An In-Depth Analysis of the National Bridge Inventory Database Utilizing Data Mining, GIS and Advanced Statistical Methods

STEVEN B. CHASE
EDGAR P. SMALL
Federal Highway Administration
CHRIS NUTAKOR
GIS Trans

ABSTRACT

The National Bridge Inventory Database (NBI) is the most extensive repository of data on highway bridges in the United States. Initiated in 1972, this database now contains detailed historical data on over 600,000 bridges for a span of 26 years. The archived and current NBI files contain more than 6.2 billion bytes of data. To efficiently utilize this information for research and analysis, the authors investigated and developed several different relational database management approaches and data warehousing techniques. From the resulting system, data mining methods were used to efficiently access this data and extract information on the Nation's highway bridges. This has resulted in a significantly better understanding of the bridge inventory. Key descriptive statistical summaries of the NBI resulting from this work are presented. Although the NBI, in itself, is a tremendous resource, the true power of data mining methods was not realized until the data inherent in the NBI was expanded by implementing a spatial relationship capability utilizing a geographic information system (GIS). This facilitated extensive visualization of geographic patterns in the NBI data, several examples of which are included in the paper. More importantly, it enabled a study of relationships between bridge behavior and other factors, such as climate. Advanced analyses have been performed using the GIS capabilities coupled with statistical modeling and analysis methods. One research study, which is summarized in this paper, focused on the development of a new model of bridge deterioration. Using the expanded data sets available from the combined NBI and GIS databases, three different regression methods were applied to model the relationship between condition state and plausible factors causing deterioration. The variables included in the study were age, average daily traffic, precipitation, frequency of deicing, temperature range, freeze thaw cycles and type of bridge construction. Different models were developed for deck, superstructure and substructure deterioration. Generalized linear models, generalized additive models and a combination of the two were applied. The generalized linear model gave the best prediction. This new model is presented.

INTRODUCTION AND BACKGROUND

The safety of the nation's bridges is an issue of great concern. It has been widely discussed that more than 40% of the nation's bridges are either structurally deficient or functionally obsolete and in need of maintenance, repair, rehabilitation, improvement or replacement. Pertinent research to better understand bridge deterioration patterns and related activities is therefore easily justified.

Inventory and inspection data have been collected on the bridges within the United States and maintained in databases (National Bridge Inventory databases) over the past 26 years. This information represents a significant resource for examination and evaluation of the U.S. highway bridge population. In addition, the Bridge Management Information Systems (BMIS) laboratory at the Federal Highway Administration has collected and maintained a database of environmental and natural hazard data using GIS technology. These include climatological, hydraulic/hydrologic, geotechnical and seismic data. Both the NBI and the environmental data are stored within a relational database structure which helps provide a comprehensive data source for detailed analysis and research. With the establishment of the two databases, the BMIS laboratory has initiated research in advanced analysis of the NBI data sources. Studies performed have focused on an investigation of the correlation between the bridge conditions and environmental information. Insight obtained through these and other studies may enable more effective and efficient design and management of bridges.

Some of the research activities by the BMIS laboratory are summarized in this paper. The procedures utilized in the establishment of the environmental and natural hazard database are outlined. Descriptive statistical summaries resulting from the exploration of the NBI are also presented. Development of regression models for predicting condition ratings of bridges has been discussed and the models have been presented. Three different regression models, which include a linear model, a non-linear parametric model and a non-parametric model, were developed. Generalized linear and generalized additive modeling procedures were used in the development of the regression models. The explanatory variables used include age of bridge, average daily traffic, precipitation, frequency of deicing, temperature range, freeze thaw cycles and type of bridge construction. The linear model gave the best prediction results. A summary and an outline of future research directions conclude the presentation.

DATA DEVELOPMENT

The environmental and natural hazard database was primarily developed using GIS tools. An essential step was the development of a spatial data layer for the bridges in the National Bridge Inventory (NBI) database. The NBI database is the repository of information on the composition, location and condition of all bridges in excess of 20 feet located on public roadways. The information on the bridges is collected by States and bridge owning agencies as part of the comprehensive bridge inspection program established about 30 years ago. This information is reported to the Federal government and stored within the National Bridge Inventory (NBI) and is primarily utilized for fund apportionment and cost allocation. In the subsequent paragraphs, brief descriptions of the procedures used in the development of the bridge data layer and the database elements are described.

Spatially Locating Bridges

The objective of this phase of the research was to create a spatial layer in the GIS system where each bridge is represented as a point in vector space. In turn each point maintains the related NBI structure number to allow for relational linkage back to the NBI database attributes. Difficulties arise in assigning accurate vector space locations due to errors and lack of data. Methodologies and GIS procedures were developed and implemented to assign bridges a spatial location, which is then used to associate structures with environmental and natural hazard information.

The NBI [Coding Guide] provides three location references for each structure:

1. Location description,
2. Inventory Route and Milepoint,
3. Latitude and Longitude in degrees and decimal minutes.

The Location field contains a narrative description of the bridge location. This does not lend itself well to automation or assignment of a location within the spatial environment of the GIS. The Inventory Route and Milepoint fields in the NBI provide more useful information. To utilize these fields for assignment of locational attributes requires definition and development of GIS spatial highway networks with the fully developed Linear Referencing Systems (LRS). The fully developed LRS network has Inventory Route and continuous mileage designations attached along the graphical highway network. The National Highway Planning Network Version 2.02 (NHPN) provides this information with a spatial highway network and LRS developed for most states. LRS definitions utilized in the NHPN are defined and reported by State DOTs. Geo-coding bridges to the NHPN using the LRS method revealed good support and accuracy for bridges on higher functional class roads (such as Interstates), but fair to poor support for bridges on lower functional classifications. The capability to locate structures located along non-state-maintained or local roads is not available using LRS systems at this time due to lack of data.

The use of latitude and longitude is an obvious consideration for a study of this nature. However, it was known from other GIS efforts that these coordinates were often difficult to correlate spatially with reasonably accurate GIS spatial data (for example, data collected at 1:100,000 scale). We found that approximately 28 percent of all bridge records lack a valid non-zero number for the latitude and longitude fields. Structures with seemingly valid latitude and longitude coordinates were then reviewed. Using the specified coordinates, it was found that approximately 2 percent of the structures were spatially located outside of the designated county indicated within the NBI record. These spatial attributes were deemed unreliable and the designated county codes were then used for assignment of the structures within the GIS. The county GIS layer used for this evaluation was taken from USGS 1:100,000 scale data with an estimated positional accuracy of better than 150 feet on the earth’s surface. This provides more than adequate accuracy for the research performed.

Further examination was performed to locate structures within the GIS. The NBI latitude and longitude field values and the designated Inventory route were compared, spatially, to the NHPN and its inventory route designations whenever route designation could be related between the NBI and the NHPN. Where route matches could be found, 98 percent of the bridges were located within 2 miles, as measure perpendicularly, from the specified NHPN route. Further review of these matches revealed that Interstates comprised the majority of the successful route identifier correlations. A similar exercise was undertaken using the Census TIGER network. Route identifiers could not be related between the NBI and the TIGER files due to a lack of standard route identifier nomenclature. From this work we determined that approximately 30 percent of all latitude and longitude locations provided in the NBI are invalid or sufficiently inaccurate to be used as a better measure of location than the NBI county designation.

Creating GIS Spatial Data from Environmental and Natural Hazard Data

Disparate data sources were required in order to correlate deterioration patterns with external variables, such as precipitation, snowfall, temperature, etc. Additional data sources were desired to enable examination and facilitate the development of network level analysis of natural hazard and extreme event impact on bridges, such as scour and earthquakes. A background search was performed to identify available environmental and natural hazard datasets. The datasets obtained can be classified into four broad categories including the following:

- Climatological
- Hydraulic/hydrologic
- Soil
- Seismic

Table 1 itemizes the information which has been used within these various data categories. Hydraulic/hydrologic and geotechnical data were acquired in ARC/Info format, hence required very minimal processing. Seismic and climatological data sets were essentially acquired in ASCII format and processed into GIS point coverages.

GIS facilitates spatial modeling and analysis and has been used in the development of a linkage between the environmental and natural hazard variables and the national bridge inventory database. Two approaches have been used to associate the environmental and the natural hazard data with the bridge point features utilizing the GIS.

Creating an Integrated Relational Data Model—Association of Information with Bridges

For point spatial data models of environmental and natural hazard data, three-dimensional surface data models were developed covering the United States for each data element using the three-dimensional surface interpolation capabilities provided by the GIS. The three-dimensional surface formed a web which connects every point on the surface. Considering a cartesian coordinate system, the x and y coordinates reflect the longitude and latitude while the z coordinates represent the magnitude of the attribute being

Table 1: Required Environmental and Natural Hazard Data

Data Representation Class	Type of Data
Climate	Precipitation-rain
	Precipitation-snow
	Temperature (freeze/thaw)
Water	Hydrologic unit codes
	Flood data
	Stream flow data
Soil	Soil Ph
Seismic	Spectral acceleration
	Peak ground acceleration
	Earthquake magnitude and depth

modeled for a given layer. This may reflect the snowfall at given points, earthquake peak ground acceleration, temperature extremes, or any other scalar quantity.

The bridge point data was overlaid on the three-dimensional surface(s) using GIS layer overlay functions to interpolate the attributes at the bridge locations. The information was then assigned to the structures as attributes within related tables of the RDBMS. Thus, every bridge became associated with a snowfall value, rainfall value, earthquake magnitude, etc.

Similar to using layers modeled as surfaces, bridges can also be associated with polygon data models by overlaying bridges directly on the polygons using GIS tools. Thus each bridge was associated with the attribute of the polygon feature in which the bridge was located. For example, all bridges falling within a soil polygon assigned the attribute of 4 (for the pH) will automatically be assigned a pH value of 4.

Using these techniques, each structure was assigned a quantifiable value for each external factor. A relational data model was developed which allows storage and access of these external scalar values supporting statistical analysis, GIS operations and future modeling.

DESCRIPTIVE STATISTICAL SUMMARIES

The exploration of the NBI has revealed very useful and informative statistics, some of which are presented below. Figures 1 through 3 show information for the entire contiguous United States, while Figures 4 through 10 show information for a more focused area, which is the New Madrid States area. The New Madrid States area was chosen because of an on-going earthquake analysis project for that area. The information displayed in the figures includes the following:

- Distribution of bridges by year of construction and material types
- Distribution of bridge materials by number, deck area and average daily traffic
- Spatial distribution of deficient bridges
- Differences in average bridge condition ratings over time and space

(*text continues on page C-6 / 11*)

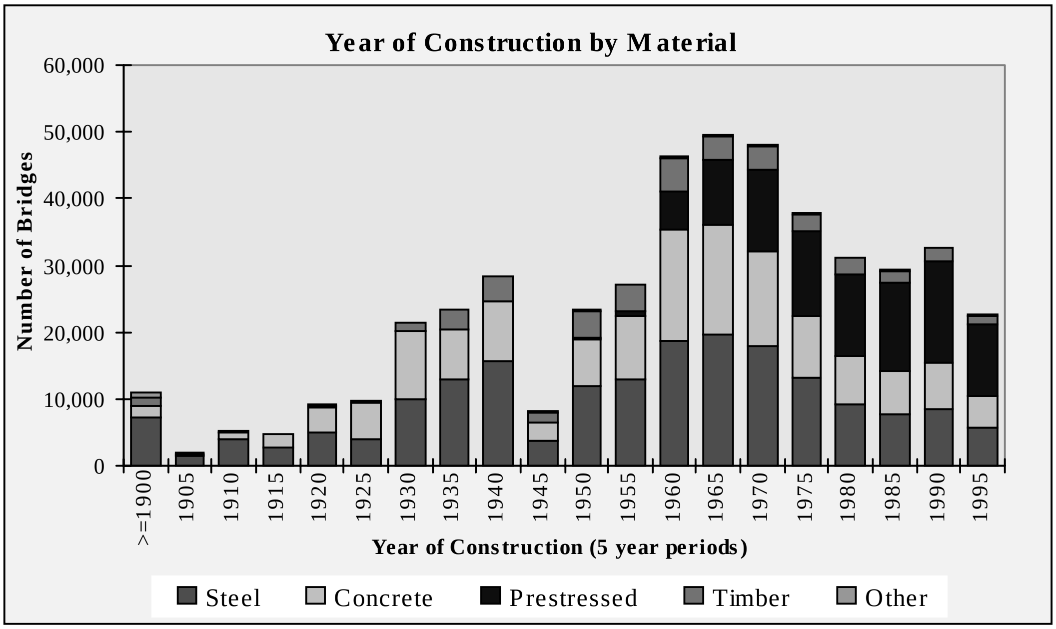

Figure 1: Distribution of bridges by year of construction and material types.

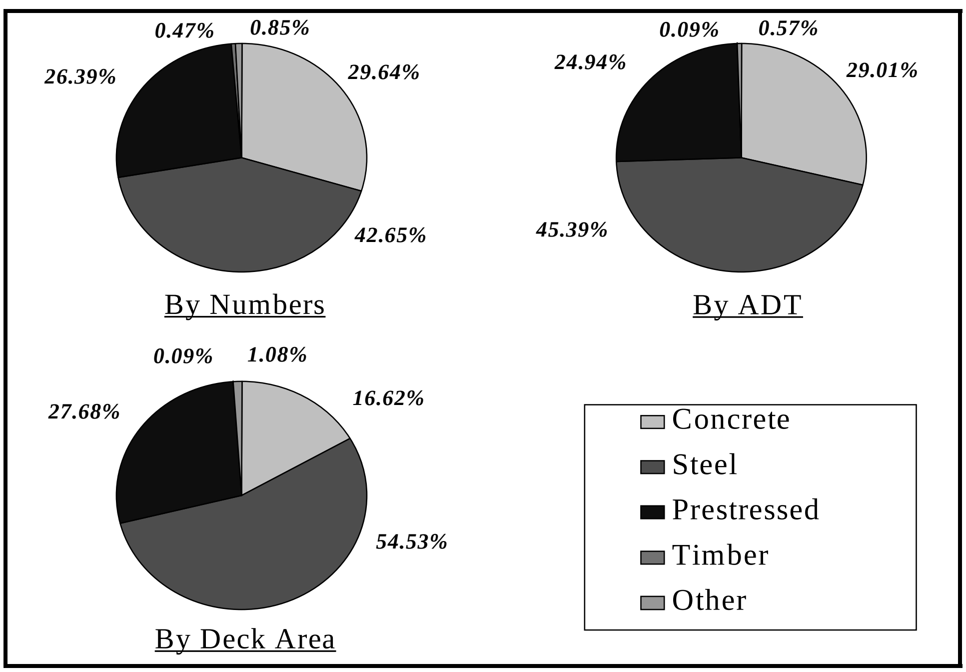

Figure 2: Distribution of bridge materials by number, deck area and average daily traffic.

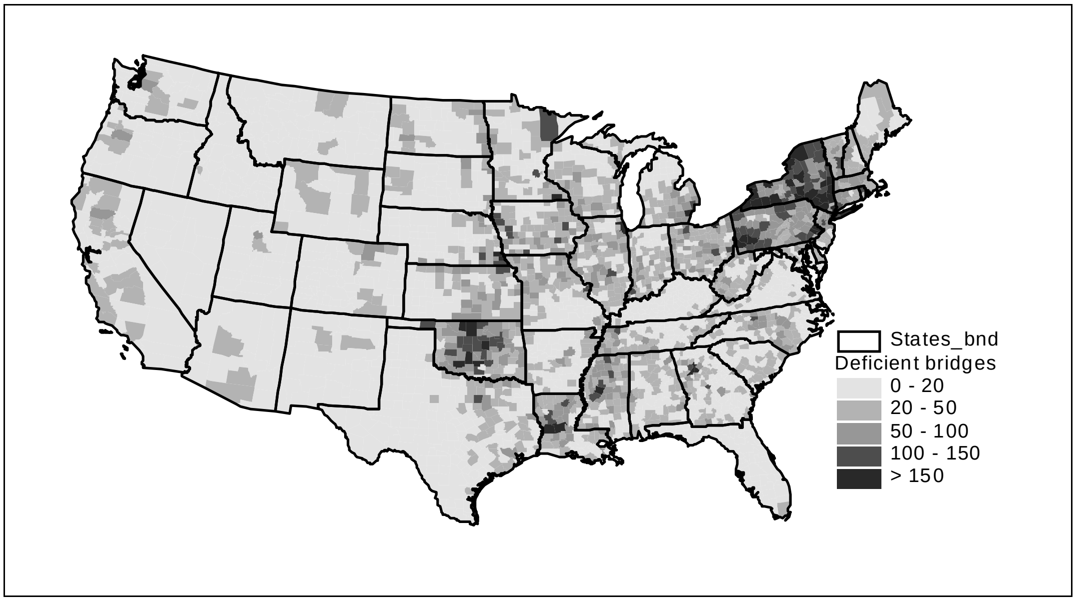

Figure 3: Spatial distribution of structurally deficient bridges by county.

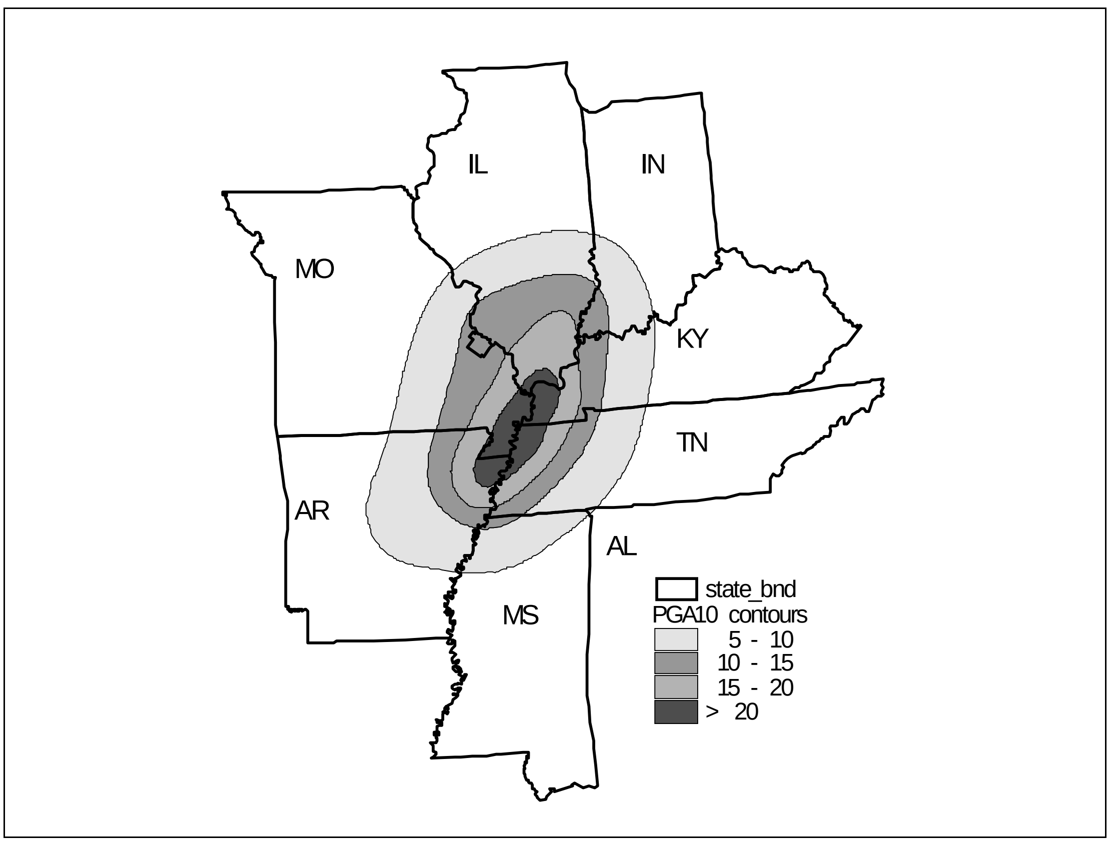

Figure 4: Contours of peak ground acceleration with 10% probability of exceedance in 50 years for New Madrid States.

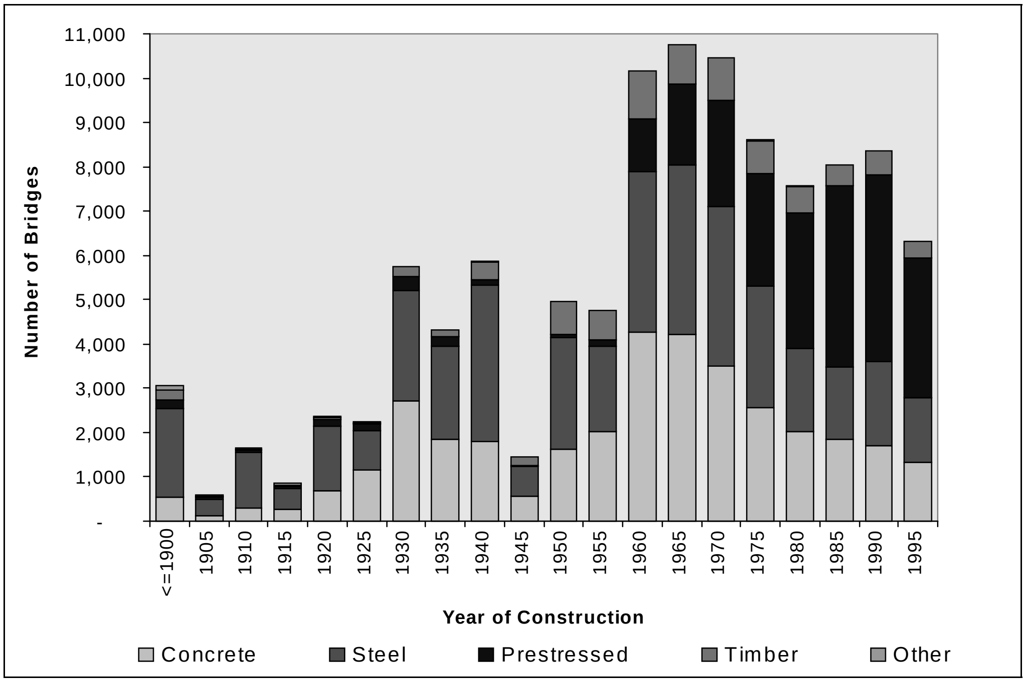

Figure 5: Distribution of bridges by year of construction and material types for New Madrid States.

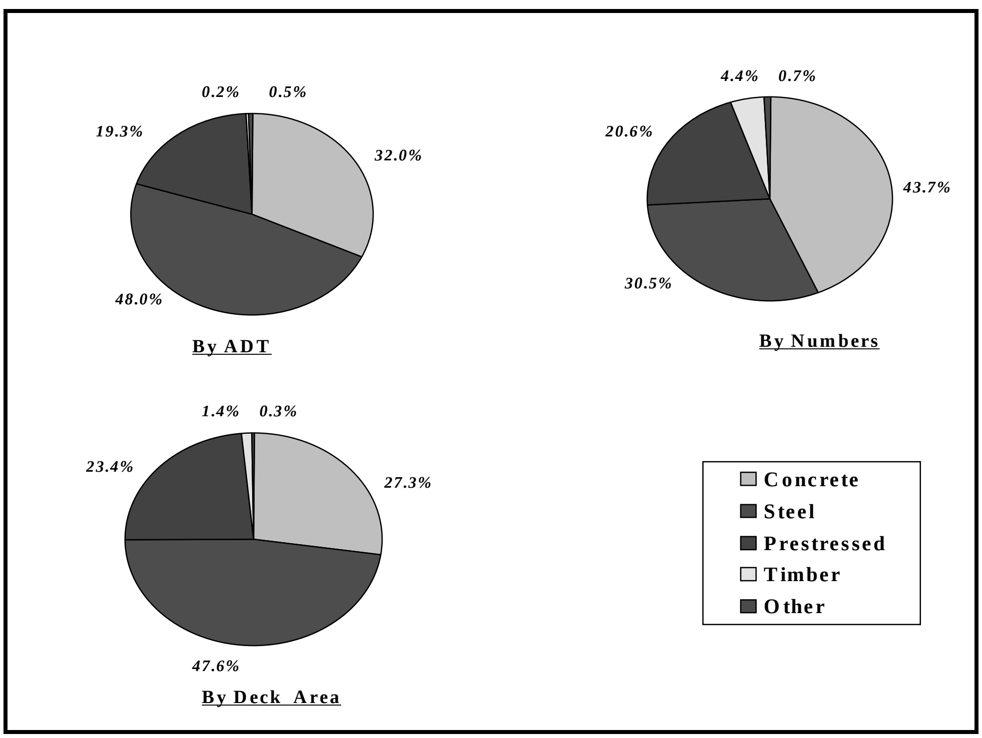

Figure 6: Distribution of bridge materials by number, deck area and average daily traffic for New Madrid States.

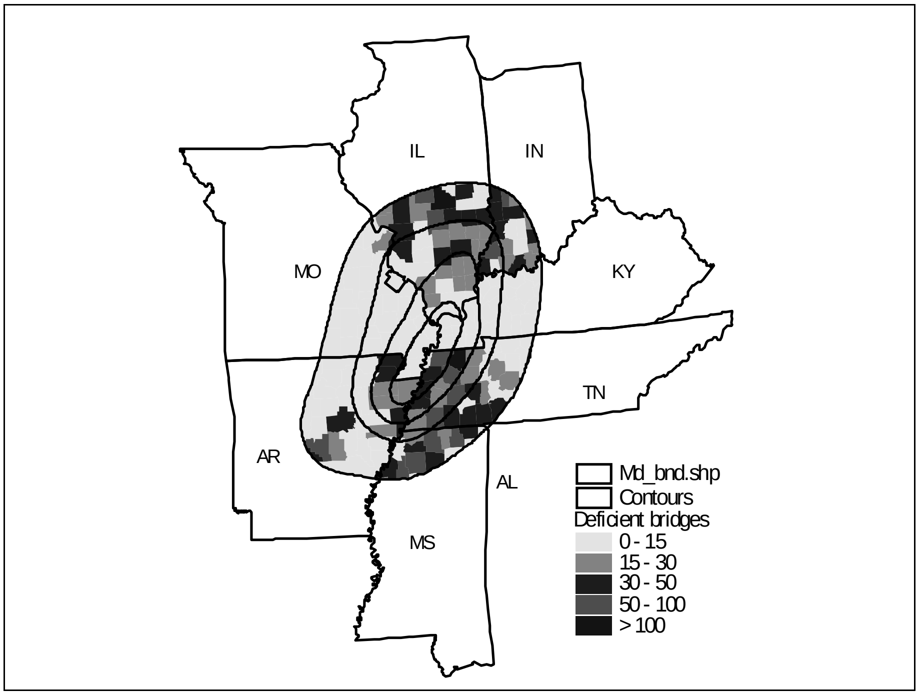

Figure 7: Spatial distribution of structurally deficient bridges by county for New Madrid States.

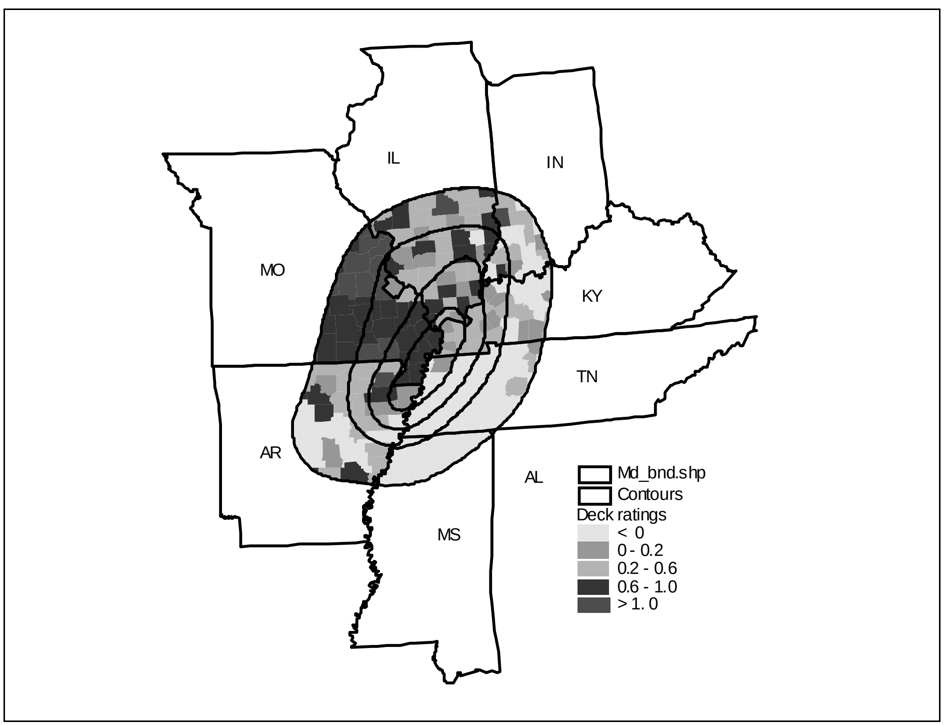

Figure 8: Reduction in average deck condition ratings for the New Madrid States (1985–96).

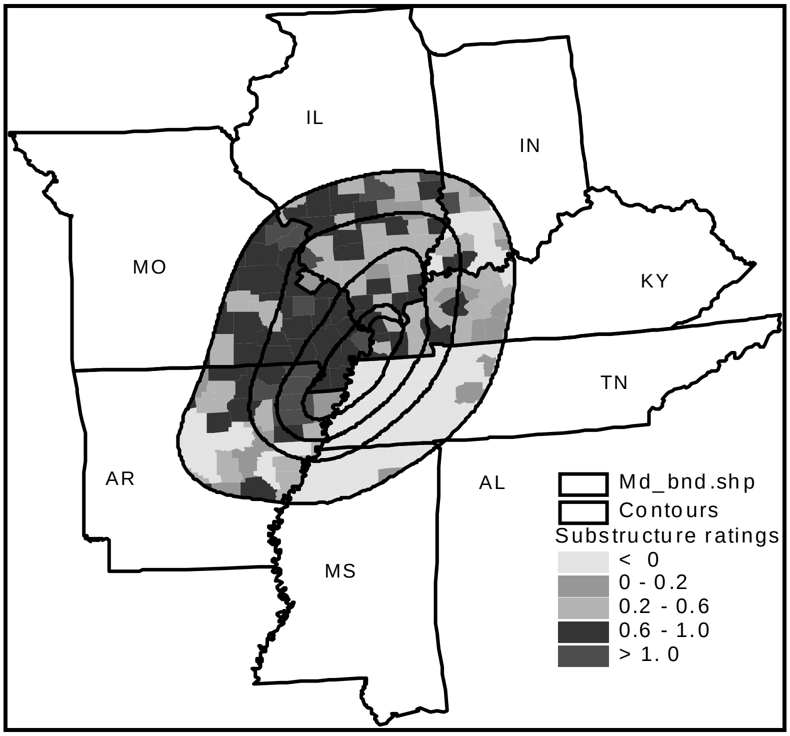

Figure 9: Reduction in average substructure condition ratings for the New Madrid States (1985–96).

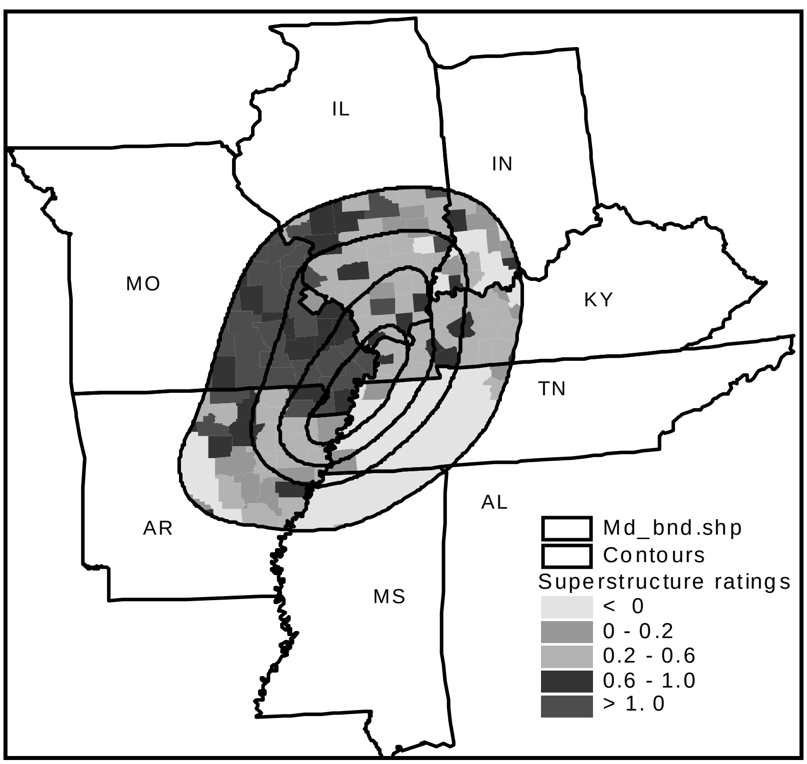

Figure 10: Reduction in average superstructure condition ratings for the New Madrid States (1985–96).

REGRESSION MODELING

There have been numerous efforts by many individuals and institutions to develop models for predicting bridge deterioration and future condition state distributions. A bridge management systems report (FHWA 1989) discussed available deterioration models in some detail.

The bridge deterioration models developed through this research and which are summarized below utilize an approach which is uniquely different. The approach is more detailed as it considers many prevalent environmental factors considered at the bridge level. Most of the existing models consider only the age of the bridge and the average daily traffic carried by the bridge while disregarding important factors such as freeze-thaw cycles, frequency of salting, rainfall and temperature ranges. These additional factors have been considered in the development of the models described in the following sections.

Response (Dependent) and Predictor (Independent) Variables

The source of data for the response variables is the National Bridge Inventory (NBI) database. The items in the database that were used as determinants of bridge deterioration are condition ratings for the bridge deck, superstructure and substructure. These condition ratings were used as the response variables in the regression analysis. The condition ratings are categorical variables that take on discrete integer values from 0 through 9. Table 2 below shows the interpretations of the categorical variables as described within the NBI recording and coding guide.

NBI items used as predictor variables include the average daily traffic (ADT) carried by each bridge and the age of the bridge. Other predictor variables are those which describe the bridge environment. These include precipitation, temperature range, number of freeze-thaw cycles and the frequency of salt applications to the bridges. The main material types used in the construction of the deck and the superstructure have also been included in the model as predictor variables. Table 3 shows the predictor variable data. The predominant construction material type refers to the material used in the construction of the deck or the superstructure. The material types for the bridges used in the modeling process and the variable symbols used are summarized in Table 4.

Table 2: Dependent Variable Ratings

Condition Ratings	***Interpretations***
9	Excellent condition
8	Very good condition
7	Good condition
6	Satisfactory
5	Fair condition
4	Poor condition
3	Serious condition
2	Critical condition
1	Imminent failure condition
0	Failed condition

Table 3: Independent Variables

Variable	***Units of Measure***
AGE	Years
Average daily traffic (ADT)	Number of vehicles per day
Annual precipitation (PRCP)	100th of inches
Frequency of salting (SALT)	Number of times per year
Temperature range (TRANGE)	Degrees
Freeze-thaw cycle (CYCLE)	Number of times per year
Predominant construction material	Not applicable

Data Sampling

A sample of data drawn from the NBI was used in the development of the regression models. The 1996 NBI database contains information on about 650,000 bridges and culverts in the United States. The database was initially cleaned up to eliminate any erroneous entries. Reconstructed bridges were eliminated since they will have erroneous effect on the age of the bridge in the analysis. A random sample of 30,000 bridges used for the analysis was generated from the NBI database.

Graphical exploration of the data revealed that deterioration values below 3 are generally outliers and hence have been eliminated from the sample. The analysis is therefore valid only for condition states from 3 through 9 inclusive. Other outliers were removed by trial and error and visual discrimination before the final regression analysis was carried out. Three different regression models were developed: (1) a linear model, (2) a non-linear non-parametric model (3) a non-linear parametric model.

The discrete nature of the response variables does not facilitate the usage of classical regression techniques. Generalized linear and generalized additive modeling capabilities which better model discrete variables were used.

Linear model (Model 1)

A generalized linear modeling procedure was used in the development of the linear models. The linear regression equations obtained for predictions of superstructure, deck and substructure conditions are presented below. The model coefficients are tabulated in Tables 5, 6 and 7 for the superstructure, deck and substructure respectively.

Table 4: Bridge Construction Materials

Material Name	***Variable Symbol***
Concrete cast-in-place *(for deck)*	CC
Concrete precast panels *(for deck)*	CP
Timber *(for deck and superstructure)*	T
Concrete *(for superstructure)*	C
Concrete continuous *(for superstructure)*	CC
Steel *(for superstructure)*	S
Steel continuous *(for superstructure)*	SC
Prestressed concrete *(for superstructure)*	PC

Table 5: Coefficients and Variables for the Superstructure Linear Model

I	Variables	Description	Coefficient	Value
1	V_1	AGE	β_1	$-5.13*10^{-3}$
2	V_2	PRCP	β_2	$-7.09*10^{-4}$
3	V_3	CYCLE	β_3	$-2.3*10^{-3}$
4	V_4	SALT	β_4	$-7.44*10^{-4}$
5	V_5	S	β_5	$-3.49*10^{-2}$
6	V_6	T	β_6	$-2.35*10^{-1}$
7	V_7	SC	β_7	$-3.87*10^{-2}$
8	V_8	CC	β_8	$-2.51*10^{-2}$

Table 6: Coefficients and Variables for the Deck Linear Model

I	Variables	Description	Coefficient	Value
1	V_1	AGE	α_1	$-4.72*10^{-3}$
2	V_2	SALT	α_2	$-4.46*10^{-3}$
3	V_3	CYCLE	α_3	$-2.41*10^{-3}$
4	V_4	ADT	α_4	$-5.85*10^{-7}$
5	V_5	TRANGE	α_5	$1.14*10^{-3}$
6	V_6	CP	α_6	$3.38*10^{-2}$
7	V_7	T	α_7	$-2.73*10^{-2}$

Table 7: Coefficients for the Substructure Linear Model

I	Variable	Description	Coefficient	Value
1	V_1	AGE	γ_1	$-5.3*10^{-3}$
2	V_2	SALT	γ_2	$-4.75*10^{-3}$
3	V_3	PRCP	γ_3	$-1.94*10^{-3}$
4	V_4	ADT	γ_4	$-6.0*10^{-7}$
5	V_5	TRANGE	γ_5	$4.48*10^{-4}$
6	V_6	CYCLE	γ_6	$-3.04*10^{-3}$

Regression equation for superstructure deterioration (Model 1):

$$SUP = EXP\left(C + \sum_i \beta_i V_i \right)$$

Where: C = 2.13
β_i, V_i = Summarized in Table 5

With: Pr(Chi) = 0.0
Residual standard error = 0.154

Regression equation for deck deterioration (Model 1):

$$DECK = EXP\left(C + \sum_i \alpha_i V_i \right)$$

Where: C = 2.06
α_i, V_i = Summarized in Table 6

With: Pr(Chi) = 0.0
Residual standard error = 0.151

Regression equation for substructure deterioration (Model 1):

$$SUB = EXP\left(C + \sum_i \gamma_i V_i \right)$$

Where: C = 2.28
α_i, V_i = Summarized in Table 6

With: Pr(Chi) = 0.0
Residual standard error = 0.134

Non-linear non-parametric model (Model 2)

The non-linear non-parametric model was developed using the generalized additive modeling (GAM) procedure. With GAM, smoothing operations were used to generate smooth plots of the transformed mean response and the predictor variables. The models from this procedure are however non-parametric in nature and hence not readily usable for prediction. Instead non-linear parametric models were developed based on the smoothed models.

Non-linear parametric model (Model 3)

Development of the non-linear parametric model was based on the non-linear non-parametric model and utilization of GLM. Polynomial functions were estimated from the smooth fits obtained from Model 2. The polynomials are as follows:

- Temperature (TRANGE) as a third degree polynomial for superstructure, deck and substructure
- Cycle as a fourth degree polynomial for deck, third degree for superstructure and deck
- Average daily traffic (ADT) as third degree polynomial for substructure and deck
- Precipitation (PRCP) as a fourth degree polynomial for superstructure and deck and as a third degree polynomial for substructure.
- Salting (SALT) as a third degree polynomial for superstructure and substructure and as a quadratic for deck.
- Age as a quadratic for all three (deck, superstructure and substructure)

The smooth of average daily traffic (ADT) is not a significant predictor for superstructure conditions, hence average daily traffic is not included for superstructure.

The resulting models from the generalized linear modeling using the estimated equations from the smooth fits are presented below. The coefficients for the predictors are shown. Tables 8, 9 and 10 are for superstructure, deck and substructure respectively. Insignificant coefficients of higher polynomial terms have been ignored.

Regression equations for superstructure deterioration (Model 3)

$$SUP = EXP\left(C + \sum_i \left(\sum_j \beta_{ij} V_i^j\right)\right)$$

Where: $C = 1.93$

Pr(chi) = 0
Residual Standard Error = 0.134

Regression equations for deck deterioration (Model 3)

$$DECK = EXP\left(C + \sum_i \left(\sum_j \alpha_{ij} V_i^j\right)\right)$$

Where: $C = 2.16$

Pr(chi) = 0
Residual Standard Error = 0.135

Table 8: Coefficients for the Superstructure Non-Linear Parametric Model

			Coefficients - β_i			
i	**Variable**	**Descript.**	**j = 1**	**j = 2**	**j = 3**	**j = 4**
1	V_1	AGE	$-7.83*10^{-3}$	$3.92*10^{-5}$	0	0
2	V_2	CYCLE	$-9.12*10^{-3}$	$8.0*10^{-4}$	$-1.73*10^{-6}$	0
3	V_3	PRCP	$-6.9*10^{-3}$	$1.86*10^{-4}$	$-3.14*10^{-7}$	$-1.81*10^{-8}$
4	V_4	TRANGE	$5.16*10^{-3}$	$-1.63*10^{-5}$	$-2.46*10^{-8}$	0
5	V_5	SALT	$-4.57*10^{-3}$	$4.24*10^{-4}$	$-7.67*10^{-6}$	0
6	V_6	S	$-6.42*10^{-2}$	0	0	0
7	V_7	T	$-7.5*10^{-1}$	0	0	0
8	V_8	CC	$-4.14*10^{-2}$	0	0	0
9	V_9	SC	$-2.26*10^{-2}$	0	0	0

Table 9: Coefficients for the Deck Non-Linear Parametric Model

i	Variable	Descript.	Coefficients - α_{ij}			
			j = 1	j = 2	j = 3	j = 4
1	V_1	AGE	$-1.6*10^{-3}$	$2.18*10^{-5}$	0	0
2	V_2	ADT	$-1.26*10^{-5}$	$1.98*10^{-10}$	$-9.73*10^{-16}$	0
3	V_3	CYCLE	$-4.02*10^{-3}$	$2.94*10^{-3}$	$-1.92*10^{-4}$	$3.17*10^{-6}$
4	V_4	PRCP	$-2.11*10^{-2}$	$8.69*10^{-4}$	$-1.27*10^{-4}$	$5.7*10^{-10}$
5	V_5	SALT	$-3.31*10^{-3}$	$8.76*10^{-5}$	0	0
6	V_6	TRANGE	$-3.88*10^{-3}$	$2.48*10^{-5}$	$-5.32*10^{-8}$	0
7	V_7	T	$-3.18*10^{-2}$	0	0	0

Regression equations for substructure deterioration (Model 3)

$$SUB = EXP\left(C + \sum_i \left(\sum_j \gamma_{ij} V_i^j \right) \right)$$

Where: $C = 2.28$

Pr(chi) = 0
Residual Standard Error = 0.135

Comparison of the models (linear and non-linear parametric) based on their standard residual errors and statistical significance does not reveal any obvious differences. The residual standard errors (indicated below the table of coefficients) are approximately the same for both deck deterioration models (Model 1 and Model 3). The trend is the same for substructure and the superstructure models. The statistical test of significance [Pr(Chi) also indicated below the table of coefficients] came out as zero for all the models, indicating that all the models are significant. The linear model has fewer variables than the non-linear parametric model, and it is therefore recommended.

CONCLUSIONS AND FURTHER RESEARCH

Bridge management systems research is a focus area for the Federal Highway Administration. As part of the research efforts, the BMIS laboratory of FHWA has acquired NBI data covering many years. In addition, disparate sources of environmental and natural hazard data have been acquired and set up in a relational database structure

Table 10: Coefficients for the Substructure Non-Linear Parametric Model

i	Variable	Descript.	Coefficients - γ_{ij}		
			j = 1	j = 2	j = 3
1	V_1	AGE	$-8.8*10^{-3}$	$5.06*10^{-5}$	0
2	V_2	SALT	$-1.08*10^{-2}$	$1.98*10^{-4}$	$-9.88*10^{-7}$
3	V_3	PRCP	$2.08*10^{-2}$	$-6.86*10^{-4}$	$5.94*10^{-6}$
4	V_4	CYCLE	$-2.73*10^{-2}$	$2.67*10^{-3}$	$-1.05*10^{-4}$
5	V_5	TRANGE	$3.39*10^{-2}$	$-3.49*10^{-4}$	$1.77*10^{-6}$
6	V_6	ADT	$1.24*10^{-6}$	$-8.67*10^{-11}$	$1.14*10^{-15}$

using GIS technology. The databases provide an invaluable resource for detailed analysis and research. Exploration of the NBI revealed very informative statistical summaries, some of which were presented in the paper. The data were also used in the development of regression models using advanced statistical modeling procedures. The regression models are useful for predicting the deterioration of bridge decks, superstructures and substructures. Three categories of regression models were developed: a linear model, a non-linear non-parametric model and a non-linear parametric model. The linear model was recommended over the others, mainly because of its simplicity.

Further research is being performed in the BMIS laboratory. Currently, there is an investigative effort by the laboratory to determine if bridges with epoxy-coated reinforced decks have performed better over time than bridge deck reinforcements without any coating. This research is being conducted using information from the NBI and the relational database on environmental data. Also, recently some states have initiated efforts to collect GPS data on bridge locations. The BMIS laboratory intends to acquire the GPS data as it becomes available. The GPS data will be utilized to more accurately locate the bridges in space and the improved spatial data will be used to update the models previously developed.

REFERENCES

1. Agresti, A., *Categorical Data Analysis*. John Wiley and Sons Inc., 1990.
2. FHWA, *Recording and Coding Guide for the Structure Inventory Appraisal of the Nation's Bridges*. Bridge Division, Office of Engineering R&D, Dec. 1988.
3. FHWA, *National Bridge Inventory Information System Documentation*. Bridge Division, Office of Engineering R&D, 1992.
4. FHWA, *Bridge Management Systems.* FHWA-DP-71-01R, 1989.
5. Hastie, T.J. and Tibshirani R.J. *Generalized Additive Models*. Chapman and Hall, 1990.
6. Hearn, et al., *Report on Bridge Management Practices in the United States*. University of Colorado at Boulder, 1995.
7. West, et al., *A Nonlinear Deterioration Model for the Estimation of Bridge Design Life*. Research Project No. 86-07. Prepared for Pennsylvania Department or Transportation, 1989.
8. S-PLUS Guide to Statistical and Mathematics Analysis, 1995.