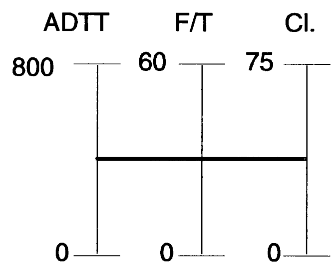

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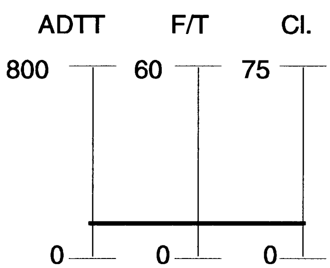

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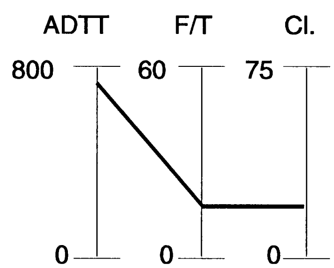

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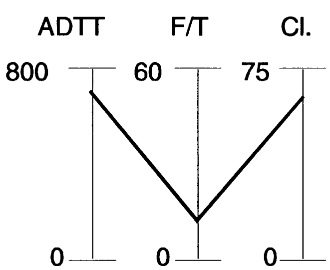

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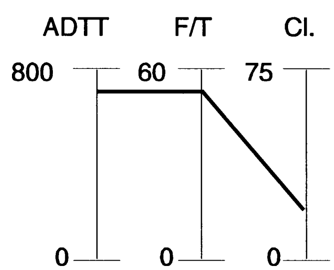

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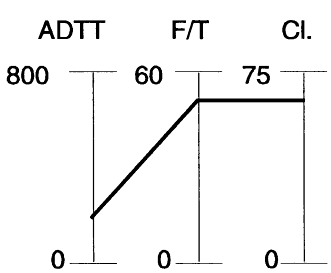

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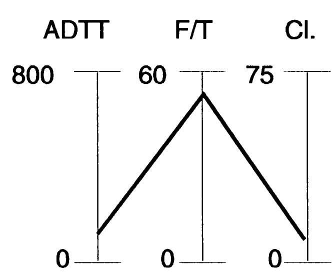

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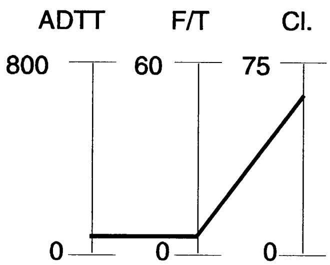
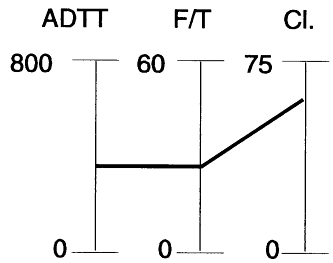


- ☐ slow
- ☐ med. slow
- ☐ med. rapid
- ☐ rapid



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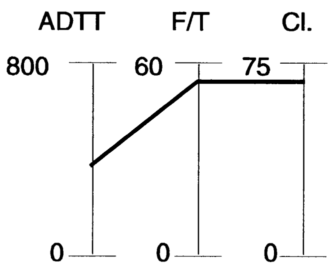

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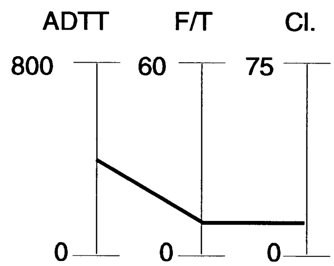
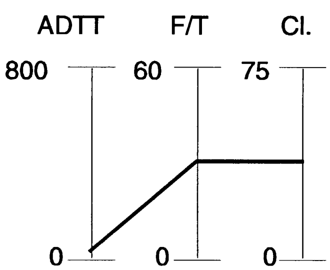
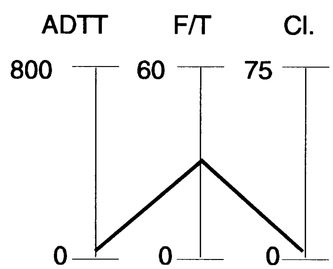
- ☐ rapid



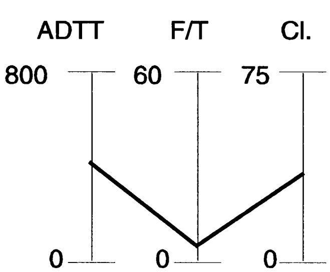
- ☐ slow
- ☐ med. slow
- ☐ med. rapid
- ☐ rapid



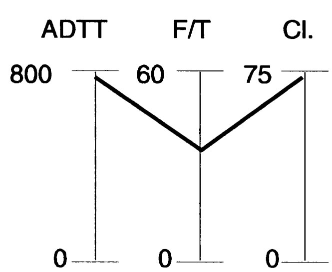
- ☐ slow
- ☐ med. slow
- ☐ med. rapid
- ☐ rapid



- ☐ slow
- ☐ med. slow
- ☐ med. rapid
- ☐ rapid

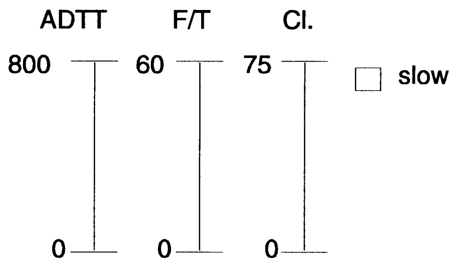


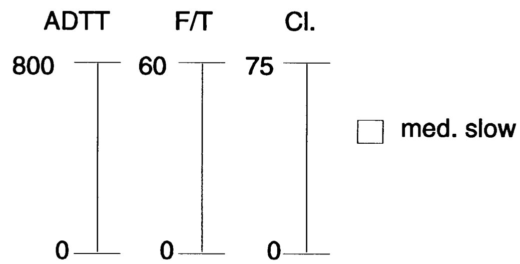
- ☐ slow
- ☐ med. slow
- ☐ med. rapid
- ☐ rapid

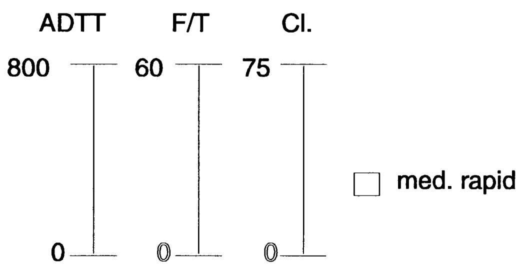


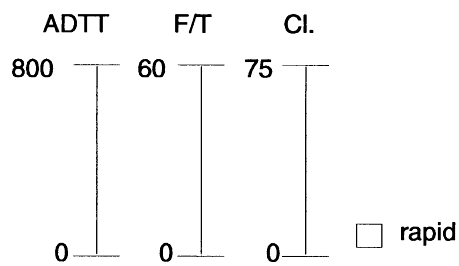
- ☐ slow
- ☐ med. slow
- ☐ med. rapid
- ☐ rapid

Using the same relative groupings that you used on the previous pages, please describe the general characteristics for the category in *your district.* If you feel that you do not have the category listed in your district, leave it blank or write NA.

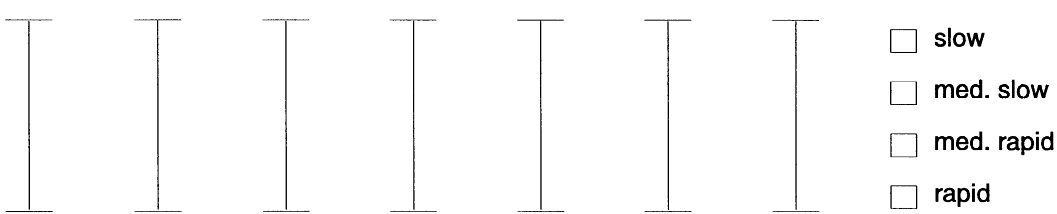








Are there any factors, which in your experience, affect the deterioration of concrete bridge decks and were not included in this survey? If so, what are they and can you quantify them?



APPENDIX C

SURVEY RESULTS

SURVEY RESULTS

Appendix C is comprised of one table. Unfortunately, it was necessary to spread it on three pages. The column on the far left gives the question asked on the survey (see Appendix B). The values in the columns indicate the environment assignment made by each respondent. As was the case throughout the report, 4 is used to distinguish the severe environment, which for the survey was labelled rapid. One indicates the slowest rate of deterioration, which is considered to be the benign environment. One person responded to the survey from Culpeper, Fredericksburg, Northern Virginia, Richmond, Salem, Staunton, Suffolk, and the Central Office. Three responses were received from Lynchburg, and this is indicated by the three responses in each cell within the Lynchburg column.

The table continues onto the third page, although the format changes slightly. The four final rows of the table give the values that the respondents indicated as being typical for their districts. Again, the left column indicates the question asked on the survey. As shown in Appendix B, the respondent was asked to draw a typical situation for each of the four rates of deterioration. The three values in these rows indicate the ADTT, F/T, and Cl values that were indicated by each of the respondents.

Survey Results by District

	Culpeper	Fredericksburg	Lynchburg	No. Virginia	Richmond	Salem	Staunton	Suffolk	Central Office
ADTT 800 F/T 60 Cl. 75	4	4	4 4 4	4	4	4	4	4	4
ADTT 450 F/T 35 Cl. 45	3	2	3 3 3	3	3	3	3	3	2,3
ADTT 150 F/T 10 Cl. 15	1	1	1 1 1	1	1	1	1	2	2,3
ADTT 800 F/T 20 Cl. 25	2	2	2 2 2	3	2	3	3		4
ADTT 800 F/T 20 Cl. 75	4	n/a	3 3 3	4	4	3	n/a	3	4
ADTT 800 F/T 60 Cl. 25	3	2	3 2 2	3	2	3	3	2	4
ADTT 150 F/T 60 Cl. 75	3	2	2 4 3	2	3	3	3	4	3
ADTT 100 F/T 60 Cl. 15	1	1	1 1 2	1	2	1	1	2	1

Survey Results by District (Continued)

	Culpeper	Fredericksburg	Lynchburg	No. Virginia	Richmond	Salem	Staunton	Suffolk	Central Office
ADTT 50 F/T 5 Cl. 70	2	n/a	2 3 3	2	n/a	2	n/a	3	3
ADTT 400 F/T 30 Cl. 70	3	3	3 3 3	2	4	3	n/a	3	3
ADTT 400 F/T 60 Cl. 75	3	2	3 4 4	3	4	3	4	4	3
ADTT 400 F/T 10 Cl. 15	2	2	2 1 1	2	2	2	2	2	2
ADTT 0 F/T 30 Cl. 40	2	2	2 3 3	2	2	2	3	3	2
ADTT 0 F/T 30 Cl. 0	1	1	1 1 1	1	1	1	1	1	1
ADTT 400 F/T 0 Cl. 40	2	1	2 2 2	2	2	2	2	3	2
ADTT 800 F/T 40 Cl. 75	4	3	4 4 4	4	4	4	3	4	4

Survey Results by District (Continued)

	Culpeper	Fredericksburg	Lynchburg	No. Virginia	Richmond	Salem	Staunton	Suffolk	Central Office
slow	0,25,15	100,10,15	100,10,15 50,5,5 100,10,15	150,30,10	300,45,0	150,50,15	150,40,10		100,10,15
med. slow	250,25,25	800,40,50	300,20,25 150,15,20 200,15,20	300,40,10	500,45,15	n/a	400,40,45		150,30,70
med. rapid	700,40,35	500,40,70	500,35,40 500,35,40 500,40,50	700,40,50	500,35,45	400,55,70	500,40,45		500,40,50
rapid	750,50,40	750,55,70	500,55,70 750,55,70 750,55,70	700,55,70	800,40,70	750,55,70	700,40,70		900,10,60