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COST BENEFIT ANALYSIS OF BRIDGE DEGRADATION

Final Report
to
Materials Research Program
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NCPTT promotes and enhances the preservation of prehistoric and historic resources in the United States for present and future generations through the advancement and dissemination of preservation technology and training.

Abstract

The economic impacts of regional emissions reductions on facilities and materials is difficult to assess. This report documents two approaches to doing for painted steel bridges. The first approach explores the uses of models for an assessment framework that would facilitate the joint estimation of degradation in acid environments and the agency response to the degradation. This is a theoretical study. The second approach involved the exploration of the relationships between bridge paint condition data that has been screened to remove the effects of agency response and depositional environment. Data from Ohio and New York were obtained. The county level data for Ohio was for 1992 and no correlations to deposition data from RADAM and NTN could be identified. The New York state data consisted of bridges that had not been repainted in the period 1986 to 1993. The data was correlated with acid deposition environments identified as low, medium and high. Surprisingly, areas with high deposition were associated with bridges in the best condition and showing the slowest deterioration rates and areas with low acid deposition were associated with bridges in the worst condition and showing the highest degradation rates. While previous studies and experimental work have not necessarily involved the type of paint systems used on bridges or the typical exposure levels, additional experimental work may provide some interesting insights. However this project suggests that the inherent variability in the condition rating process, the number of variables that are not observed and the local variations in depositional environments are likely to exceed the variation attributable to changes in emission levels nationally.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

Assessing the economic impacts of regional emissions reductions on facilities and materials is a difficult task. The absence of both models and data means that any analysis is based on tenuous assumptions and inferences. In an attempt to build a defensible model of these impacts, this project addressed one aspect, painted steel bridges. This particular class of facilities is selected because of the availability of data and models. This research was intended to form the central core for a comprehensive analysis of the impacts of emissions reductions. However, inconsistent correlations between deposition environments and paint degradation suggests that the variability in acid environments is a relatively insignificant variable in the degradation of bridge paint. compared with bridge paint specific variables and local conditions.

This report documents the data, models and analyses that form the bases for these conclusions. Specifically, the following section outlines the objectives of the project. Section 3 describes the approach as proposed and what was actually done. Section 4 presents an influence diagram graphically depicting the relationships between variables. Section *5* describes previous studies, bridge paint degradation models and cost models. Sections 6 and 7 describe the deposition and condition data respectively. Section 8 presents the analyses for Ohio and New York. The final section draws some conclusions and makes some recommendations. An annotated bibliography is included as an appendix for reference. Data and analyses are also included in the appendices.

2. Objectives

The objective of this particular project was to develop an approach to the assessment of the impacts of deposition in terms of costs related to the degradation and maintenance of steel bridges, specifically, the superstructure. The approach would take into consideration:

- the available data,
- the necessary assumptions,
- the accuracy of the results, and
- the transferability of the methodology to other types of facilities or components.

This objective is based on the following hypothesis. The painted surface of a bridge degrades as the bridge ages. We hypothesize that the degradation process is accelerated in acid environments. The process is also influenced by the original quality of the painting system[1] and the type of painting system used. Examples of the hypothesized relationships are represented

[1]A painting system include the method and extend of cleaning, and choice of paint type (for example, alkyd, polyeurethane) and layers (undercoat, intermediate coat and overcoat), number of coats and coating thickness.

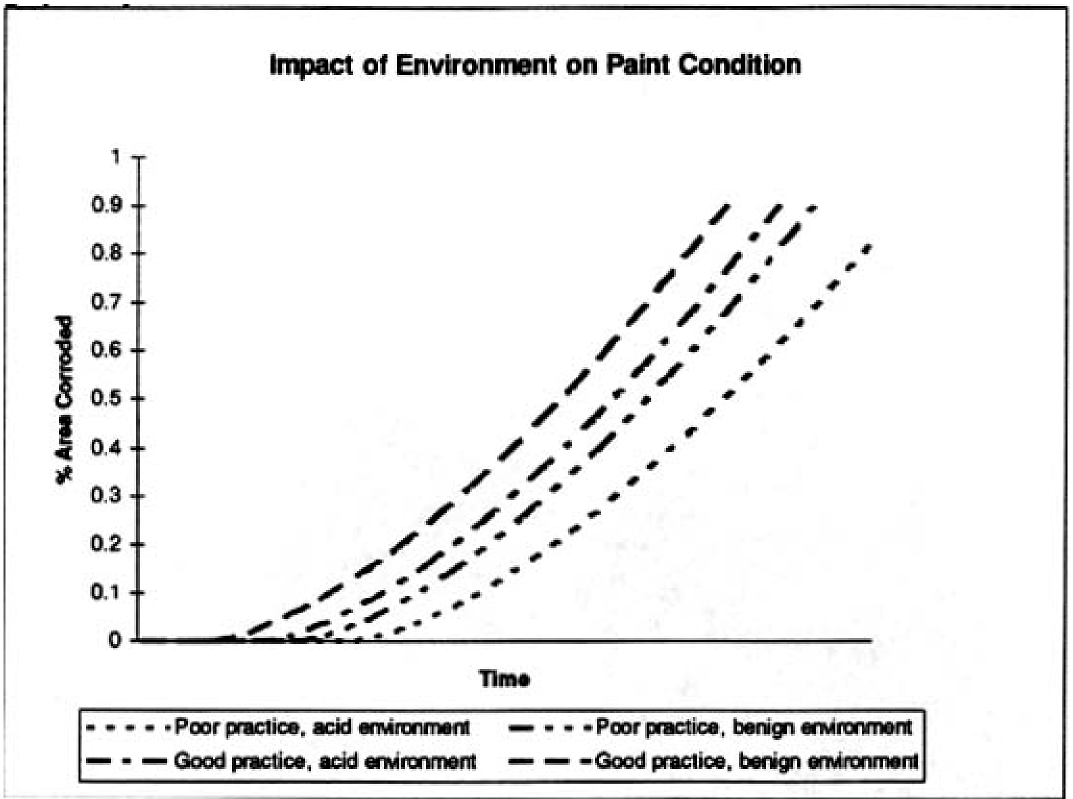


Figure 1. The figure suggests that the area corroded increases faster in a more severe environment and when there is poor painting practices (including coating system design and application.) The complex relationships between these and other factors complicate the analysis.

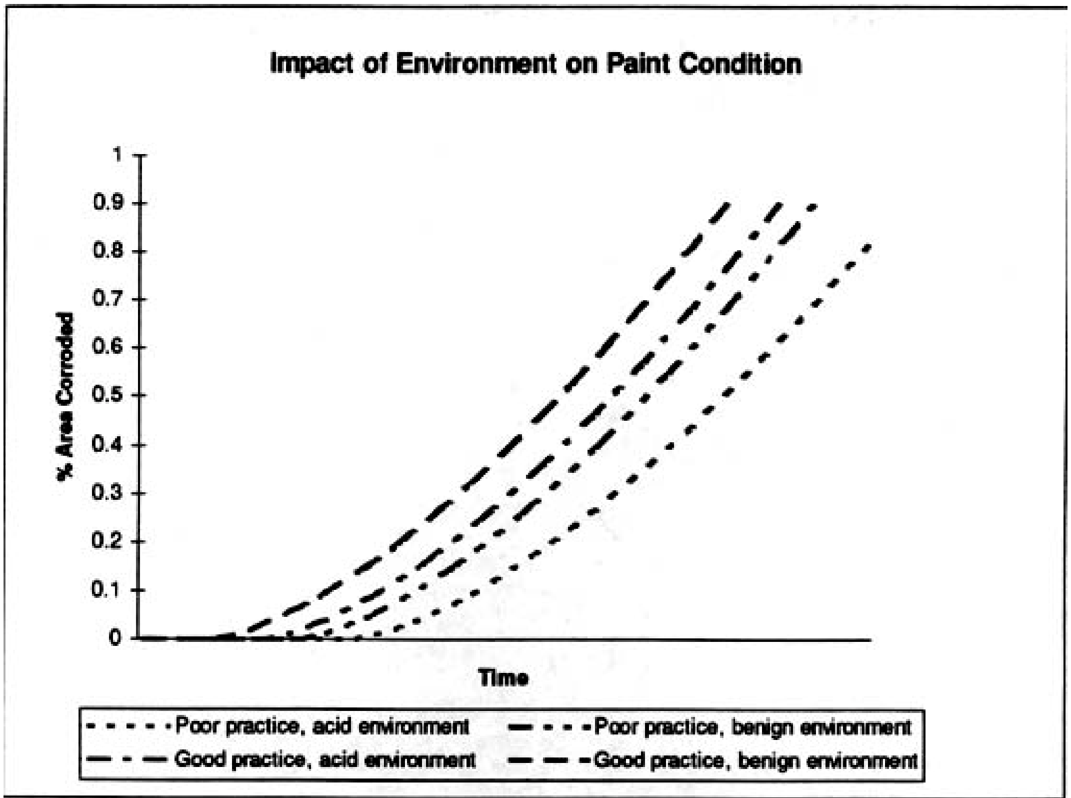


Figure 1: Hypothesized relationships between paint condition and time.

3. Approach

3.1. Original Approach

The original concept presented is based on "The Tagged Species Engineering Model" (TSEM) a described in (McHenry, 1992). While TSEM was developed to simplify the analysis of source-receptor relationships, this approach tracks "indicator species" for infrastructure to model materials degradation. That is, the approach was to develop a model based on science for an "indicator species," in this case, painted steel bridges, and use it to evaluate the importance of materials damage assessment.

The approach used in this research relied on published bridge condition data and deposition data. The original proposed approach was based on the assumption that data from the National Bridge Inventory (NBI) data and RADAM and NTN deposition data would allow for an aggregate analysis of degradation and agency responses. For each federal aid bridge in the US, the condition data biannually records inspector visual ratings of the condition of the bridge superstructure. Location, type of bridge, materials and other factors are also recorded. This inventory and condition data can be used with region specific deposition data, and models.

Inferences regarding the relationship between degradation and deposition can be made to determine the impacts on the life of the structure, the required painting frequency and potential for catastrophic failure at different emissions levels. This relationship between deposition and degradation may be inferred from an historical analysis of the NBI data or from mechanistic models of corrosion and paint degradation. Actual degradation is strongly influenced by maintenance policy and practice, specifically, the actual frequency and extent of bridge painting. Therefore, rather than developing dose response functions for model degradation alone, agency response to the degradation must also be modeled. This type of simultaneous equation modeling system has been used for roadway pavements.

The proposed analysis was intended to be a “what-if” analysis where parameters can be altered and the results compared. Therefore, the relative costs rather than absolute values are the relevant outcomes. Some specific issues that must be considered in this approach are:

- long time horizon -- bridges degrade slowly, the eleven years of data available from the NBI may not be sufficient to show any trend in dose response models. However, trends in maintenance practice may be reflected.
- unobserved variables -- other variables such as maintenance policy impact the degradation process. Explicitly modeling this is difficult as not only is the frequency important, but the quality of the surface preparation, and the chemistry and thickness of the coating. Other approaches such as latent variables and fuzzy set theory may also be useful. In other cases, where data are not available, ranges of values may be assumed.
- lack of data -- the superstructure rating is a very aggregate assessment of condition which is collected every two years. Similarly, deposition data is defined or a region and period of time. In either case a specific combination of conditions and bridge type may cause accelerated degradation in a particular period that will not be recognized in the models. Alternatively, regional deposition models may not reflect urban conditions.
- inconsistencies and inaccuracies in the data -- bridge numbers change, bridges are reconstructed, bridges are painted, and inspectors vary in their qualitative assessment.

These are all factors that must be considered in developing the approach.

3.2. Actual Approach

The NBI does not require states to explicitly record paint condition. What is recorded is superstructure condition. This value will only reflect paint degradation once loss of section occurs. This data was considered to be inadequate.

States were sought that specifically rate paint condition and show variability in depositional environments. New York, Pennsylvania and Ohio meet this criteria. What varies from state to state is the quality of the rating data and the available detail to cross reference condition to specific painting events or activity.

The approach used was to complete some aggregate analysis once the data was obtained. This aggregate analysis focused on relating overall condition to depositional environment in Ohio, and rate of deterioration to depositional environment in New York. As this evidence was inconclusive, no further analysis was completed. However, some cost and degradation models were explored and these are described in the background section.

4. Relationship between Paint Condition and Other Variables

To understand the relationships between paint condition, environment and agency actions, an influence diagram was developed to represent the complex set of interactions and influences. An influence does not necessarily represent causal relationships but factors that influence the outcome. The diagram is shown in Figure 2.

In developing the influence diagram. factors that are clearly identified subsets of influences, have been excluded for clarity. These are described below.

4.1. Emissions policy and bridge painting

There are two nodes that reflect the final decision that is made with regards to forcing the reduction of emissions or altering the bridge painting systems (including type of paint, thickness of paint and painting frequency) that are currently being used.

Bridge painting policy is influenced by the total cost of a bridge painting system which in turn is a function of the
•cost of renovating a bridge,
•cost of repainting a bridge, and
•level of emissions.

Either emissions can be reduced and as a result the rate of bridge degradation reduced or bridge painting practices can be improved and the effect of emissions on the bridge can be reduced. Both approaches will result in lower life cycle costs.

4.2. Location

The location of the bridge determines how often the bridge is used and the environmental factors the bridge is subject to. While different depositional environments represent one factor, the location in an urban or rural environment is also quite specific. The location also determines the level of other pollutants, such as proximity to emitters such as power stations.

Location also influences usage. Usage also determines the amount of salt used on a bridge and its resultant degradation.

4.3. Cost of Bridge Repainting

The cost of repainting a bridge is a major consideration. The cost of painting removal of old paint, and application of new paint including supervision. This varies with the type of paint and the thickness and frequency with which it is applied.

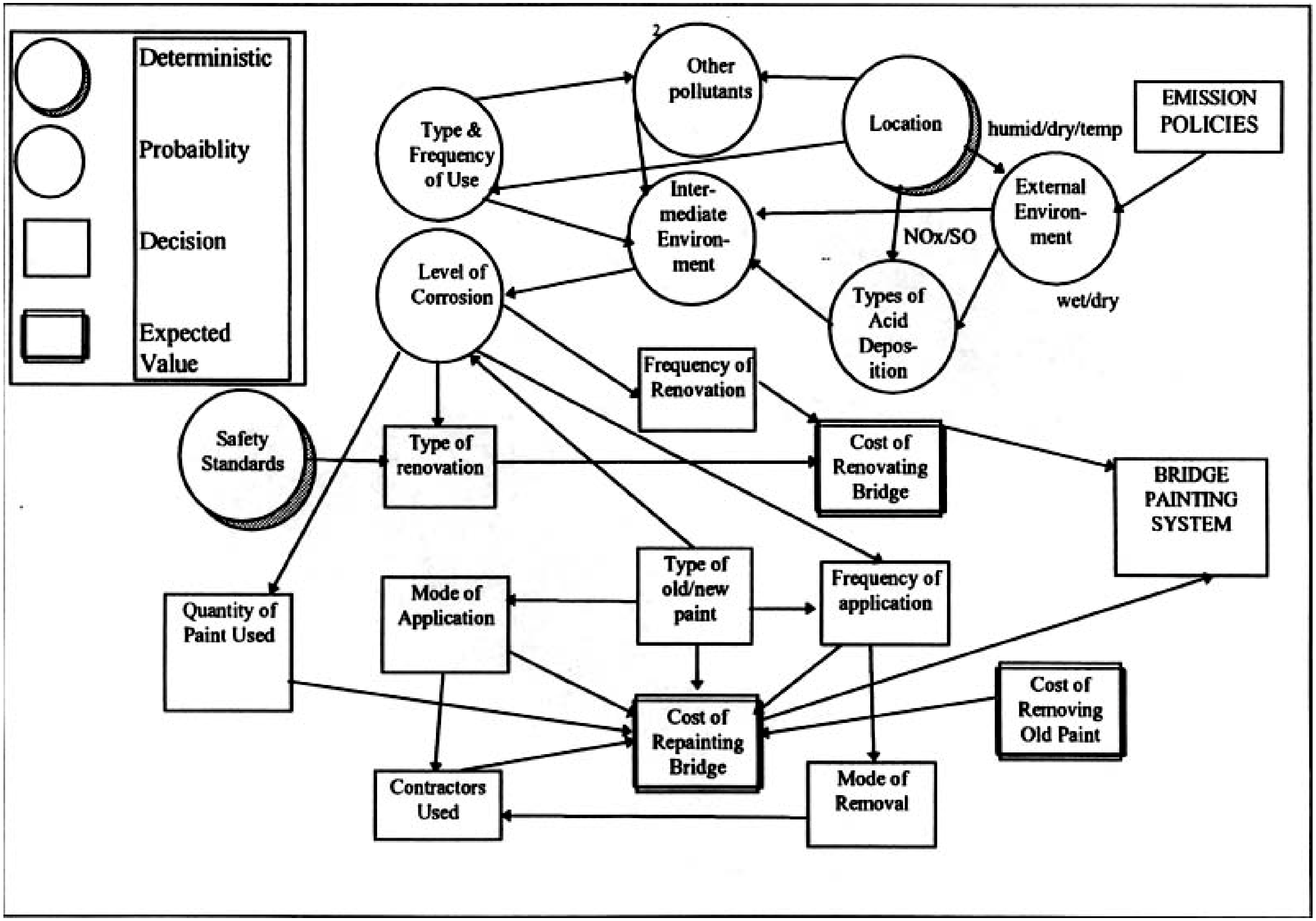


Figure 2: Influence Diagram

5. Background

This section reviews previous studies and models of bridge degradation, painting costs and agency response that may be appropriate to this analysis.

5.1. Previous Studies

The National Acid Precipitation Assessment Program. 1990 Integrated Assessment Report (NAPAP, 1991b) reports on the impacts of acid deposition on materials and cultural resources (Section 2.4). The more comprehensive document (NAPAP, 1991a) reports on materials (Report 19) and structures (Report 20.) The materials considered were metals (iron, copper and aluminum based products), carbonate stone, and painted wood and metals. While this previous study included both laboratory and field work it focused on samples in controlled environments. Specifically, in the case of painted metal the causal relationship between accelerated corrosion due to attack of the metal from acidic moisture due to paint degradation or through permeable paint is somewhat inconclusive. The magnitude of the damage, and rate of occurrence are difficult to quantify, and the mechanics of the damage is disputed It is suggested that temperature, humidity and UV exposure also play a significant role. No research was conducted on human responses to degradation of painted metal structures. The research on the response of owners to the degradation of galvanized iron fencing and painted wooden structures was anecdotal.

Although much of this previous work is not directly relevant to this study, some of the models for dose response functions, particularly for galvanized steel can serve as building blocks.

5.2. Bridge Degradation

A two phase model is posed to attempt to estimate the service life of bridge paint based on environmental factors. Such two phase models have been used in road and bridge degradation in the past and take the form (Patterson, 1987):

t = time to initiation of degradation
A = extent and/or severity of degradation.

These models take the form of the typical S-shaped curve but model the period of time represented by the length of the tail of the “S” representing the beginning of deterioration as a function of location specific parameters. This approach is supported by laboratory work (SSPC 91-07, Davis, Shaw et al 1990, Simpson, Hampel et al 1992).

Phase I Model:

Time to initiation of corrosion can simply be a look up value, derived from the literature and based on the environment.

Phase II Model.

a) (Benarie, 1986)

Rate of Change of Area Corroded = a $t^{1/2}$

where t is the time since corrosion initiated.

b) (Matsumoto, 1989)

Corrosion Depth = $A+BX_1+C X_2+D X_3+E X_4+F X_5$

where X_1 - temperature
X_2 - humidity
X_3 - precipitation
X_4 - sulfur dioxide concentration
X_5 - sea salt particles

c) (Spence, Haynie et al 1992)

$dC/dt = a_0 H- \pm a_1 + a_2 SO_2 \text{ dry} + a_3 SO_2 \text{ wet}$

d) (Haynie. 1980)

$K= \{A+B\{0.0134\}v^{0.781} C SO_2 t_w$

K - corrosion in mm
v - wind speed in m/s

SO_2 - average concentration in mg/m3,
t_w - time of wetness in years

Coefficients A and B based on regression for Zn samples are given on Page 19-60 (NAPAP III)

5.3. Cost Models

A simple engineering cost model that provides the unit costs of bridge painting for a specific type of bridge. condition, type of paint, method of surface cleaning and thickness of paint. The existing paint condition is implicit as the initial model assumes that bridges are painted as a response to a specified minimum acceptable condition. The cost model is simply a look-up table (Brevoort, 1992).

For example, the costs of bridge painting over the life of the coating systems can be established as follows:

Typical system: Alkyd primer with two top coats of alkyd primer. (SSPC system 7)
Surface Preparation: SSPC 6 (Commercial Blast to Near white metal?)
Minimum thickness: 6DFT

Life in mild environment: P = 13.5 years (assume practical not ideal conditions)
Maintenance: Touch up at 33% of P

Maintenance Repaint 50% of P

Costs: Materials:

Alkyd Primer $0.040/sq ft
Alkyd Top coat $0.044/sq ft

Labor

SP -6 Cleaning $0.50/sq ft
Application (Spray) $0.20/sq ft
Touch-up (10% area) $0.16/sq ft

Maintenance

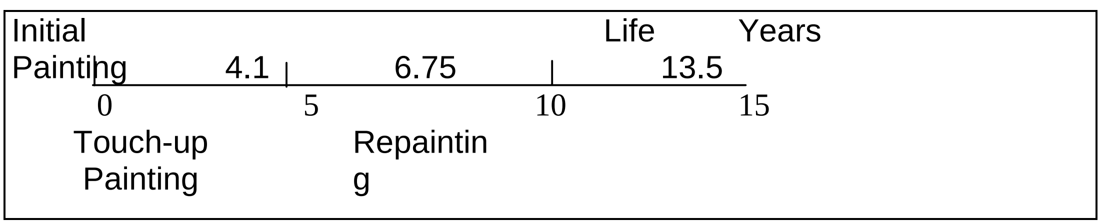
100% installation

Structure >50'
+50% on labor

Initial Bridge Painting costs: 0.04+2*0.044+ (0.5+0.2*3)* 1.50=$1.778/sq ft

Touch up: 0044*01+0l6*150= $0.229/sq ft

Maintenance Painting: $1 .778/sq ft



Clearly, the cost of touch up and repainting and the initial cost of painting as well as the life of the coating system will be sensitive to changes in environment.

It is critical to use a method of comparison of alternative scenarios (depositional and maintenance) that does not bias the results and accounts for the time value of money. While the equivalent uniform annual costs assume infinite planning horizons they provide a useful tool for evaluation in this case and allow comparison of alternatives on the basis of cost per year.

Assuming painting occurs in year 0, 4, 6 and 13 then the equivalent uniform annual cost of painting is:

$(1.778 + 0.229/(l+i)^4 + l.778(l+i)^{13})(U/P.i.13)$/sq ft

where i is the discount rate.

Figure 3 shows the impact on costs of increasing or decreasing the life of the bridge paint assuming discount rates of 4, 6 and 8%. For example, if the discount rate is 6% and the paint life is shortened from 15 to 13 years. the equivalent annual cost goes from $0.39 to $0.41 per square foot. This represents a 5% increase in costs which is very significant.

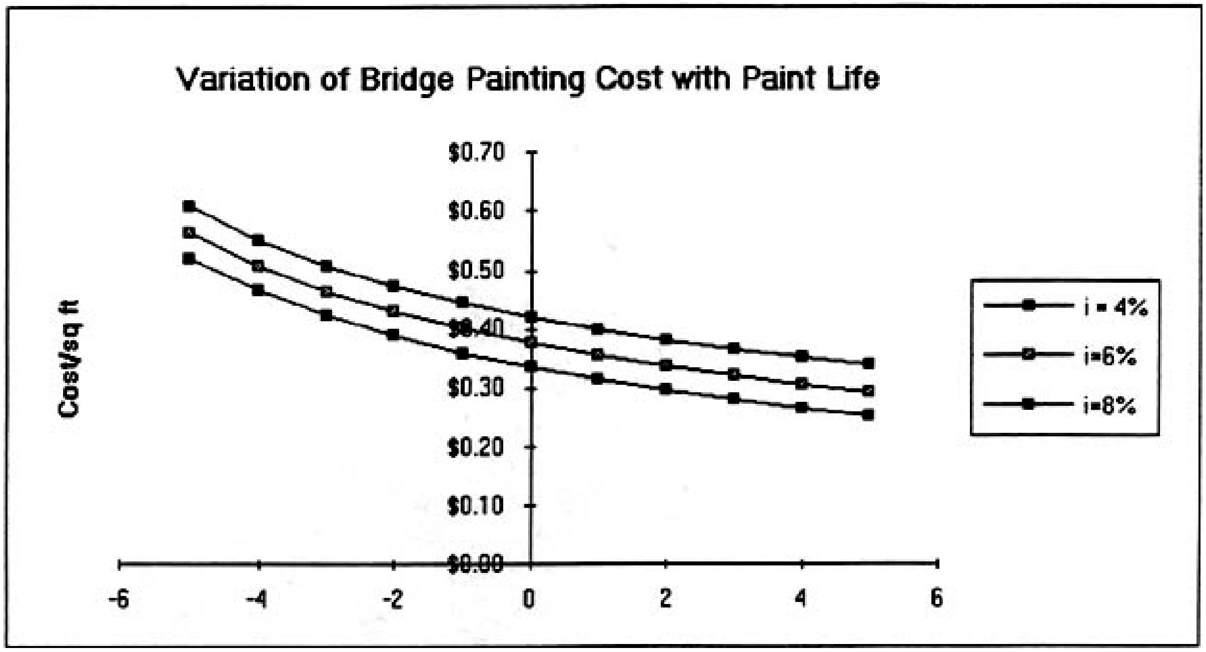


Figure 3: Variation in Painting Cost with Paint Life

5.4. Agency Response Models

Agencies respond to accelerated degradation by maintaining (or painting) the facility more frequently. Therefore, on average facilities in more severe environments or subject to more severe usage will not be in worse condition that facilities in benign environments or facilities that have relatively low usage. To capture this effect a simultaneous equation model is required (Ben-Akiva, 1992.) The model assumes both expenditures and condition are endogenous variables.

6. Deposition Data

The National Atmospheric Deposition Program and National Trends Network (NADP/NTN) is a 200 station rural wet-only deposition network These monitoring sites are located throughout the continental United States. Alaska, Hawaii and Puerto Rico. It is the only long-term deposition monitoring program in the U.S. with national coverage.

The NADP was established in 1978 to start to address the problem of acid deposition. The Central Analytical Laboratory (CAL) which is operated by the Illinois State Water Survey, provide chemical analyses for the network samples, and a Coordination Office is located at Colorado State University. This program is designed to provide regional data on spatial distributions and temporal trends in concentrations and depositions of major cations and anions in precipitation.

Each monitoring station has its own CAL code. The data used in this analysis were drawn from the database (NAPAP, 1993.)

From currently available data, the trend in acid deposition (NAPAP, 1991. Deposition Monitoring 6-CP-1 - 6-CP-18) several trends in ion deposition can be observed:

- Dry, SO_x, NO_x and H^+ ion deposition follow similar spatial distributions
- Wet, SO_x. NO_x and H^+ ion deposition follow similar spatial distributions Therefore, we will use these ions as indicators for the depositional environment. Another important issues to be considered to be considered is the difference between urban and rural environments. In urban areas, No_x emissions have the largest impact on acid deposition, where in rural areas SO_x emissions make the largest contributions.

6.1. Ohio

Four monitoring stations are available for Ohio. Data for 1992 were selected to correspond to the bridge paint condition data provided by Ohio DOT. The four locations are:

- Butler County, OH09;
- Delaware County, OH17;
- Noble Country, OH49; and
- Wayne County, OH71.

These locations are shown on Figure 4.

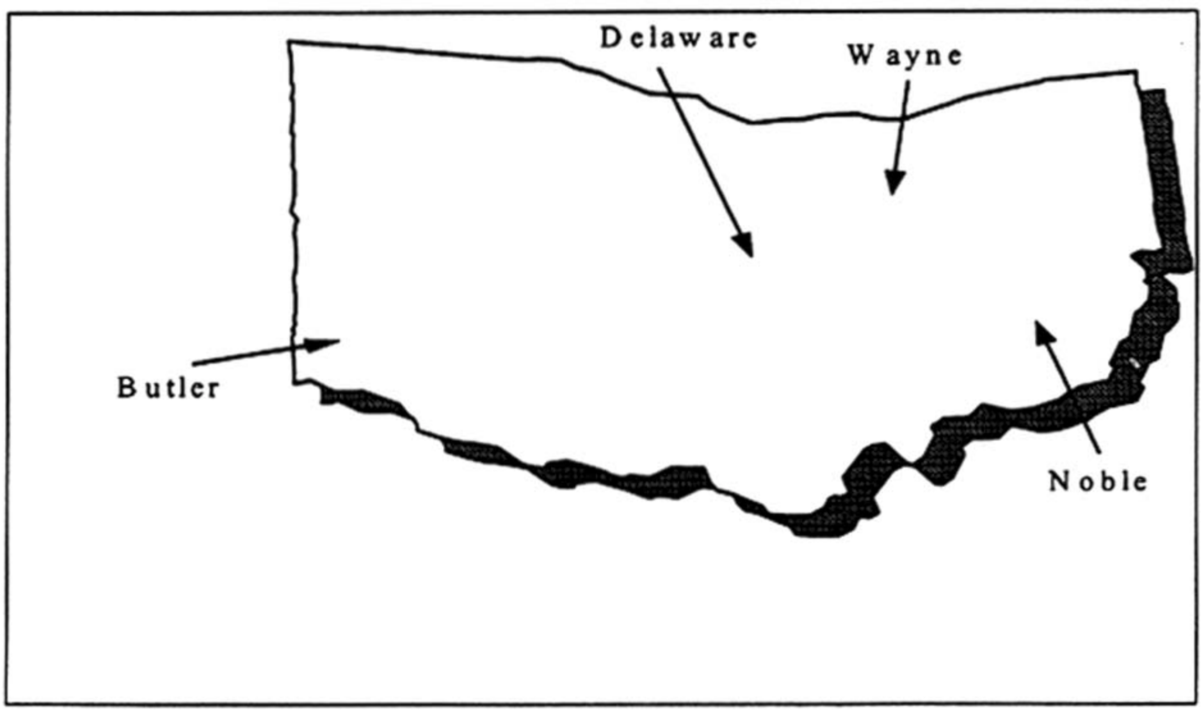


Figure 4: Ohio, showing monitoring stations

In order to compare the data, the deposition quantities were standardized as a percentage of a particular chemical collected at a particular site. The data are summarized in Table 1.

Site	NO_3		SO_4		H^+	
	Value	Rank	Value	Rank	Value	Rank
ButlerCounty.OH09	12.85	4	21.6	4	0.045	2
DelawareCounty, OH17	16.76	1	26.57	3	0.041	4
Noble Country. OH49	14.51	3	27.96	2	0.056	1
Wayne County. OH71	15.63	2	28.21	1	0.044	3

Table 1: Summary Deposition Data for Ohio (kilograms per hectare)

6.2. New York

For the state of New York, there are eight monitoring stations as shown in Table 2 and in Figure 6. An area around each monitoring station has been designated. For example, the area around Station NY52 is defined to be between 43 and 44 degrees latitude and 78° and 75° 30' longitude.

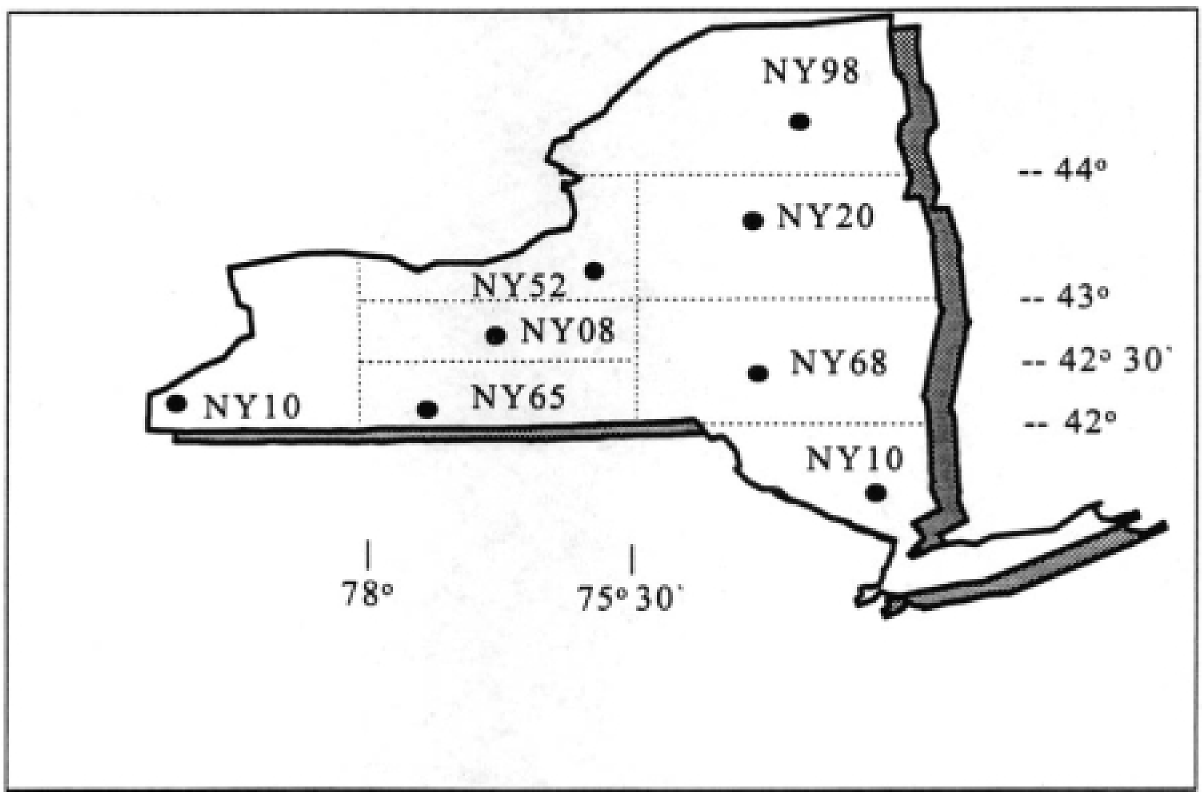


Figure 5: New York, snowing monitoring stations

In addition to the SO_x, NO_x and H^+ ions considered in the Ohio study, NH_4 is considered. Table 2 shows the average annual deposition for each ion and each station for the period 1986 to 1993.

Site	NO_3	SO_4	H^+	NH_4	Cum Ranking -NO_3 +SO_4+ H^+ + NH_4	Rating
Auroroa Research Farm, NY08	16.9	26.3	3.2	0.55	5+5+3+5 = 18	medium
Chautauqua, NY10	193	29.0	3.4	0.55	4+3+2+4 = 13	medium
Huntington Wildlife, NY20	14.9	19.5	2.1	01.45	6+8+7+8 = 29	low
Whiteface Mountain, NY98	13.8	19.7	2.2	0.46	7+7+6+7 = 27	low
West Point, NY99	20.8	303	2.5	0.74	2+2+5+2 =11	high
Bennett Bridge, NY52	30.6	36.5	4.8	0.75	1+1+1+1 = 4	high
Jasper, NY65	12.9	20.7	2.0	0.46	8+6+8+6 = 28	low
Biscuit Brook,, NY68	19.8	28.5	2.6	0.70	3+4+4+3 = 14	medium

Table 2: New York Deposition Data (kilograms per hectare)

Using these averages, each station was ranked from 1-9 in terms of severity of depositional environment for each ion. Then each station was identified as having either a high, medium or low depositional environment based on the cumulative rankings. For example for Aurora Research the NO3 deposition is the fifth highest, the SO4 deposition is the fifth highest, the H+ deposition is the fifth highest, and the NH4 deposition is the fifth highest. Simply summing these rankings provides a score of 18 for the total ranking. The state was then divided into areas of low, medium and high deposition rates based on total station ranking and location. These regions are shown in Figure 6.

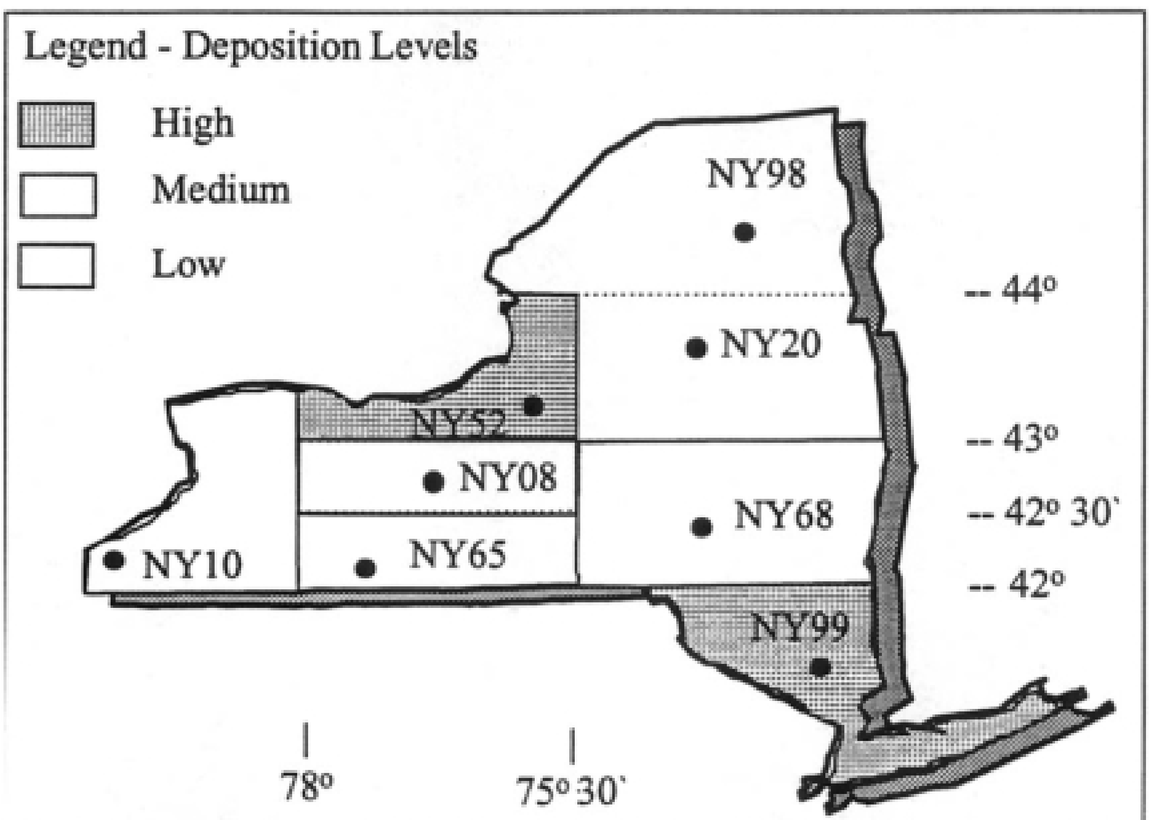


Figure 6: Depositional Environments

7. Condition Data

7.1. General

The NBI does not require paint rating data. However, many states collect additional data but data collected by individual states is not necessarily reported to the Federal Government. Pennsylvania is a logical starting point for this work because of Penn DOT's inclusion of paint condition and painting activities in the Bridge Management System and the variability in acid deposition environments across the state.

The requested data for steel structures in Pennsylvania is shown below, including the BMS coding value (PennDOT, 1986).

Years: All available
Structure Type: Steel Bridges
Length: Over 20 feet
BMS Data:

A0l – SR ID
A07 - Latitude
A08 - Longitude
A09 - City/Borough
A16 - Year Built
A20 - Ownership
A23 - Maintenance Code
A26 - Type of Service
A33 - Bridge Deck Width
C05 - Structure Type
C07 - Structure Length
C12 - Steel Types
Cl6 – Total Number of Spans
E6 - Date Insp
E19 - Paint
G08 - Painting Reference Number
G09 - Year
G10 - Tons of Steel
G1l - Estimated Area of Surface
G12 - Number of Coats
G13 - Gallons of Paint
G15 - Type of Cleaning
G16 - Paint Type. Extent, Thickness
G17 - Paint Cost

After several months of negotiation, Pennsylvania Department of Transportation refused to release this data as all BMS data is under litigation [Rogers, 1994-95]. While the specific fields requested may not be under litigation, and much of the data is public domain (as part of the NBI), and despite assurances that the data would be kept confidential, PennDOT refused to release the data.

7.2. Ohio

The data for Ohio represents a snapshot of bridge condition for one year, 1992. As Ohio claims to paint bridges with the same paint system irrespective of location and condition, bridges were selected that had not been painted in the past 5-10 years. Ohio DOT records subjective ratings on a scale of one to four to represent paint condition. A rating of "one" represents new or excellent condition and a rating of "four" represents significantly deteriorated condition. Appendix B shows the number of bridges in each county in one of the four condition states. A weighted average was computed. The averages were divide in the ranges 1 to 1.75, 1.76 to 2.5, 2.51 to 3.25 and 3.26 to 4. The counties in each range are shown in Figure 7.

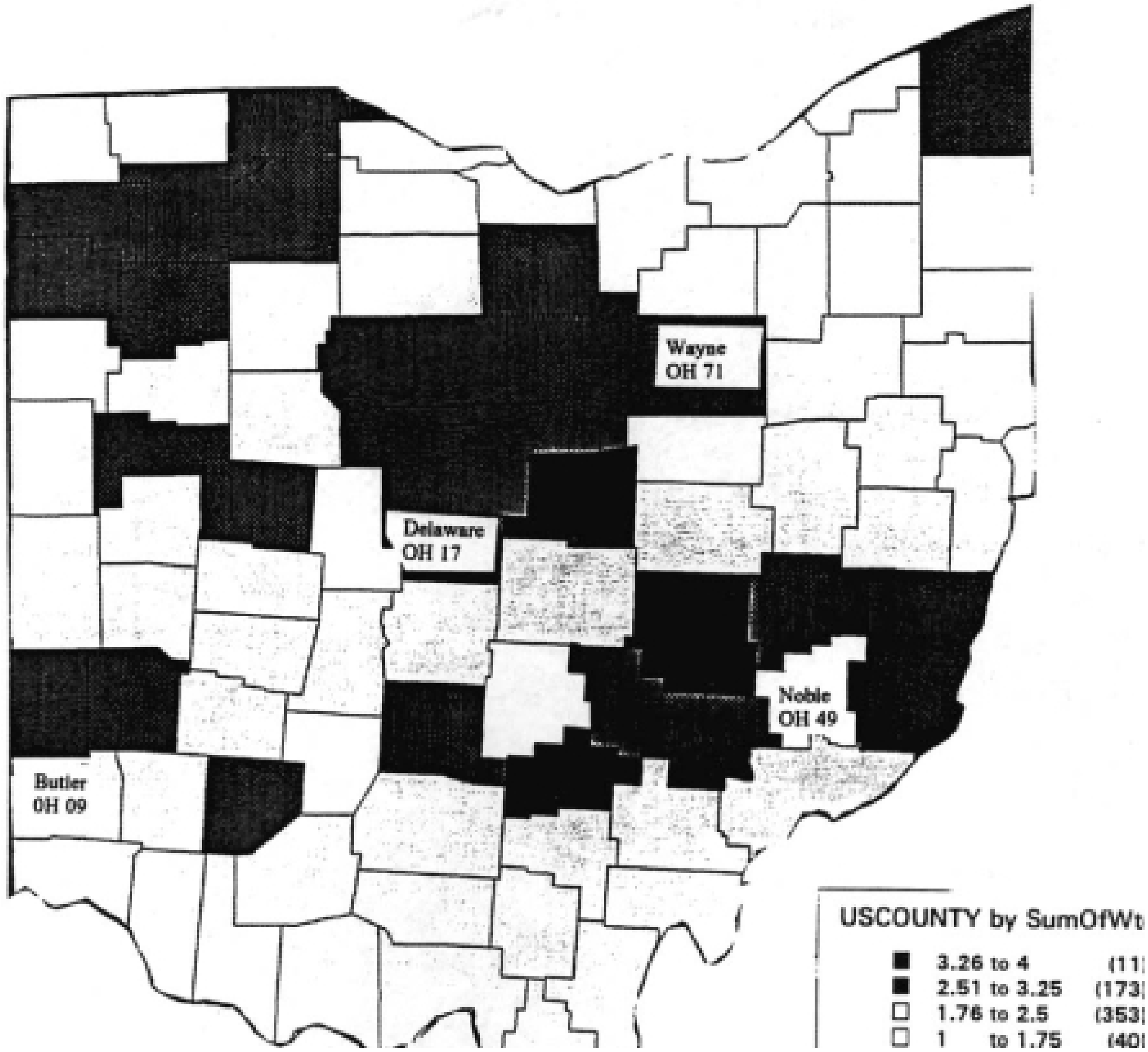


Figure 7: Average Ohio Bridge Condition by County

7.3. New York

The New York bridge paint condition rating data, included latitude and longitude for each bridge in the state and a condition rating for every span of every bridge (Classen, 1994.) The ratings 1 through 7 are interpreted as follows:

1. paint in poor condition and extensive serious corrosion is present
2. paint is generally in poor condition and serious condition in localized areas
3. paint is generally in poor condition and corrosion is present but not serious
4. paint system is poor in localized areas and minor corrosion is present
5. generally showing signs of deterioration but no corrosion is yet present
6. generally good but requires some touch-up painting.
7. good

These ratings reflect the physical condition of the paint system on the structural steel. Inspectors look for peeling, cracking, rust pimples and excessive chalking. The rating includes both the physical condition of the paint, and the amount of corrosion on the member

All data from the geographical area representing low deposition levels are aggregated together for analysis and similarly data for medium and high levels. From this set of data, bridges which have not been painted in the period 1986-1993 were identified. Also, bridge spans where the paint condition increased from the previous years were discarded due to coding errors or variability in the rating. That is, only records where there was a monotonic degradation in condition over time were retained. Also, bridges with condition ratings missing or coded as numerical values not between 1 and 7 were excluded. Bridges below 42 degrees latitude were also excluded as the urban influence was thought to be dominant. Table 3 summarizes the quantity of data available for analysis.

Deposition Level	Raw Data	Selected Data
Low	3,462	1,447
Medium	10.747	4.520
High	6.003	2.872
Total	20,120	8.839

Table 3: New York Bridge Data

8. Analysis

8.1. Ohio

With the average bridge paint condition data plotted by county and the monitoring stations located, spatial correlations were sought. Two of the monitoring stations (Delaware and Wayne county) are in the average condition range between 2.51 and 3.25. Qualitatively, these two counties show moderate deposition levels and moderate degradation. Similarly, Butler is in a country with low to moderate deterioration. In contrast the monitoring station in Noble county is an anomaly. The average bridge condition in this area is excellent, yet the depositional environment is the worst of the four monitoring stations. This county is adjacent to five counties with moderate bridge deterioration and one county with severe bridge deterioration.

As can be seen from the map, there are clusters of poor bridge condition counties in the northwest and mid-central Ohio. However, there are also counties with good bridge condition adjacent to counties with poor bridge paint condition.

A closer review of the deposition data suggests that there is not a sufficiently large variation in the depositional environments to have an impact on the bridge paint condition, considering all the other variables that effect this value. Also, the fact that there were only four stations for Ohio made the analysis difficult.

8.2. New York

For each of the three environments identified (low, medium and high), the average condition of bridges was computed for each year. These results are shown in Table 4 and plotted in Figure 8. The data and plot suggests that bridges in less severe environments are in worse condition than bridges in more severe environments. This result is supported by an analysis of variance. Using the analysis of variance. the hypothesis that the average condition in each of the three environments are the same, can be rejected at the 0.002 % level of significance. As this result is based on aggregate data and is counter intuitive further analysis was undertaken.

Environment	1986	1987	1988	1989	1990	1991	1992	1993
Low	4.58	4.37	4.06	3.87	3.61	3.46	3.34	3.26
Medium	4.5	4.3	4.1	3.93	3.77	3.65	3.54	3.44
High	4.62	4.44	4.29	4.17	4.06	3.93	3.89	3.74

Table 4: Average Bridge Paint Condition, New York, 1986-1993

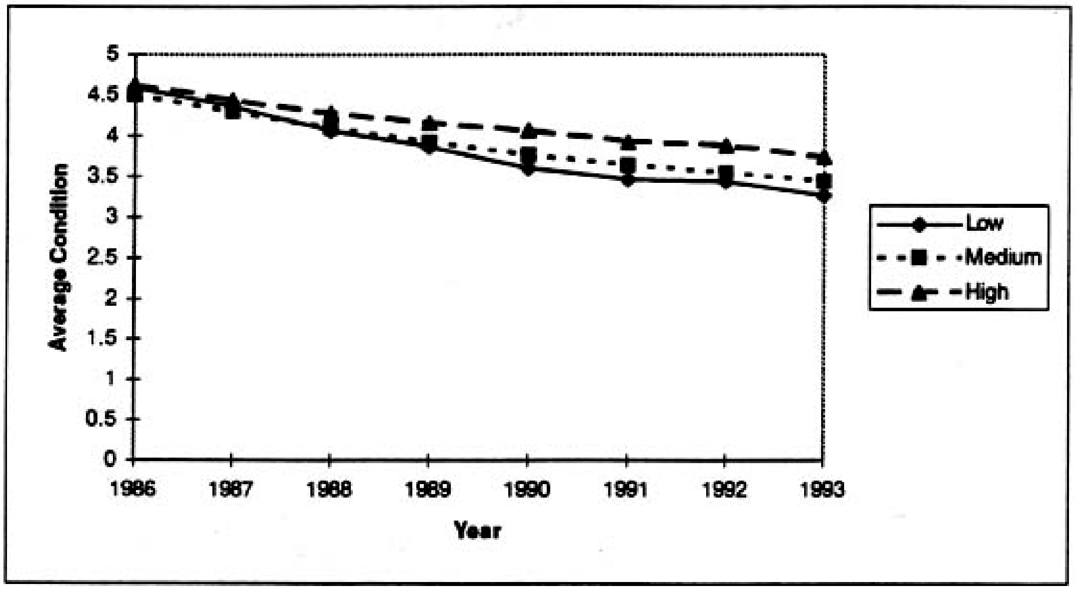


Figure 8: Average Bridge Paint Condition in New York State (1986-1993)

The aggregate data also suggests that bridges in more severe environments, on average deteriorate slower than bridges in less severe environments. To examine this more closely the data was segregated according to initial condition. For each environment and each initial condition, and each year, the average condition of the bridge is calculated. Based on a simple linear regression model the average degradation rate was computed for the data. The plots are shown in Appendix D. Interpreting the slope of the regression line as the average rate of deterioration, Table 5 shows that in general the rate of degradation is less for more severe environments, than less severe environments, and as the initial condition at the beginning of the analysis period gets worse, the rate of degradation slows down. The only exception is the rate for the medium environment, when the initial condition is 2. The degradation rate of 0.057 exceed both the low and high environments degradation rate. This is probably due to small sample sizes.

	Initial Condition						
Environment	**All**	**7**	**6**	**5**	**4**	**3**	**2**
Low	0.196	0.394	0.274	0.192	0.164	0.086	0.039
Medium	0.152	0.343	0.238	0.148	0.115	0.083	0.057
High	0.120	0.289	0.196	0.100	0.082	0.035	0.019

Table 5: Average deterioration rates

One possible explanation for the results was that the deposition data used are strictly levels of deposition and not concentrations of deposition [Davidson, 1994]. Typical precipitation levels were found for each of the monitoring stations [Weather. 1993].

Site	**Previous Ranking**	**Precipi-tation (inches)**	**NO_3**	**SO_4**	**H^+**	**NH_4**	**Ranking - NO_3 +SO_4 + NH_4**	**Revised Rating**
NY08	18	31.3	0.54	0.84	0.017	0.102	2+2+3+=29	medium
NY10	13	37.5	0.51	0.77	0.015	0.090	4+4+5+3=16	medium
NY20	29	39.1	0.38	0.50	0.011	0.054	6+8+7+8=29	low
NY98	27	36.5	0.38	0.54	0.0 13	0.060	6+6+6+6=24	low
NY99	11	41.8	0.50	0.73	0.018	0.061	5+5+3+5=18	high
NY52	4	39.1	0.78	0.93	0.019	0.123	1+1+1+1=4	high
NY65	28	36.8	0.35	0.56	0.013	0.056	8+6+6+7=27	low
NY68	14	36.8	0.54	0.78	0.019	0.071	2+3+1+4=10	medium

Table 6: Acid Concentrations, New York

Deposition levels are divided by annual precipitation as an estimate of concentration. The rankings remain the same, with the exception of two areas: NY99 went from high to medium and NY08 could be interpreted as high rather than medium. The high area containing station 99 was excluded from the analysis because of the proximity to New York city, and area containing station NY68 is close to NY68 which is still medium. Therefore, the results do not change.

Other explanations focus on the data quality. For example, the deposition data may not reflect that conditions at the bridge site, or the use of salt for snow and ice removal has a stronger influence that is not captured. However, the consistency of the results suggest that this is unlikely.

Alternatively, it is possible that the paint system used on New York Bridges forms a protective layer in acid environments that acts in much the same way as the rust layer on Cor-Ten. Previous studies of painted metal have focused on degradation in environments much more severe than found in practice and without the same types of painting systems used on bridges.

9. Conclusions and Recommendations

The preceding analysis is based on very aggregate deposition data and qualitative condition rating data for bridge data condition. No clear correlation between paint condition and the environment was found using cross-section data on paint condition for bridges in Ohio when condition data was aggregated by county. However, deposition data from only four monitoring stations was available. Seven monitoring stations in New York provided deposition data and this was used to identify three depositional environments - high, medium and low. Panel data for New York bridges represented paint condition throughout the state and the period 1986 - 1993. Data south of 42 degrees latitude was excluded from the analysis because of the dominant effect of highly urban New York City and West Chester County. For the seven year period, 8.839 bridge spans were identified that show continuous degradation or their paint condition remained constant. The overall condition was worse and rate of degradation was higher for the low severity deposition environment that for the medium and high acid deposition environments.

Some conceptual cost and agency response models and were identified and sources of data for bridge painting cost models were identified. However, these were not calibrated as the New York yielded results that was inconsistent with prior research. While a framework has been developed for this type of analysis, additional experimental work using typical oil alkyd painting systems (including typical surface preparation and thickness) and exposures should be pursued before model development. From a practical point of view, this research suggests that the inherent variation far exceeds the effects of acid environments on bridge paint.

10. References

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Spence, 1992 — Spence, J.W., F.H. Haynie, F.W. Lipfert, S.D. Cramer, and L.G. McDonald, "Atmospheric Corrosion Model for Galvanized Steel Structures," *Corrosion*, December, 1992, Volume 48, Number 12, Pages 1009-1019.

SSPC 91-07 — "Effect of Contaminants on Coating Life,"S. Boocock, R. Weaver, B. appleman, and G. Soltz, Steel Structures Painting Council, Pittsburgh, PA, 1991.

Weather. 1993 — Weather in U.S. Cities, 3rd Edition, Volume 2.

Appendix A. Selected annotated Bilbliography.

Author: Brevoort, G. and A, Roebuck,
Title: Costing Considerations for Maintenance and New Construction Coating Work
Journal: *Corrosion 92*
Number: 335
Year: 1992
Notes: Provides an annual update to "The Paint and Coating Cost and Selection Guide" published through NACE. The information is also available electronically in the form of a computer program for bridges known as Spec-Mate- 2.
Keywords: Costs, coating systems

Author: Brevoort. G. and A, Roebuck,
Title: Selecting Cost-Effective Protective Coating Systems
Journal: *Coatings and Linings*
Number: 335
Month: February
Year: 1991
Notes: Describes the methodology used to select and cost a coating system. Includes examples and tables.
Keywords: Costs, coating systems

Author: Chang, Luh-Maan and Hsie, Machine,
Title: Realistic Specification for Steel Bridge Painting
Journal: Proceedings of the Materials Engineering Congress. Materials; Performance and Prevention fo Deficiencies and Failure, 92
Year: 1992
Notes: Discusses practicial issues related to developing and enforcing a specification for steel bridge painting. Paper is based on interviews with contractors and bridge owners in the midwest.
Keywords:Specificiations, painting

Author: Davis, G.D., B.A. Shaw, C.O. Arah, T.L. Fritz, W.C. Moshier, T.C. Simpson, PJ. Moran and K.L. Zankel
Title: Effects of SO_2 Deposition on Painted Steel Surfaces.
Journal: *Surface and Interface Analysis*
Year: 1990
Volume: 15
Number: 2
Pages: 107-112
Notes: The effect of SO_2 on painted surfaces in a controlled environment is described based on x-ray photoelectron spectroscopy and adhesion tensile tests. The SO_2 was found to cause discoloration and accelerated loss of adhesion.
Keywords: Degradation. sulfate deposition

Author: Johansson. E. and Linder, M.
Title: The Influence of Environmental Acidification on the Atmostpheric Corrosion of Zinc
Journal: Proceedings of the 12th International Corrosion Conference, v. II,
Month: September 19-24
Year: 1993
Location: Houston, TX
Sponsor: NACE
Notes: Based on laboratory and field exposure of panels.

Keywords: Atmostpheric corrosion, zinc and galvanized steel

Author: Komp, M.E., Coburn, S.K., Lore. S.C.
Title: Worldwide Data on the Atmostpheric Corrosion Resistance of Weathering Steels
Journal: Proceedings of the 12th International Corrosion Conference. v. II.
Month: September 19-24
Year: 1993
Location: Houston. TX
Sponsor: NACE
Notes: Documents exposure tests for weathering steel
Keywords: Weathering steel, mass loss.

Author: Knotkova, D
Title: Atmospheric Corrosivity Classification Results of the International Testing Program ISOCORRAG
Journal: Proceedings of the 12th International Corrosion Conference, v. II,
Month: September 19-24
Year: 1993
Location: Houston, TX
Sponsor. NACE
Notes: Corrosion lossessnad environemtnal characteristics are recorded and analyzed for unalloyed carbon steel. zonc, aluminium and copper based on standardized tests.
Keywords: Atmostpheric corrosion, materials degradation

Author: Knotkova, D., Vickova, J., Rozlivka, L.
Title: Defects of Steel Structures Caused by Atmostpheric Corrosion
Journal: Proceedings of the 12th International Corrosion Conference, v. II.
Pages: 734-747
Month: September 19-24
Year: 1993
Location: Houston, TX
Sponsor: NACE
Notes: Cased based analysis of steellstrucutres. Emphasizes the importance of selection of an appropriate coatin system and proper application and maintenance.
Keywords: Atmostpheric corrosion, mass loss, structures

Author: Kucera, V., Henricksen. J., Leygraf, C., Coote. A., Knotkova, D., and Stöckle, B.
Title: Materials Damage Caused by Acidifying Air Pollutants - 4-Year Results from an International Exposuere Programme within UN ECE
Journal: Proceedings of the 12th International Corrosion Conference, v. II,
Month: September 19-24 Year: 1993 Location: Houston, TX Sponsor: NACE
Notes: Reports on the first four years of an eight year study of European test sites to quantify the effects of acid deposition on material (structural metals. calcareous stone, painted coatings and electric contact materials) degradation. Due to the slow deterioration of paint coatings, only data on the impact of atmospheric pollutants on damaged coating is available. On steel panels with cut paint SO_2 concentration appears to be the most significant parameter.
Keywords: atmostpheric corrosion, paint coatings, degradation

Author:. Mansfeld, F., Xiao. H., Henry, R.C.
Title: The effects of Acid Deposition on the Atmostpheric Corrosion Behavior of Structural Materials in California.
Journal: Proceedings of the 12th International Corrosion Conference, v. II,

Month: September 19-24
Year: 1993
Location: Houston, TX
Sponsor: NACE
Notes: Exposure test of galvanized steel, nickel, aluminium, house paint on stainless steeland nylon fabric were conducted and evaluated based on material lost. Low corrosion rates were observed.
Keywords: Atmostpheric corrosion, mass loss.

Author: Matsumoto, M, Shiraishi, N., Rungthongbaisuree, S., Kikuta, T.,
Title: Corrosion of Steel Bridges - Its Long-Term Prediction and Effect on Safety
Journal: Proceedings of the Japan Society of civil Engineers, Structural Engineering/Earthquake Engineering
Month: October
Year: 1989
Volume: 6
Number: 2
Notes: Develops models or the predition of corrosiong of painted bridge members.
Keywords: Life, deteriortation, paint, prediction

Author.McHenry, J., Binkowski, F., Dennis. R., Chang, J. and Hopkins, D.
Title: The Tagged Species Engineering Model (TSEM)
Journal: Atmospheric Environment
Year: 1992
Volume: 26A
Number: 8
Pages: 1427-1443
Notes: Describes the TSEM in terms of RADM and presents basic model concepts and hypothetical examples of application.
Keywords: Acid deposition, tagged species, TSEM, RADM

Author: Spence, J.W., F.H. Haynie, F.W. Lipfert, S.D. Cramer. and L.G. McDonald
Title: Atmospheric Corrosion Model for Galvanized Steel Structures
Journal: *Corrosion*
Month: December
Year: 1992
Volume: 48
Number: 12
Pages: 1009-1019
Notes: Develops model for corrosion of galvanized steel structures based on the formation and dissolution of the zinc carbonate film. The model produces results that are consistent with field data.
Keywords: Corrosion, degradation, emissions, air quality

Author: Simpson, T.C., H. Hampel, G.D. Davis. C.O. Arah, T.L. Fritz, P.J. Moran, BA. Shaw, and K.L. Zankel
Title: Evaluation of the effects of acidic deposition on coated steel substrates
Journal: *Progress in Organic Coatings*
Month: May
Year: 1992
Volume: 20
Number: 2
Notes: Accelerated laboratory exposure tests have investigated the effects of acidic deposition on painted metal substrates. Surface analytical, electrochemical and mechanical tests identified accelerated loss of mechanical properties and discoloration.

Appendix B. Ohio Condition Data

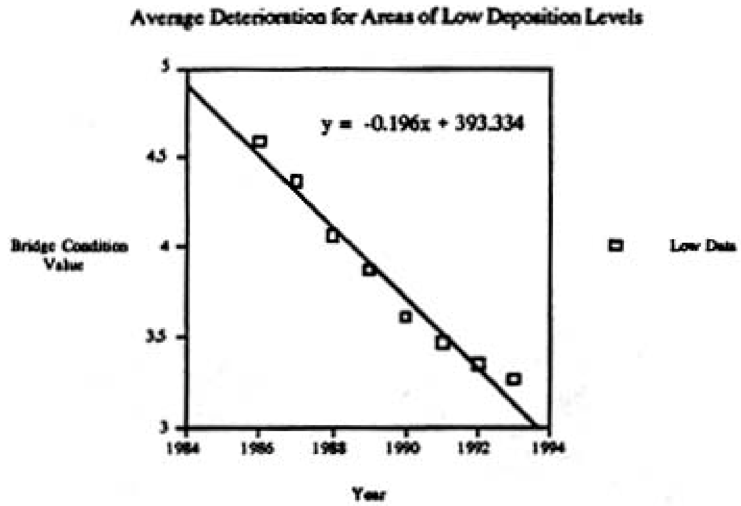
The following table summarizes the bridge paint condition data for each county in Ohio for 1992. The three digit county abbreviation represents the first three digits of the county and each of the numbers represents the number of bridges in condition state 1, 2, 3 and 4 respectively. The final column is the total number of bridges.

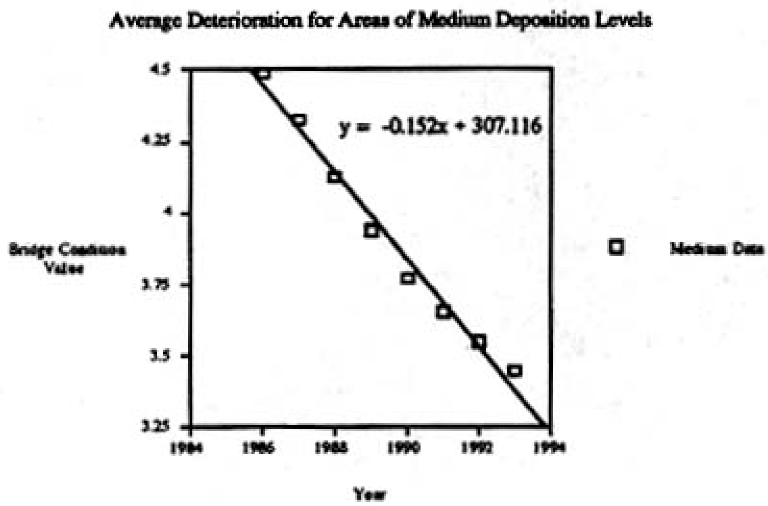
County	Condition 1	Condition 2	Condition 3	Condition 4	Totals Bridges
ADA	13	26	15	2	56
ALL	52	47	38	6	143
ASD	27	58	45	49	179
ATB	11	58	18	12	99
ATH	24	84	26	40	174
AUG	2	32	10	28	72
BEL	39	52	50	51	192
BRO	47	132	34	6	219
BUT	20	67	45	24	156
CAR	56	28	8	36	128
CHP	6	1	1	2	10
CLA	26	85	49	11	171
CLE	26	68	50	16	160
CLI	12	37	33	27	109
COL	34	76	32	13	155
COS	36	117	79	42	274
CRA	13	16	31	19	79
CUY	151	295	109	65	620
DAR	15	25	6	1	47
DEF	8	47	59	22	136
DEL	23	45	17	72	157
ERI	39	66	29	10	144
FAI	149	54	11	10	224
FAY	20	32	5	0	57
FRA	121	288	85	25	519
FUL	44	39	12	4	99
GAL	46	135	93	0	274
GEA	20	5	10	12	47
GRE	32	71	27	14	144
GUE	65	83	45	222	415
HAM	123	244	117	35	519
HAN	56	68	57	41	222
HAR	24	44	38	22	128
HAS	3	31	32	6	72
HEN	10	26	22	35	93
HIG	60	51	31	50	192
HOC	9	29	29	117	184
HOL	88	36	8	8	140
HUR	39	86	67	76	268
JAC	30	67	28	10	135
JEF	23	34	25	19	101
KNO	15	28	28	108	179
LAK	41	65	34	19	159
LAW	39	53	32	31	155
LIC	46	63	43	47	199
LOG	21	30	67	18	136
LOR	34	14	48	49	245

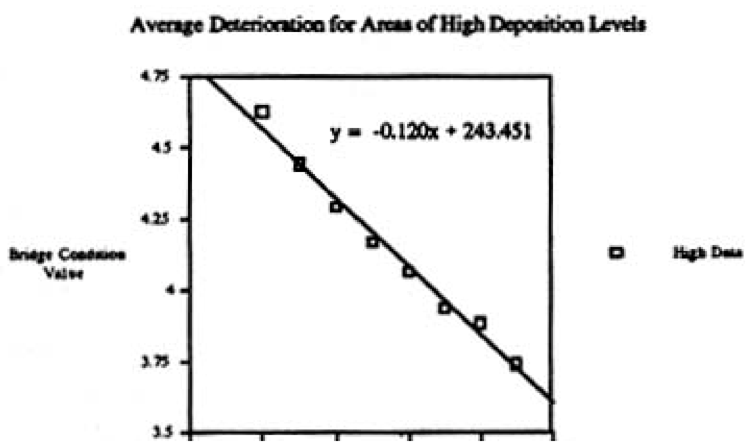
County	Condition 1	Condition 2	Condition 3	Condition 4	Totals Bridges
LUC	43	77	78	54	252
MAD	18	56	23	11	108
MAH	30	116	47	15	208
MAR	14	50	29	28	121
MED	47	40	36	47	170
MEG	21	111	21	2	155
MER	14	97	67	12	190
MIA	7	48	12	2	69
MOE	8	26	15	57	106
MOT	50	156	49	31	286
MRG	23	29	9	1	62
MRW	16	53	63	10	142
MUS	13	64	19	183	279
NOB	79	80	6	1	176
OTT	28	29	5	7	79
PAU	14	15	16	14	59
PER	18	55	31	39	143
PIC	15	23	29	46	113
PIK	26	41	28	18	113
POR	29	53	38	22	142
PRE	13	23	22	35	93
PUT	28	77	73	35	213
RIC	28	91	84	39	242
ROS	58	63	49	61	231
SAN	49	52	21	18	140
SCI	32	19	21	5	77
SEN	10	45	17	10	82
SHE	10	66	18	1	95
STA	91	100	81	4	276
SUM	75	152	94	24	345
TRU	64	104	58	37	263
TUS	49	86	68	38	241
UNI	15	12	5	0	32
VAN	66	37	24	26	153
VIN	10	26	9	0	45
WAR	18	36	13	9	76
WAS	8	91	68	14	181
WAY	68	68	56	88	280
MIL		7			7
PLA		8			8
SAL		4			4
SUG		3			3
WIL	16	35	12	15	78
WOO	58	91	72	67	288
WYA	14	8	63	9	94

Appendix C. Average Deterioration Rates for Bridges in New York State.

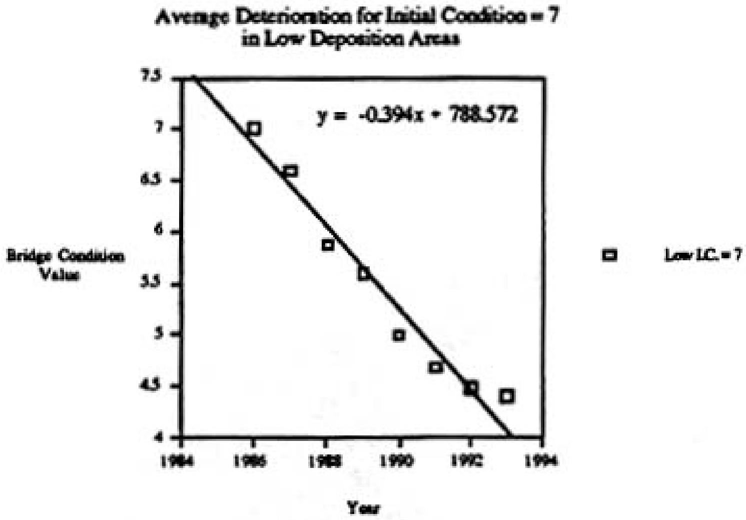
Average Overall Deterioration for Low, Medium, & High Deposition Areas

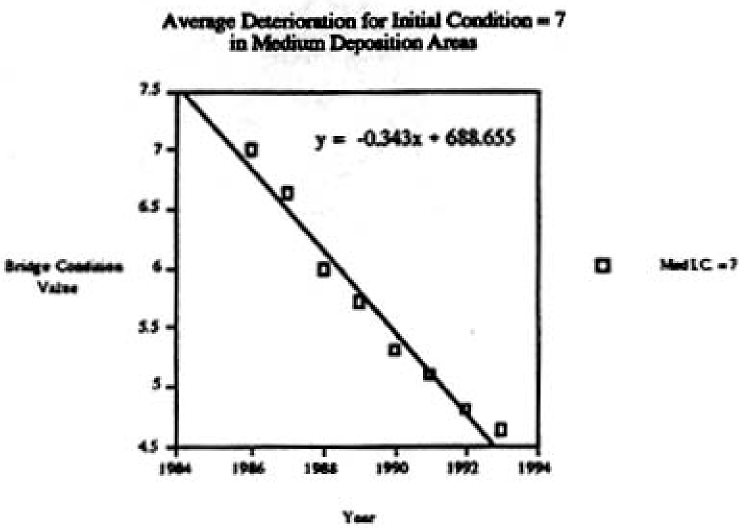


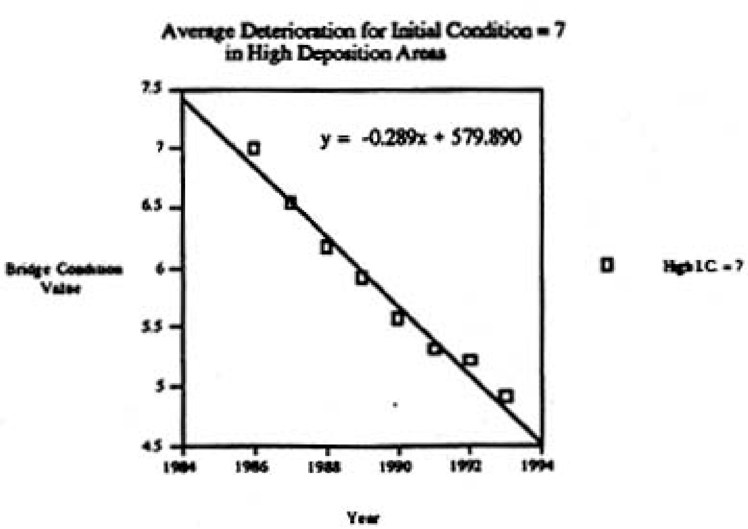




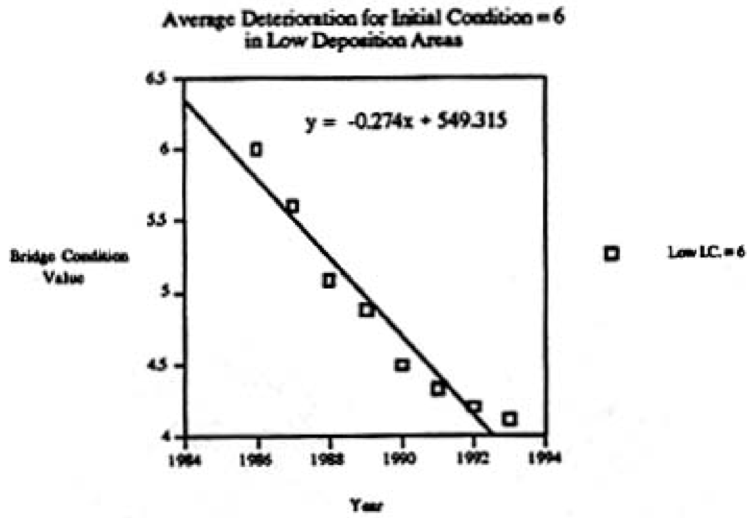
Average Deterioration for Bridges with an Initial Condition in 1986 of 7

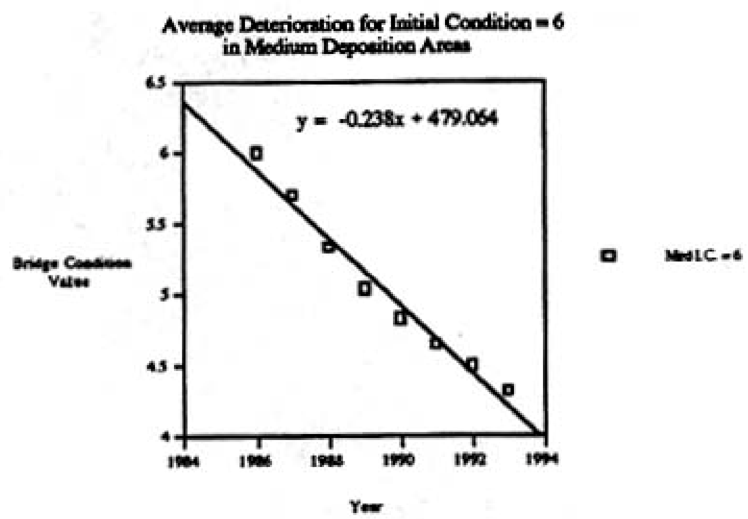


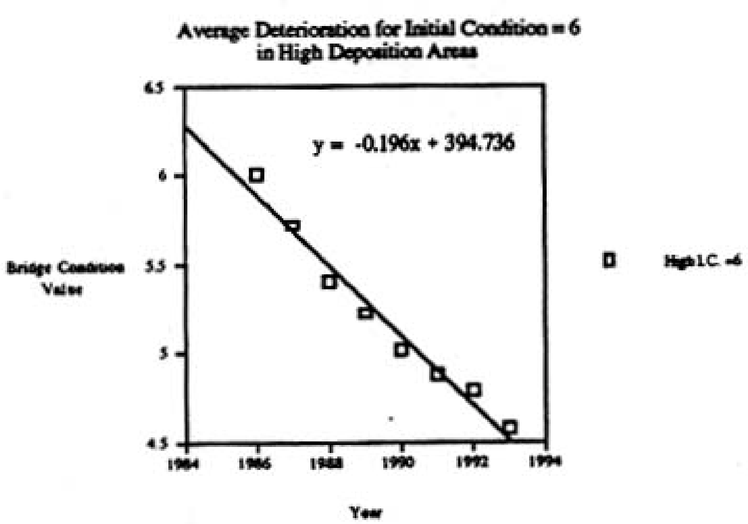




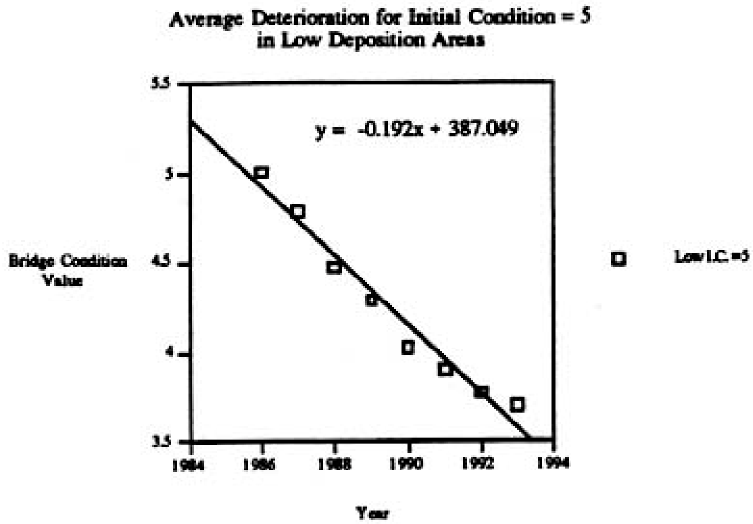
Average Deterioration for Bridges with an Initial Condition in 1986 of 6

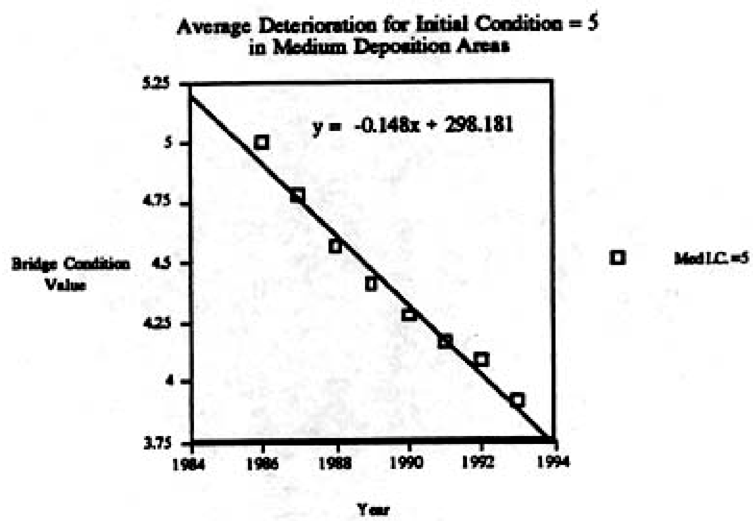


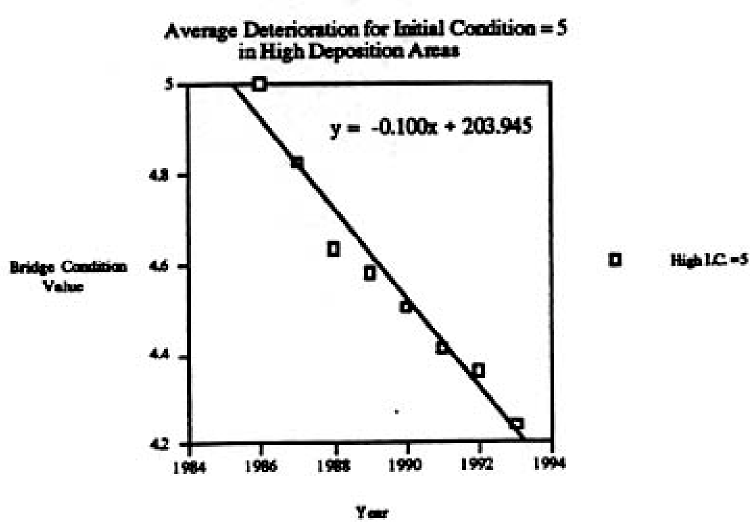




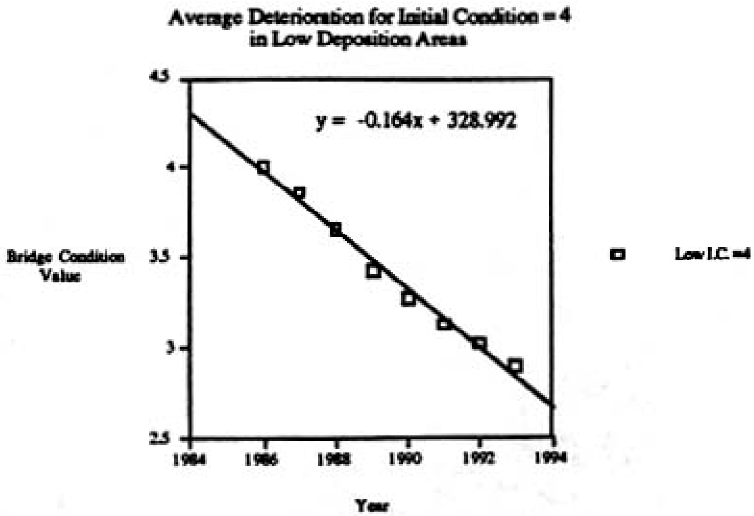
Average Deterioration for Bridges with an initial Condition in 1986 of 5

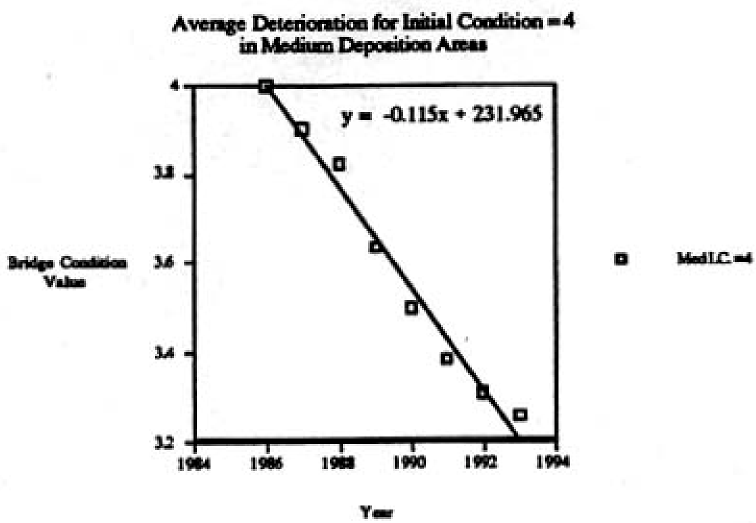


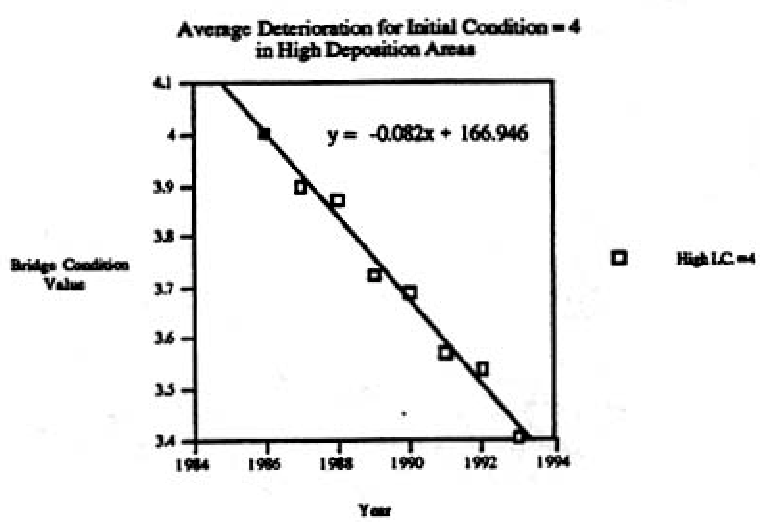




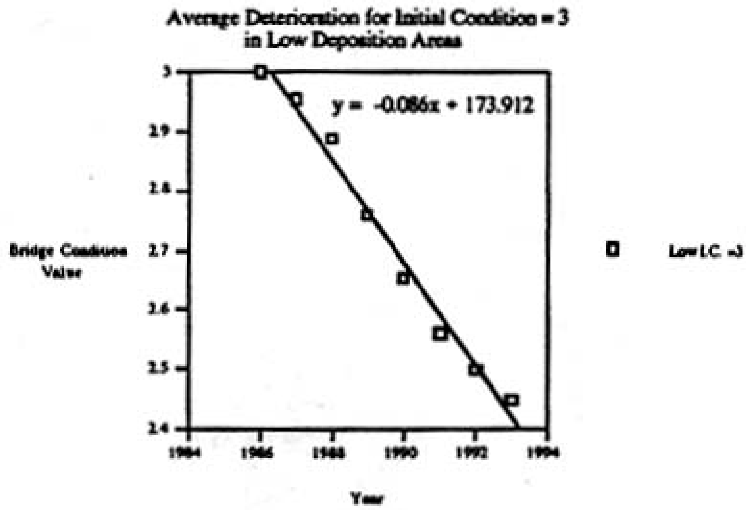
Average Deterioration for Bridges with an Initial Condition in 1986 of 4

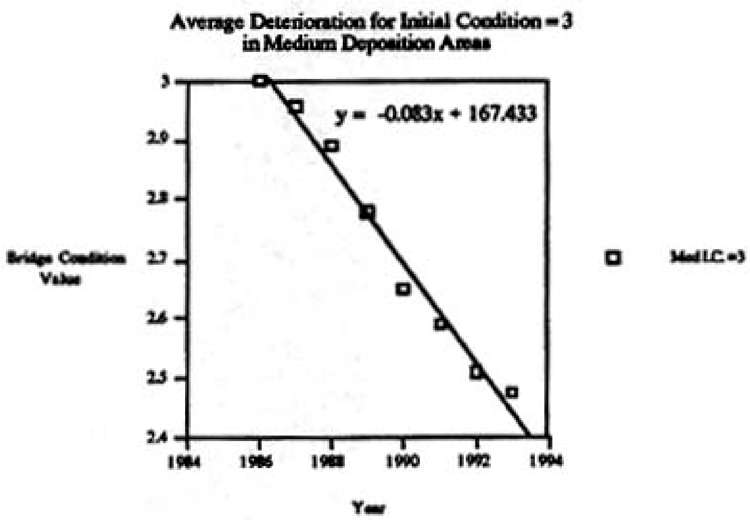


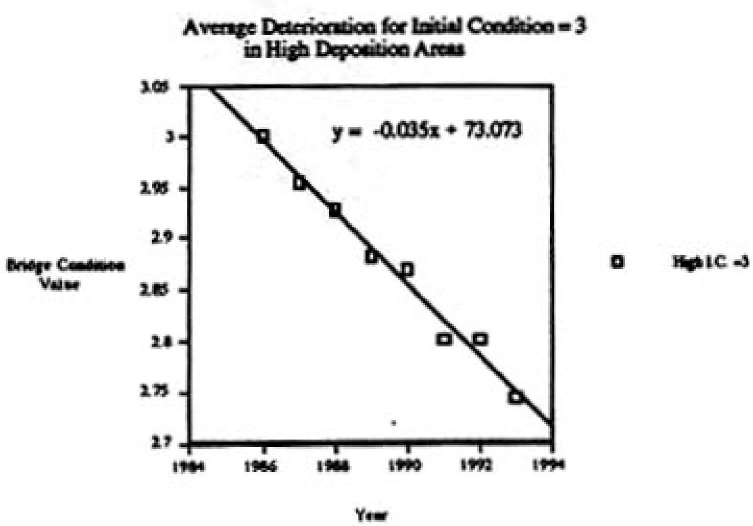




Average Deterioration for Bridges with an initial Condition in 1986 of 3







Average Deterioration for Bridges with an Initial Condition in 1986 of 2