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16. Abstract

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Deterioration models were developed for Interstate bridges in Virginia. Two sub-studies were conducted in response to VDOT interests. First, Markov Chain models were developed for condition states for the most common Pontis bridge elements on the Interstate bridges. Second, regression models for condition ratings were developed for these same elements. Two additional special studies were conducted by the Virginia Bridge Information Systems Laboratory. A special study at the National Scale was performed, examining 20 years of NBI data. This study summarized typical changes in bridge performance metrics by identifying a sample of bridges with temporally contiguous data for the period from 1992 to 2012. This study uncovered the significance of maintenance and repair actions on bridge performance. Another special study examined the characteristics of bridges which were taken out of service in this same 20 year period. Statistical summaries of service life data were developed.

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ABSTRACT

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INTRODUCTION

Summary of NBI

The National Bridge Inspection Standards (NBIS) were created in response to the 1967 failure of the Silver Bridge between West Virginia and Ohio that resulted in the death of 46 people. Implemented in the early 1970s by the Secretary of Transportation, the NBIS established the specifications for the inspection of bridges on public roads. Information from these inspections is stored in the National Bridge Inventory (NBI) database, created in 1972. FHWA uses the NBI to allocate funds to the states for bridge replacement, rehabilitation and maintenance (Small, Philbin, Fraher, & Romack, 1999).

History of Pontis

Pontis is a Bridge Management System (BMS) that has been adopted for use by 39 states / territories and 7 other agencies in the US, as well as seven countries internationally. It was created under FHWA sponsorship and is currently maintained through the American Association of State Highway and Transportation Officials (AASHTO)'s joint software development program. This program enables agencies to use and maintain a unified management system through pooled resources. Pontis has thus been cheaper (to each agency) to both implement and maintain, it also creates a de-facto industry standard of best practice to help standardize bridge management at the national level (Robert, Marshall, Shepard, & Aldayuz, 2003).

Unlike the NBI database, which stores all information in one massive file, Pontis is based upon a Relational Database Management System. This means that the information is stored in tables that are related by key fields, in order to more efficiently reference data in related tables. These tables store records in separate rows and data fields in separate columns. This system provides methods to efficiently enter, store, and generate reports from data (Chase, 2011).

Pontis was created in 1991 in response to the Intermodal Surface Transportation Efficiency Act (ISTEA) from Congress requiring each state Department of Transportation (DOT) to implement a more functional / detailed BMS. A previous system, the NBIS, provided overall condition ratings for each bridge at the deck, superstructure, substructure, channel, and culvert component levels. That was determined to be too subjective (based too heavily on the experience of the bridge inspector), with funding ultimately believed to be going to the wrong bridges (Gutkowski & Arenella, 1998).

In response to this, Pontis was developed and is a more descriptive BMS that looks at structures at the element level. These elements are well-defined subdivisions of bridge systems such as girders, joints, decks, and railings, each of which is further broken down by material type. Thus, each component of the NBIS (such as superstructure) is broken down into many more detailed elements. Being able to know which specific elements contribute most to the deteriorated state of a bridge allows more effective maintenance. Additionally, Pontis supports the entire bridge management life cycle, providing methods for inventorying, inspecting, performing needs assessment, strategy development, and project / program growth (AASHTO, Pontis User Manual, 2005).

The NBI database stores condition information on five aggregate structural units (deck, superstructure, substructure, channel, and culvert) by assigning a condition rating (abbreviated CR in tables / graphs) to each of these components of a bridge on a scale from 9 (perfect) to 1 (severe deterioration / failure). Pontis, on the other hand, assigns each defined element a condition state (abbreviated CS in tables / graphs) on a scale from 1 (perfect) to 3, 4, or 5 (severe deterioration / failure), depending on the element.

Another way Pontis provides more detail is that the elements can be assigned quantities. Inspectors using the NBIS would apply an average condition rating to each component of the bridge while those using Pontis break down the condition assessment into the units each element is assigned. For example, girders are assigned linear footage while elements such as bearings are assigned "each", thereby quantifying the total number of bearings on a given bridge. Pontis is thus a much more descriptive inspection tool enabling the determination of how much of a certain element of the bridge is in a truly deteriorated condition. Pontis also contains "smart flag" elements that track types of deterioration different from those listed in the structural element condition state definitions. Smart flags, such as scour and traffic impact damage, are used to record conditions on the bridge that "do not exhibit a logical pattern of deterioration" (VDOT, 2007). This project used data from both databases but focused on Pontis data because it was more detailed.

Pontis makes a distinction between repairs and improvements. The former comprises routine maintenance (girder painting, deck overlays, patching, etc.) whereas improvements aim to fix functional deficiencies such as vertical clearance, bridge width, or low strength or capacity. Maintenance is considered a dynamic and ongoing process, while improvement is dealt with as a one-time solution to a deficiency and is considered static (Golabi & Shepard, 1997). An "improvement" (decrease) in element condition state would likely be achieved by either of the above types of work. The associated improvement for a bridge in the NBI database would be a condition rating increase.

Pontis Element Definitions

The Virginia Pontis Element Data Collection Manual (VDOT, 207) defines 111 elements and associated condition states that can be tracked on bridges in the state of Virginia. One hundred of these are known as Commonly Recognized (CoRe) elements. These CoRe elements have standard definitions and facilitate uniform data collection and analysis nationally. The Pontis guidelines allow users to add their own additional elements to track the condition of further components states wish to evaluate, and the other eleven elements were uniquely defined by the Virginia DOT. These 111 elements define common bridge components in terms of component function and material, such as 'Steel Open Girder – Coated', 'Timber Bridge Railing' and 'Elastomeric Bearing'. Additionally, in Virginia, there are nineteen smart flags recorded, eight of which are CoRe and the remaining eleven are uniquely defined by the Virginia DOT (VDOT, 2007).

The National Bridge Inspection Standards set forth the requirements and the general guidelines for responsibility of inspection of state and federal bridges. These include the qualifications for different levels of inspection personnel, different types of inspections and suggested associated frequencies, general inspection procedures, and fields in common data collection tables (Chase, 2010). The specific procedures for inspection and reporting are outlined in the AASHTO Manual for Bridge Evaluation (AASHTO, 2011), the Bridge Inspector's Reference Manual (Ryan, Hartle, Mann, & Danovich, 2006), the Recording and Coding Guide (FHWA, 1995), and the AASHTO Maintenance Manual for Roadways and Bridges (AASHTO, 2007). These documents explain in detail the different bridge members, explain common defects, and define the associated condition ratings for the superstructure, substructure and deck. The Pontis Element Data Collection Manual defines the condition state guidelines for the Pontis element-level inspection reporting (VDOT, 2007).

PDI Output

Pontis Data Interchange (PDI) files are text files recognizable by Pontis either as imports from another program or as exports in the form of reports. The PDI files contain the data for all Tables in the database and formatting information such as Metric / English units, date format, left / right justification, and other rules that are either column-specific or table-wide. The columns and record used by Pontis to store bridge / inspection data can be converted into PDI files which can then be imported into Microsoft Excel or other programs as Comma Separated Values Files.

Five of the Pontis Tables were exported as PDI files and imported into Access for statistical analysis for this project. This was more efficient than performing this analysis on the dynamic production Pontis system. The five tables extracted were the Bridge Table, the Element Inspection (ElemInsp) Table, the Inspection Event (InspEvnt) Table, the Roadway Table and the User Bridge (UserBrdg) Table. The Bridge Table contains physical, administrative, and operation characteristics of structures. The ElemInsp Table contains the Pontis element-level inspection reports including quantity of each element in each condition state for a bridge per inspection cycle. The InspEvnt Table contains one entry per inspection, reporting specifics such as inspection type, inspector identification, and structure-level results. The Roadway Table contains information about all roadways on and under each structure, with fields such as route number, truck traffic, detour length, and number of lanes. The UserBrdg Table is defined by the agency and contains additional information about bridges; VDOT uses fields such as approach pier type, utilities present, year repainted, and drain dimensions (AASHTO, Pontis Technical Manual, 2005).

PURPOSE AND SCOPE

The Technical Advisory Group expressed interest in being able to forecast the future condition of bridges, with particular interest in forecasting those bridges which will become structurally deficient in the near future. As a first step toward this objective, statistical models of condition state were developed under this project for Element 107 (Steel Open Girder Coated). Both linear regression and Markov Chain models were investigated. The linear regression analysis produced graphs of condition state trends by age of bridge and district within the state. The Markov chain modeling produced transition probability matrices and associated deterioration prediction graphs. Both models were applied to element-level data at the state level

Data mining and modeling techniques were applied to develop deterioration models for Interstate bridges in Virginia. Three sub-studies were conducted in response to VDOT interests. First, Markov Chain models were developed for condition states for the most common Pontis bridge elements on the Interstate bridges. Second, regression models for condition ratings were developed for these same elements and third, different classification methods were investigated for these same bridges. Two additional special studies were conducted by the Virginia Bridge Information Systems Laboratory this past year. A special study at the National Scale was performed, examining 20 years of NBI data. This study summarized typical changes in bridge performance metrics by identifying a sample of bridges with temporally contiguous data for the period from 1992 to 2012. This study uncovered the significance of maintenance and repair actions on bridge performance. Another special study examined the characteristics of bridges which were taken out of service in this same 20 year period. Statistical summaries of service life data were developed.

METHODS

Three special studies were conducted by the Virginia Bridge Information Systems Laboratory in 2014. These studies analyzed legacy bridge data available from the Federal Highway Administration and Virginia Department Transportation. The studies utilized data base queries and statistical analysis and visualization tools to develop models and discover unknown information contained in the data. In particular, the raw date was imported into MS Access to enable complex queries of the data. The extracted data was analyzed with MS Excel and the R statistical software to develop models, summary statistics and statistical visualization of the data.

Predictive Modeling Overview

Two main types of modeling used for deterioration prediction are deterministic and stochastic. Deterministic models include regression analyses that model trends that follow data linearly or in a quadratic / cubic / higher power manner. The stochastic model is more probabilistic and attempts to account for more of the perceived randomness associated with deterioration of a bridge element such as the paint system (Zayed, Chang, & Fricker, 2002).

The most commonly used deterministic model is a linear least squares regression in which a line is fit to a set of data. The form of the solution is $y = f(x; \beta) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots$. This method does not always result in a straight line product; the “linear” merely refers to a one-to-one mapping between the known coefficients and unknown parameters (NIST/SEMATECH, 2012). The equation of the solution is calculated by minimizing the sum of the squared differences between the y values of the data set with the y values of the model.

A stochastic model that lends itself well to the categorical condition state descriptions associated with Pontis data is a Markov chain. In this type of model, the state of a system (such as a bridge element) is described as a vector of condition states. A probability is assigned to each possible (or permitted) transition of one condition state to another. For this project, this refers to changes from condition state 1 to 2, 2 to 3, etc. in a given time period (one year in this case). These transition probabilities can be determined based on averages from historical deterioration for each element or from expert judgment by experienced bridge engineers. The Markov chain model is characterized as being memoryless because the transition from one state to the next is based solely upon the current condition state and is not affected by prior condition states in time . The single table of deterioration probabilities created from historical averages therefore does not take into account the history of each specific element; it is limited to the average of the entire population and/or experts' experiences (Morcous, 2006).

Knowledge Discovery in Databases and Data Mining

As computational power has increased in the digital age, our ability to store vast quantities of data has also greatly increased. The flood of data that is generated by our advanced data collection methods can be difficult to make sense of, generating a need for advanced techniques for application of statistical techniques (Frawley, Piatesky-Shapiro, & Matheus, 1992). The field of Knowledge Discovery in Databases (KDD) aims to develop more efficient tools for exploring large volumes of data with the end goal being a more thorough understanding of the results. As Fayyad, Piatetsky-Shapiro, & Smyth stated in 1996, the value of data in storage is determined by "our ability to extract useful reports, spot interesting events and trends, support decisions and policy based on statistical analysis and inference, and exploit the data to achieve business, operational, or scientific goals" (Fayyad, Piatetsky-Shapiro, & Smyth, 1996, p. 27).

A distinction can be made between KDD and "data mining", where KDD is the entire procedure of drawing meaningful conclusions from patterns found in raw data while data mining is specifically the extraction of results from reduced data sets (Fayyad & Stolorz, 1997). Reducing the data to usable form, mining that information, and analyzing the types of results obtained are all necessary steps to the KDD process, often taken in an iterative manner. The application of these methods was explored in this project. Pre-defined report-generating processes often do not work well for new types of analysis as it may be difficult to know what results to expect, so new methods must often be developed over the course of the exploration.

The ultimate goal of KDD, as implied by its name, is an increased knowledge of the data. This is accomplished through identification of valid, useful, novel, and understandable patterns. Validity can be verified through certainty measures such as accuracy of predictions made. Usefulness can be quantified by a (predicted or actual) monetary gain or savings in time due to modifying a process. Novelty here means the results are new to the system being analyzed, if not also the user specifically, and is somewhat subjective. Understandability, to the researcher and the audience of the findings, is also rather subjective and can be partially represented by the simplicity of the results (Fayyad & Stolorz, 1997).

Effective investigation of data requires both the tools and the understanding to direct the analysis. The tools encompass different analytical techniques (as well as the computers themselves), while understanding the nature of the data and the expected results helps guide which types of studies to pursue. Exploratory data analysis is a useful detective method to determine trends on which to perform more judicial confirmatory data analysis. Providing summary statistics, such as averages and extrema, can be useful tools in dealing with large sets of data, but they necessarily reduce the full value of the details stored in each piece of data (Tukey, 1977).

In exploratory data analysis, the precise types of results to be created are often not known at the beginning of the exploration. Researchers must therefore "examine the data, in search of structures that may indicate deeper relationships between cases or variables" (Hand, Mannila, & Smyth, 2001, p. 53). These deeper relationships provide statistics to more easily infer significant conclusions and suggest meaningful recommendations. Visualization was frequently utilized; this method uses the pattern-finding ability of the human brain to detect trends when data is presented in certain ways, such as different types of graphs (Hand, Mannila, & Smyth, 2001).

Deterioration Models for Virginia's Interstate Bridges

Introduction

This special study was undertaken at the request of the Virginia DOT Technical Advisory Group (TAG). These models were desired to provide statistical support for a planned proposal for a new Interstate bridge maintenance initiative and the ability to better forecast deterioration for Virginia's interstate bridges was needed. The objectives of this special study were to provide technically sound and statistically valid models to predict the future deterioration of Virginia's Interstate bridges.

Modeling Methodology

Two different approaches were taken to develop these models. The first approach used the Pontis element level data and fit Markov Chain models to predict deterioration. The second approach used NBI data and fit logarithmic regression models to predict deterioration for these same bridges. The available data was reviewed and records with inconsistent quantities, too few bridges and unexplained condition improvement were excluded from the study. The bridges were then grouped into age bins. The sample provided bridges with ages ranging from 65 years to brand new. The sample of Interstate bridges extracted from the 2012 Virginia Pontis database is summarized in Table 1. All bridges had reinforced concrete decks.

Table 1 Most Common Interstate Bridge Elements in Virginia

Bridge Type	Element #	Number of Bridges
Painted Steel Superstructure	107	660
Prestressed Concrete Girders	109	222
Bare concrete decks with uncoated rebar	12	204
Concrete deck with thin overlay	18	231
Concrete deck with rigid overlay	22	309
Bare concrete deck with coated bars	26	227

Markov Chain Model

For the Markov Chain model, the proportion of bridges in each of the defined condition states for each element was determined for each age bin. This data was used to fit a Markov Chain deterioration model for each of the six elements identified. It is assumed that the proportion within each condition state will change as the element deteriorates. His change in proportion can be considered as a change in the probability that the condition state will take on one of the defined values. This transition can be modeled with a Markov Chain, where the probability of the condition state remaining unchanged and the probability of the condition state becoming lower (worsening) is assumed to remain constant for each transition (assumed to occur annually). Using this simple model, the condition state transition probabilities which resulted in the minimum squared error between a simulation and the observed data were determined with an Excel worksheet. The transition probability matrices for each of the six elements in the sample are presented in Tables 2 through 7 below.

Table 2 Transition Probabilities for Element 107

	CS1	CS2	CS3	CS4	CS5
CS1	0.9862	0.0138	0.0000	0.0000	0.0000
CS2	0.0000	0.9805	0.0195	0.0000	0.0000
CS3	0.0000	0.0000	0.9742	0.0258	0.0000
CS4	0.0000	0.0000	0.0000	0.9876	0.0124
CS5	0.0000	0.0000	0.0000	0.0000	1.0000

Table 3 Transition Probabilities for Element 109

	CS1	CS2	CS3	CS4
CS1	0.9986	0.0014	0.0000	0.0000
CS2	0.0000	0.9807	0.0193	0.0000
CS3	0.0000	0.0000	1.0000	0.0000
CS4	0.0000	0.0000	0.0000	0.0000

It should be noted that there are only four condition states defined for Element 109, which is why the matrix is only 4 x 4.

Table 4 Transition Probabilities for Element 12

	CS1	CS2	CS3	CS4	CS5
CS1	0.9667	0.0333	0.0000	0.0000	0.0000
CS2	0.0000	0.9903	0.0097	0.0000	0.0000
CS3	0.0000	0.0000	0.9618	0.0382	0.0000
CS4	0.0000	0.0000	0.0000	0.7748	0.2252
CS5	0.0000	0.0000	0.0000	0.0000	1.0000

Table 5 Transition Probabilities for Element 18

	CS1	CS2	CS3	CS4	CS5
CS1	0.9522	0.0478	0.0000	0.0000	0.0000
CS2	0.0000	0.9951	0.0049	0.0000	0.0000
CS3	0.0000	0.0000	0.9435	0.0565	0.0000
CS4	0.0000	0.0000	0.0000	0.9912	0.0088
CS5	0.0000	0.0000	0.0000	0.0000	1.0000

Table 6 Transition Probabilities for Element 22

	CS1	CS2	CS3	CS4	CS5
CS1	0.9684	0.0316	0.0000	0.0000	0.0000
CS2	0.0000	0.9947	0.0053	0.0000	0.0000
CS3	0.0000	0.0000	0.9725	0.0275	0.0000
CS4	0.0000	0.0000	0.0000	0.9684	0.0316
CS5	0.0000	0.0000	0.0000	0.0000	1.0000

Table 7 Transition probabilities for Element 26

	CS1	CS2	CS3	CS4	CS5
CS1	0.9803	0.0197	0.0000	0.0000	0.0000
CS2	0.0000	0.9905	0.0095	0.0000	0.0000
CS3	0.0000	0.0000	0.8668	0.1332	0.0000
CS4	0.0000	0.0000	0.0000	0.9999	0.0001
CS5	0.0000	0.0000	0.0000	0.0000	1.0000

These transition probability matrices were used to forecast the condition state distributions over a sixty year period. These are presented as Figures 1 through 6 below.

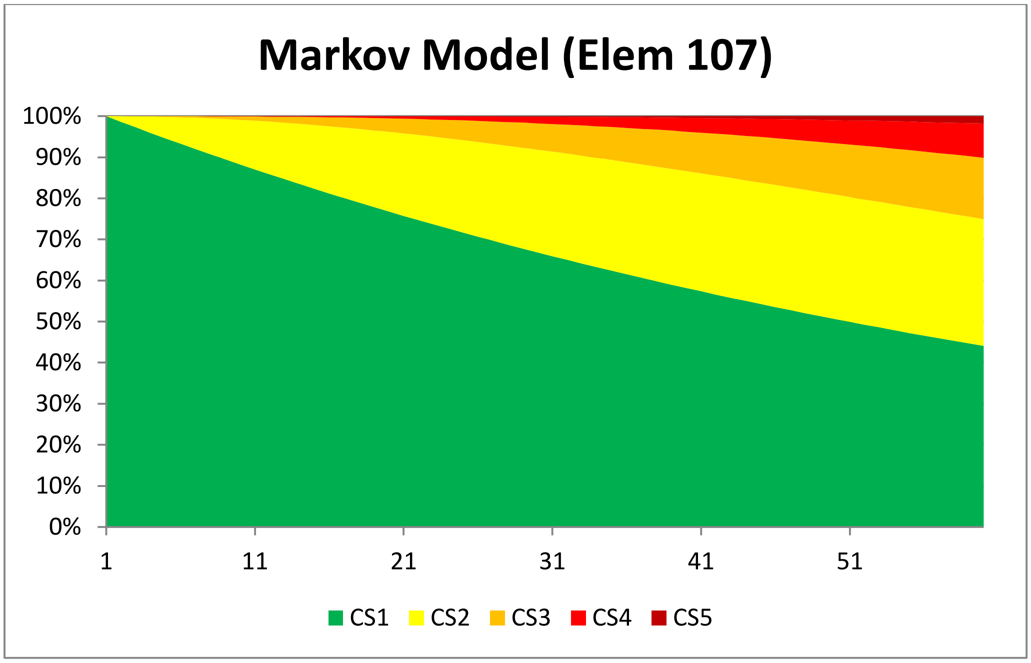

Figure 1 Markov Chain Forecast for Element 107

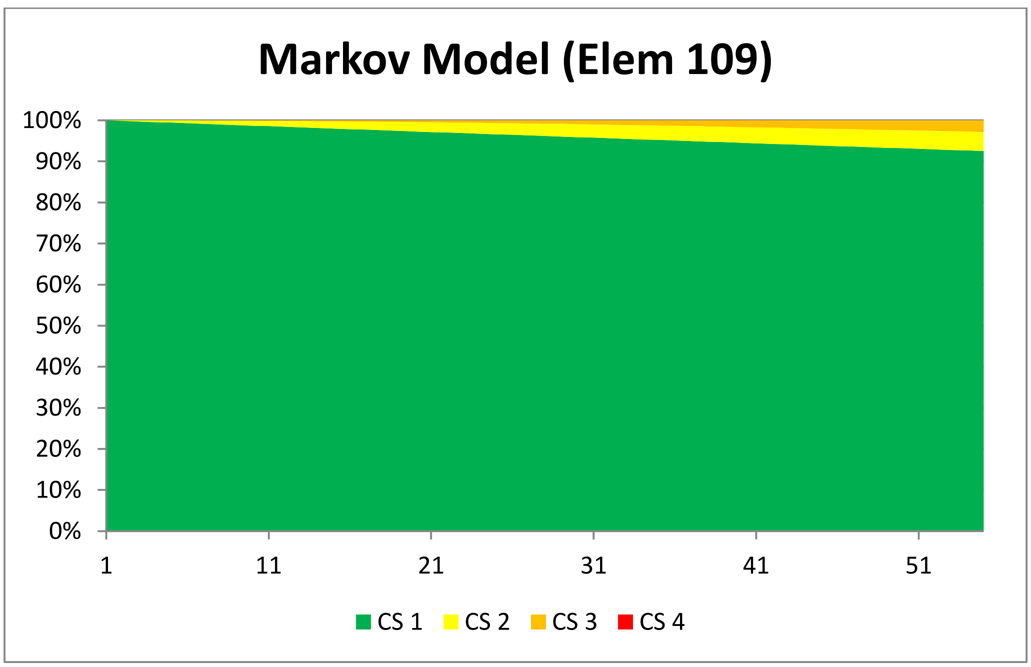

Figure 2 Markov Chain Forecast for Element 109

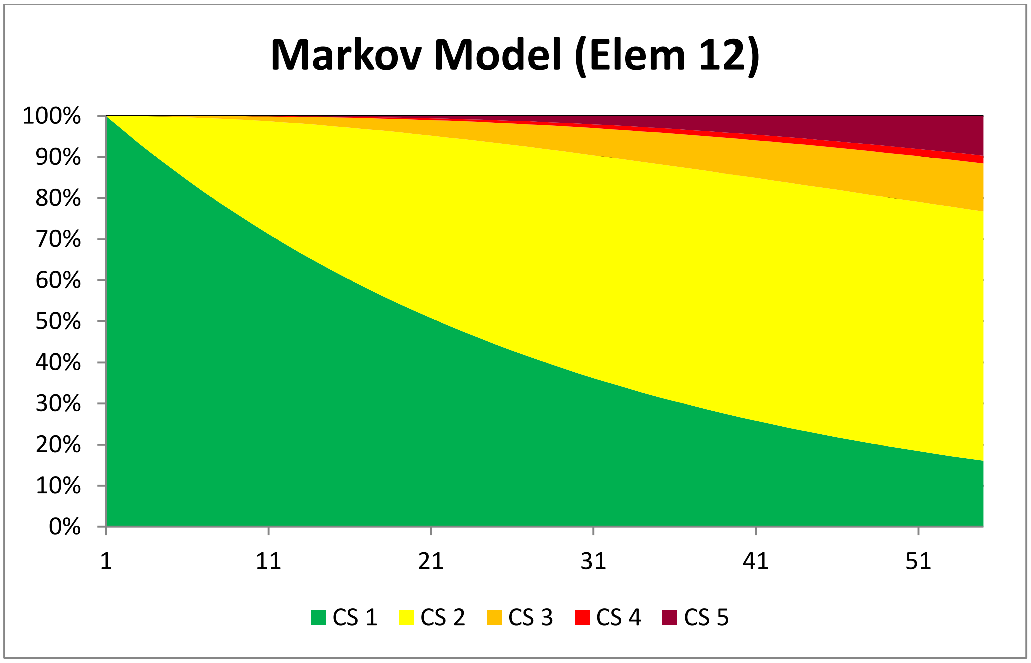

Figure 3 Markov Chain Forecast for Element 12

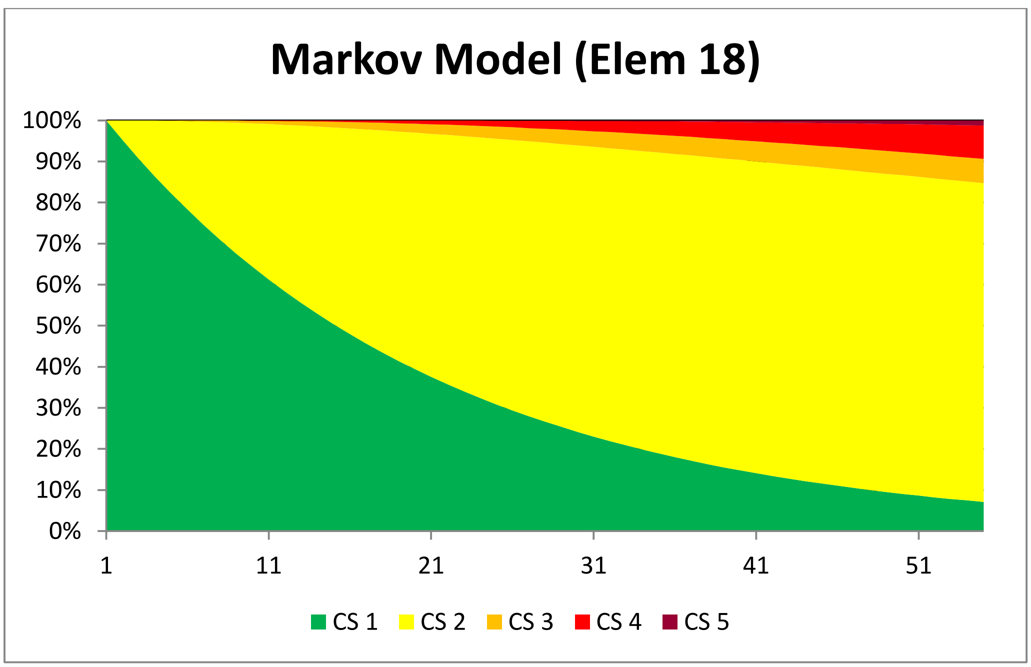

Figure 4 Markov Chain Forecast Element 18

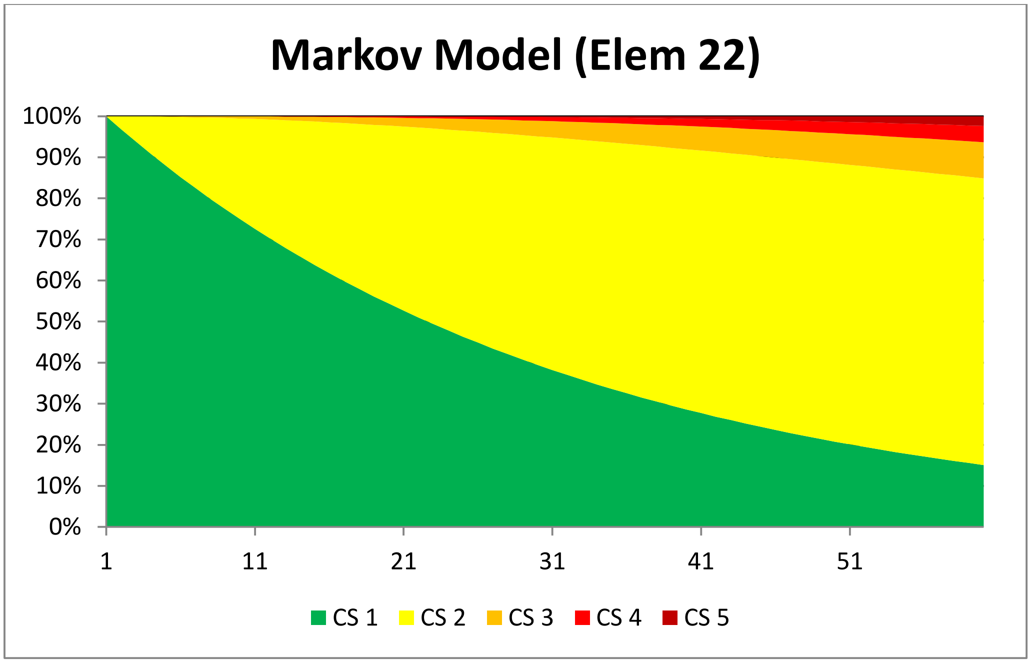

Figure 5 Markov Chain Forecast Element 22

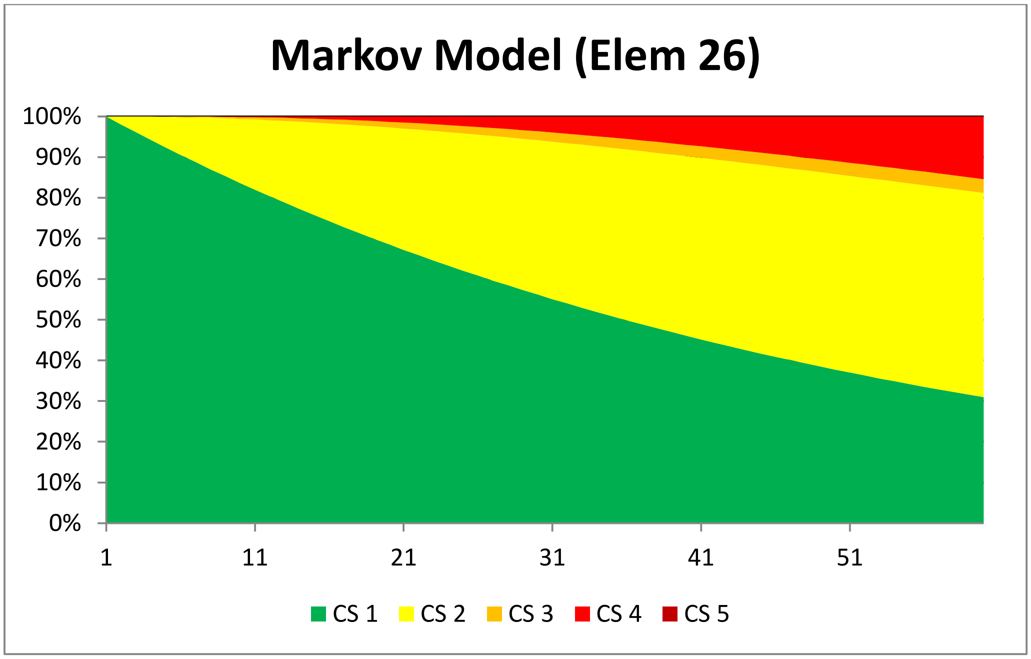

Figure 6 Markov Chain Forecast Element 26

The TAG reviewed the information presented above, and established thresholds which were considered suitable for defining when a particular element has reached the end of its service life. Different percentages for each of the different condition states were defined based upon the TAG's judgment and the condition state definitions. The thresholds and the number of years it would take for a particular element to reach a threshold value, based upon the Markov Chain models are presented in Figure 7.

Years to reach threshold values							
Condition State	Deck 12	Deck 18	Deck 22	Deck 26	PS Super (109)	Steel Super (107)	Threshold
1	23	15	23	36	> 65	51	50%
2	10	7	10	16	> 65	22	25%
3	31	40	45	40	> 65	33	10%
4	37	39	52	33	> 65	43	5%
5	21	42	38	> 65	N.A.	42	1%

Figure 7 Estimated Service Lives of Selected Elements

The TAG decided that a particular element would need to be replaced if 50 percent of the total quantity of an element was worse than condition state 1 or worse, or if 25 percent was in condition state 2 or worse, or if 10 percent was in condition state 3 or worse, or if 5 percent was in condition state 4 or worse or if 1 percent was in condition state 5. The threshold values are shown in Figure 7. A few of the corresponding values on the Markov Deterioration curves for Element 107 are shown in Figure 8 for clarification.

It was noted that the Element Condition States for Element 109, prestressed concrete girders, exhibited almost no deterioration. This was attributed to the manner in which the element level condition data is collected and recorded. The element condition state data is assigned to quantities which account for the total quantity of that element. For Element 109, it was assumed that the deterioration was usually localized and often did not represent a large proportion of the total quantity present on the bridge.

While, considered useful by the TAG, the Markov Chain models did not immediately provide an estimate of structural deficiency and also did not provide any indication of uncertainty and modeling error. Another set of models were developed, based upon regression to provide further assistance to the TAG.

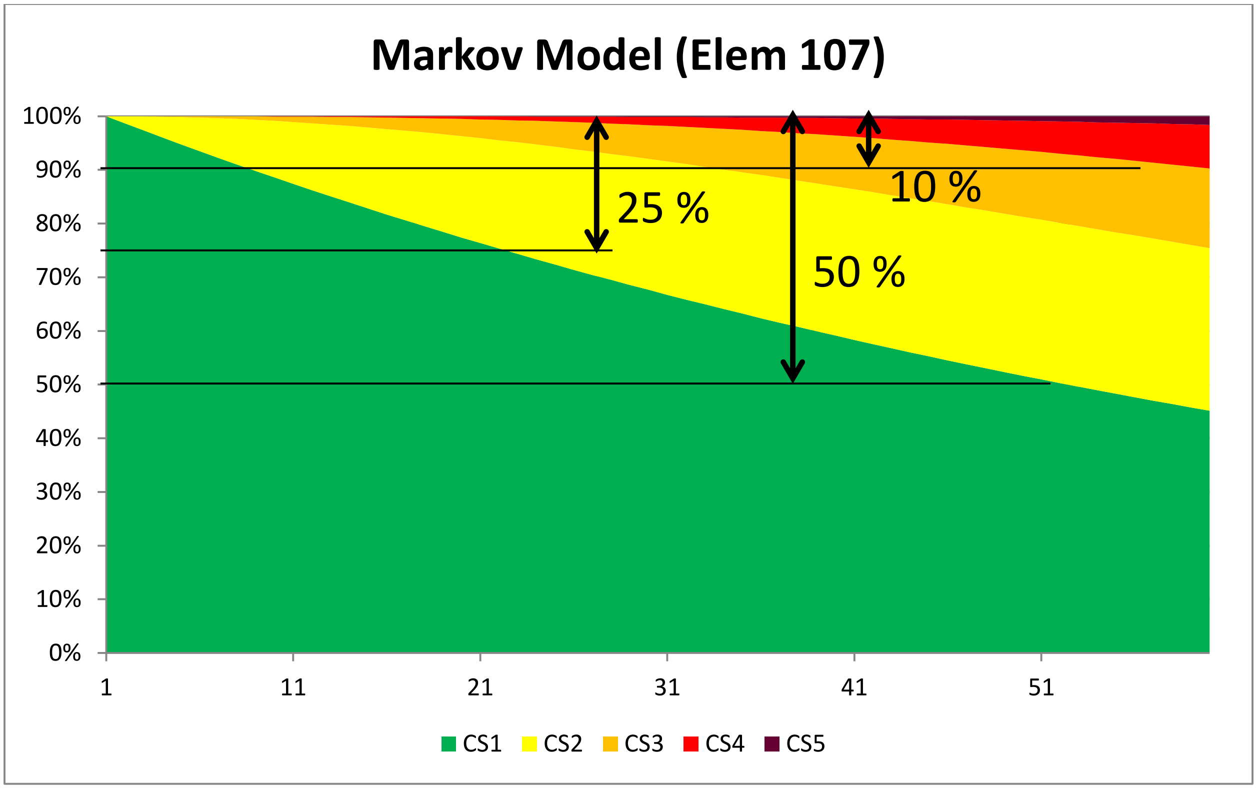

Figure 8 Clarification of Threshold Values

Regression Models

The second modeling methodology utilized was to fit a regression model to the NBI general condition ratings for superstructure and deck for the sample bridges. There was a desire by VDOT to be able to estimate the time it would take for a bridge to become structurally deficient. There was also a desire to obtain error bounds estimates as well.

For each group of bridges in the sample and using the same age bins as previously, the minimum, maximum and first, second and third quartiles of the NBI general condition rating for superstructure or deck were determined as appropriate. There were many age bins where the number of bridges was below 5 and consequently the quartile estimates were not reliable. The age bins with sufficient number of bridges were retained and a weighted linear least squares regression model was used to fit the median GCR to the log-transformed age. A similar procedure was used to define the curves for the first and third quartile estimates. The results for the six groups of bridges are presented in the figures below.

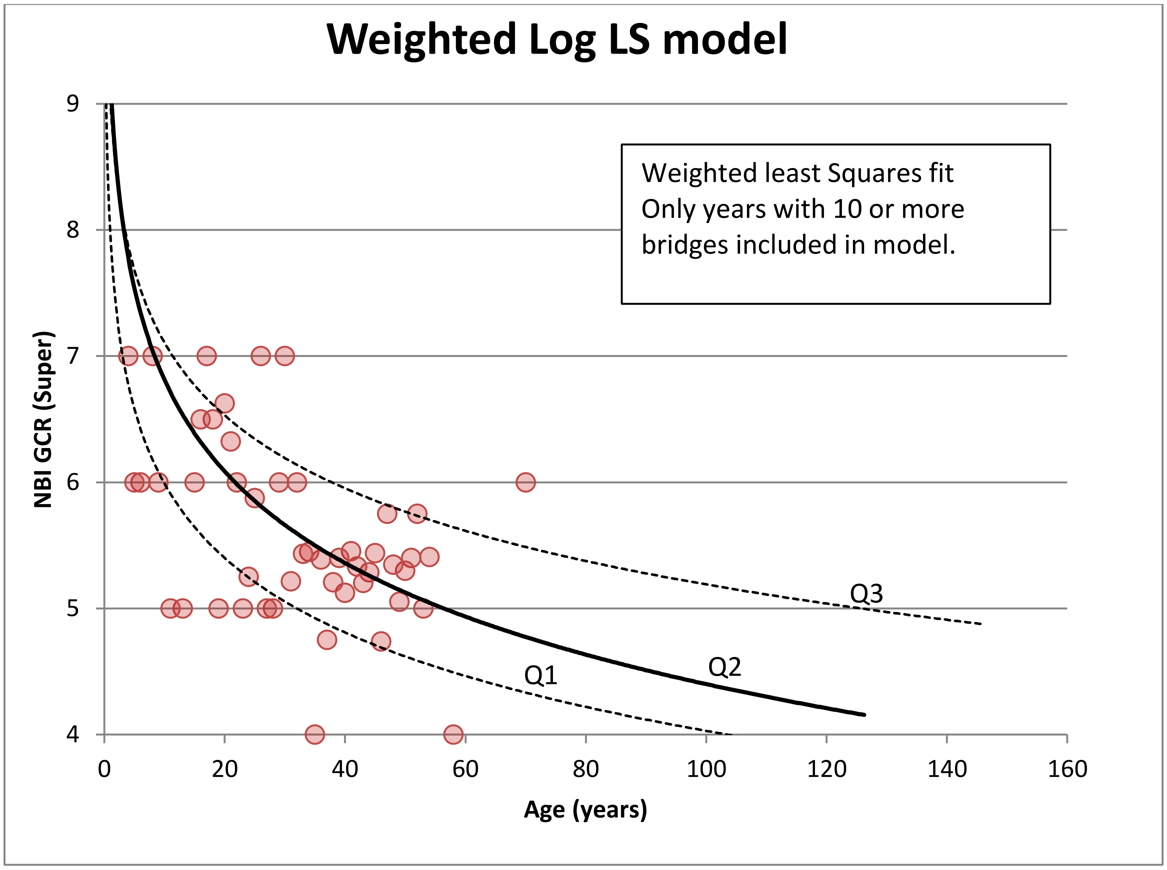

Figure 9 Superstructure GCR vs Age, Painted Steel Bridges

The observed data is plotted with transparent markers to indicate the spread and overlap of the data. Note that there were no painted steel bridges in the sample with superstructure condition ratings better than 7. Also note that the logarithmic transformation, which fit the data best, is attributed to the non-linear nature of the condition state categories.

The condition rating data for prestressed concrete bridges is presented in the next figure. Note that there were bridges with superstructure condition ratings of 8 and there were no bridges with superstructure condition ratings of 4. There is much greater spread and deterioration captured in the condition rating data than was present in the element condition state data.

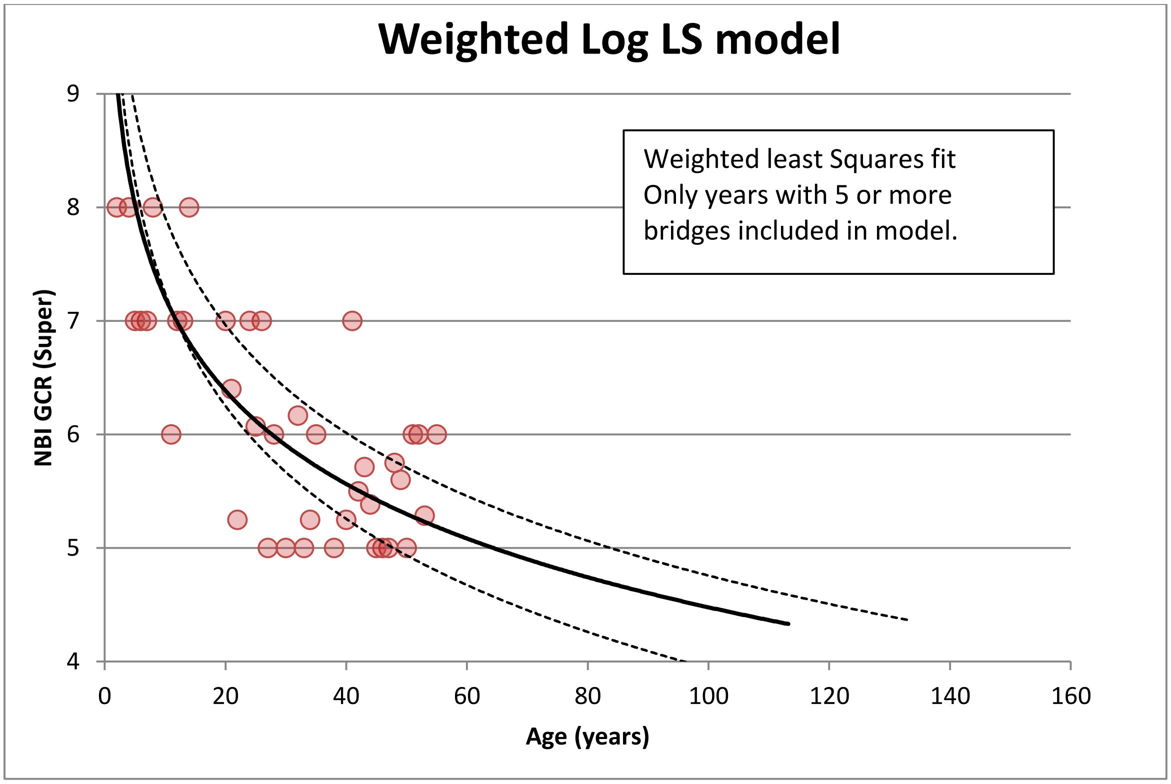

Figure 10 Superstructure GCR vs Age, Prestressed Concrete Girders

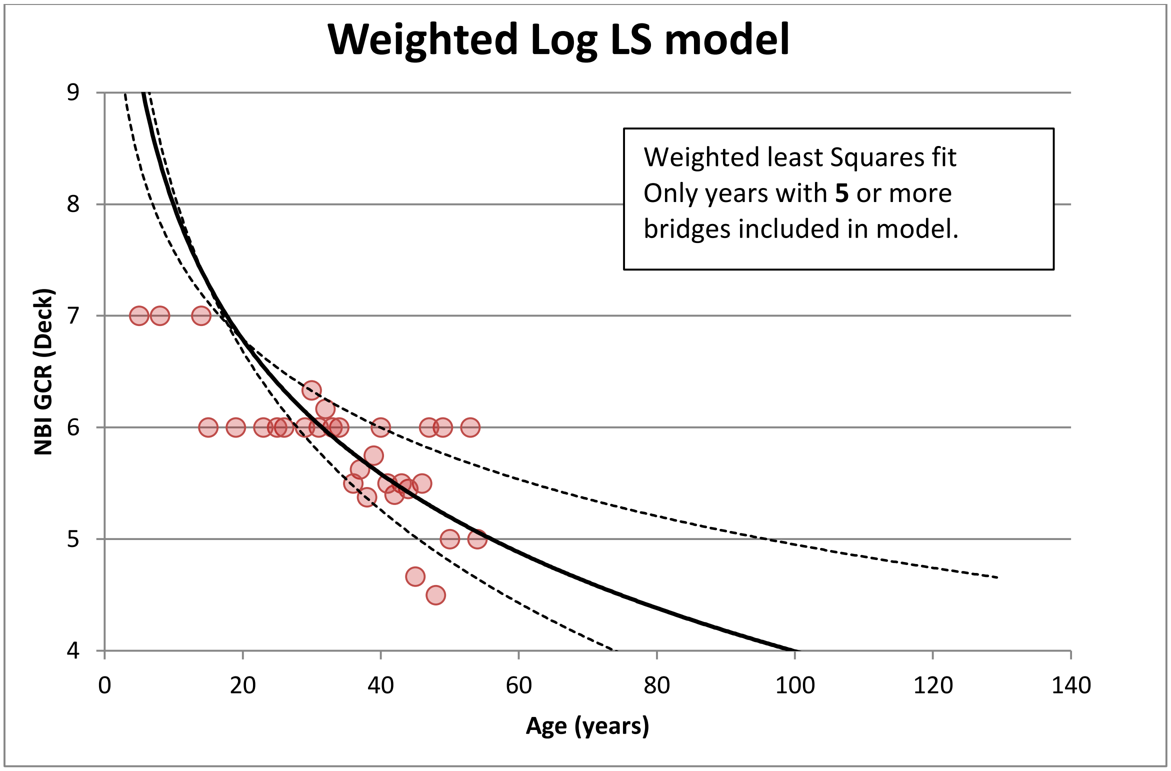

Figure 11 Deck GCR vs Age, Bare Concrete Decks Uncoated Bars

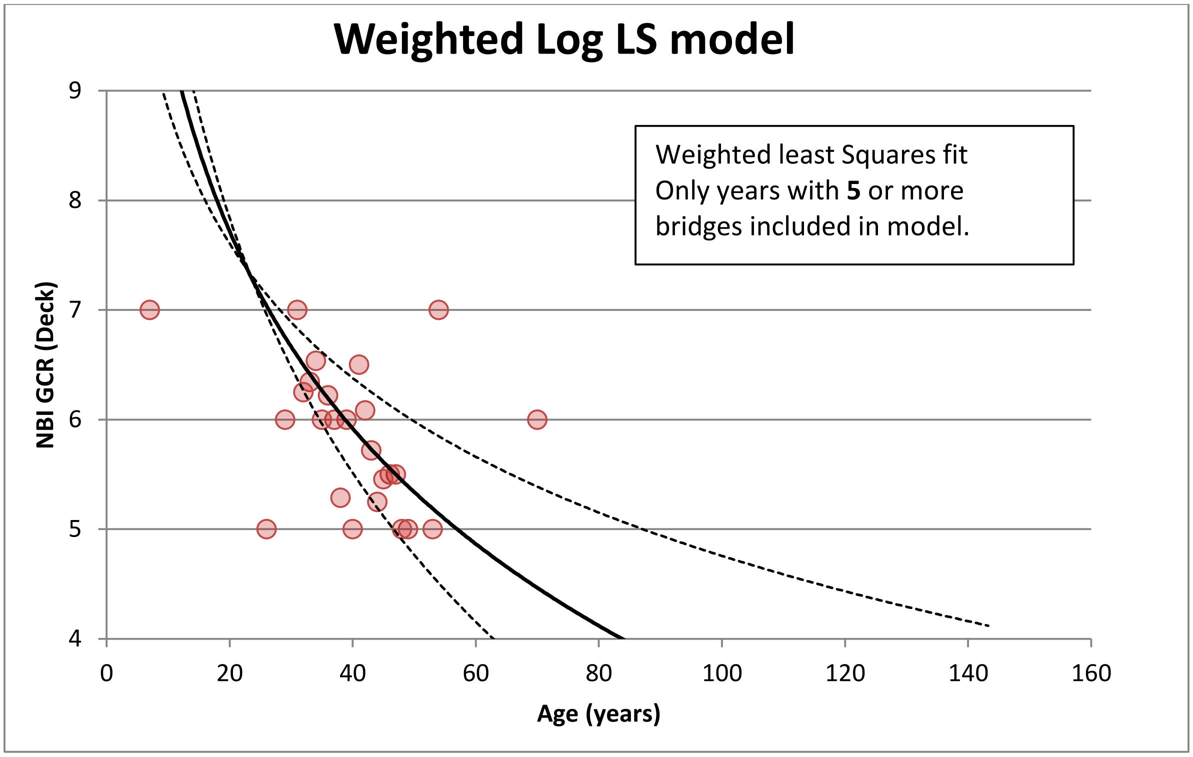

Figure 12 Deck GCR vs Age, Concrete deck with Thin Overlay

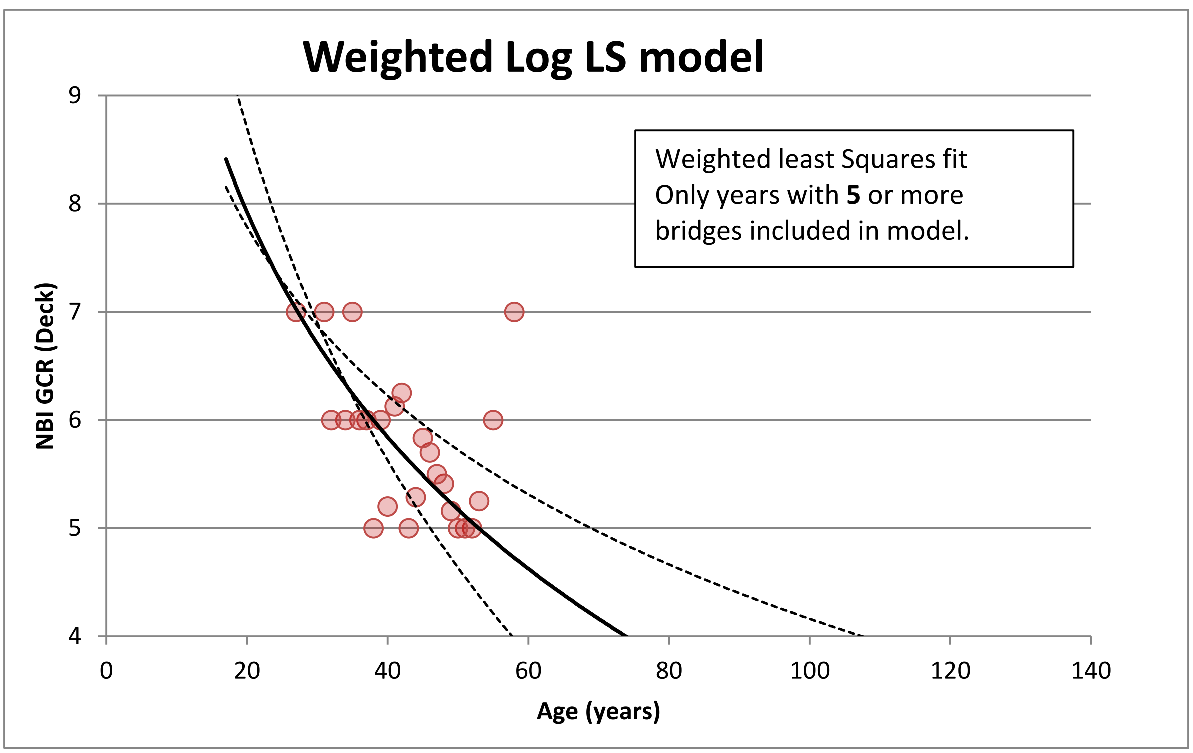

Figure 13 Deck GCR vs Age, Concrete deck with Rigid Overlay

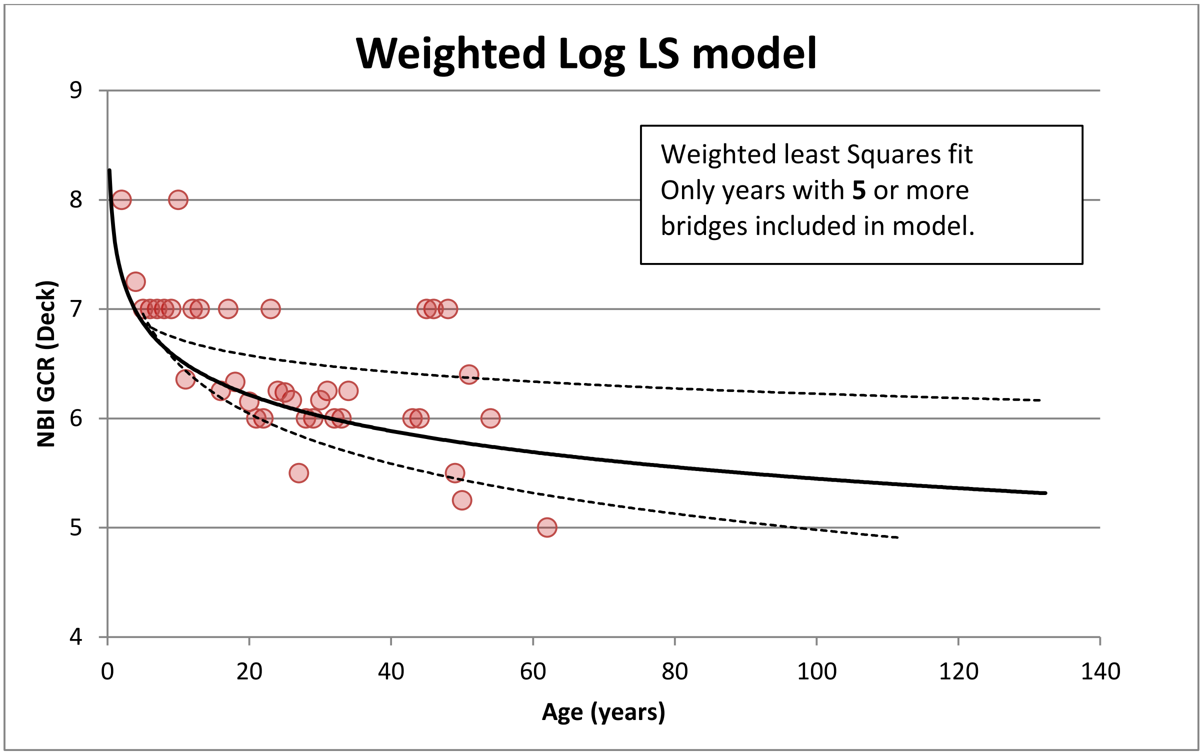

Figure 14 Deck GCR vs Age, Bare Concrete Deck with Coated bars

Based upon the regression models, an estimate of the time it would take for the GCR to become 4 can be estimated. These estimates are presented in Figure 15 below. The uncertainty can be estimated from the quartile bands provided above.

Time to Become Structurally Deficient						
Element	Deck 12	Deck 18	Deck 22	Deck 26	Super 107	Super 109
Years to SD	100	85	75	> 100	> 100	> 100

Figure 15 Time to Become Structurally Deficient

A Temporal Analysis of Twenty Yeats of NBI Data

Previous investigations of bridge performance have been limited to examination of the national bridge inventory database for a single year. While this is certainly useful, the current approach is different in that it identifies a sample of bridges which were present in both the 1992 NBI database and the 2012 NBI database. This provides the opportunity to examine how bridge performance metrics for a consistent sample of bridges has changed over a 20 year period.

Selection of a consistent sample

The first step in this analysis was to identify a sample of bridges which existed in the 1992 and the 2012 NBI inventories. This was accomplished by first importing the 1992 and 2012 NBI data into Access and then using a query to select the sample. The NBI data is provided for download from the FHWA Bridge Program website as a large flat ASCII file in fixed length format. A data import script was created to import these text files into an Access table with fields as defined in the FHWA Recording and Coding Guide. The 1992 and the 2012 data was imported into Access as separate tables. Next a query was performed to select only those bridges which exist in the 2012 Table and the 1992 Table (identical structure numbers exist in both tables) and which meet the additional criteria listed in Table 8. In addition the 1992 and 2012 deck area and ADT for each bridge was calculated for later comparison. The result was a list of 194,830 records.

Several states had fewer bridges than expected and it was determined that a systematic change in structure numbering took place between 1992 and 2012 in those states. The states where this occurred were Alabama, Kentucky, Minnesota, Michigan, Massachusetts, Missouri, North Carolina and Oklahoma. Although the National Bridge Inspection Standards require that the state provide FHWA with a translation table, mapping the new structure numbers to the old structure numbers when this occurs, these tables are not provided by the FHWA website. Given the number of states and the number of bridges involved, a different method was attempted to select sample of bridges for analysis. Rather than rely upon the unique structure numbers, it was assumed that other fields in the NBI record could be used to identify specific bridges which existed both in 1992 and 2012. These were the inventory route number; the feature intersected; the facility carried; and the location of the bridge. It was assumed that these fields would not change, even if the structure number changed. This was not successful because many states edited these fields in this 20 year period and it was decided to proceed with the original sample. It was assumed that the sample was diverse and large enough to be adequate for characterizing bridge performance over time.

Performance Metric Summaries

A group by query was then used on the resulting table to produce a summary of the number of bridges, the total deck area and the total ADT associated with each of the 11 possible ratings (0,1,2,3,4,5,6,7,8,9,N) for the 1992 and the 2012 tables. The results for each of the eight performance metrics for 1992 and 2012 are provided in Tables 9 thru 18 and Figures 16 thru 25.

Table 8 Record Selection Filters

Only “ON” records were included
1992 and 2012 Deck Condition Rating not blank
1992 and 2012 Superstructure Condition Rating not blank
1992 and 2012 Substructure Condition Rating not blank
1992 and 2012 Structural Evaluation Appraisal Rating not blank
1992 and 2012 Approach Alignment Appraisal Rating not blank
1992 and 2012 Deck Geometry Appraisal Rating not blank
1992 and 2012 Under clearance Appraisal Rating not blank
1992 and 2012 Waterway Appraisal Rating not blank
Deck Width > 0
Structure length > 0
ADT > 0
Culverts and Tunnels and Mixed Types were excluded
Bridges built after 1993 were excluded
Reconstructed bridges were excluded

The first performance metric presented and discussed is for bridge decks.

Table 9 Deck Performance Metrics

	1992 NBI			2012 NBI		
Deck_CR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	89	14,624	14,008	467	85,546	440,913
1	45	12,374	102,810	109	110,613	506,824
2	126	25,608	135,899	240	189,087	1,110,735
3	1,244	1,104,467	7,038,814	1,760	1,122,926	11,487,692
4	5,656	3,801,801	37,452,590	8,599	4,944,966	61,491,127
5	16,059	9,306,210	88,106,811	29,735	17,814,369	200,406,005
6	35,458	24,242,102	205,941,713	56,525	39,096,786	436,373,645
7	64,185	45,555,713	380,176,491	76,189	53,125,275	584,273,071
8	57,892	35,264,670	272,860,944	17,921	8,424,601	71,869,246
9	9,972	5,555,177	25,891,200	1,008	399,776	3,629,268
N	4,104	1,451,379	36,515,479	2,277	548,855	16,596,187

There was a gradual change in the overall performance of bridge decks for these bridges. The median deck condition rating (based upon deck area) changed from 6.5 to 6.0 in this 20 year period with a larger shift in number of bridges, the total deck area and the total ADT, from the higher (better) condition ratings to lower, but still not deficient, values. The proportion of deficient decks (based upon deck area) , Deck Condition Rating 4 or less, only increased from 4 percent in 1992 to 5 percent in 2012. It is noted that reconstructed bridges were excluded from the sample. The distribution based upon area is not very different from the distribution based upon the count of bridges. The distribution based upon ADT shows a somewhat more significant change in the proportion of the population in the lower condition ratings.

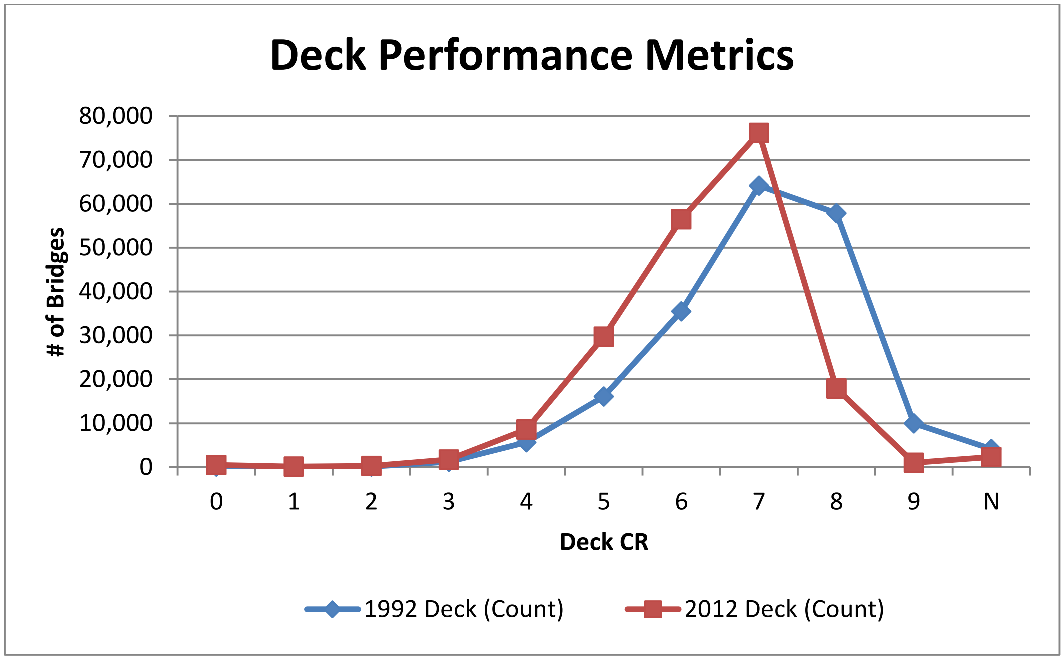

Figure 16 Deck Performance 1992 to 2012 (count)

Table 10 Superstructure Performance Metrics

	1992 NBI			2012 NBI		
Super_CR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	110	20,423	34,814	465	85,546	440,913
1	50	17,812	16,188	88	110,613	506,824
2	249	90,561	230,591	309	189,087	1,110,735
3	1668	995,475	3,887,014	1,832	1,122,926	11,487,692
4	5293	3,260,824	29,731,203	7,768	4,944,966	61,491,127
5	13805	7,509,349	70,492,699	26,003	17,814,369	200,406,005
6	30939	19,305,364	170,544,655	52,626	39,096,786	436,373,645
7	58113	37,995,226	337,606,700	76,683	53,125,275	584,273,071
8	72892	50,500,172	408,263,544	27,819	8,424,601	71,869,246
9	10769	6,322,038	29,929,963	1,161	399,776	3,629,268
N	942	316,882	3,499,388	76	548,855	16,596,187

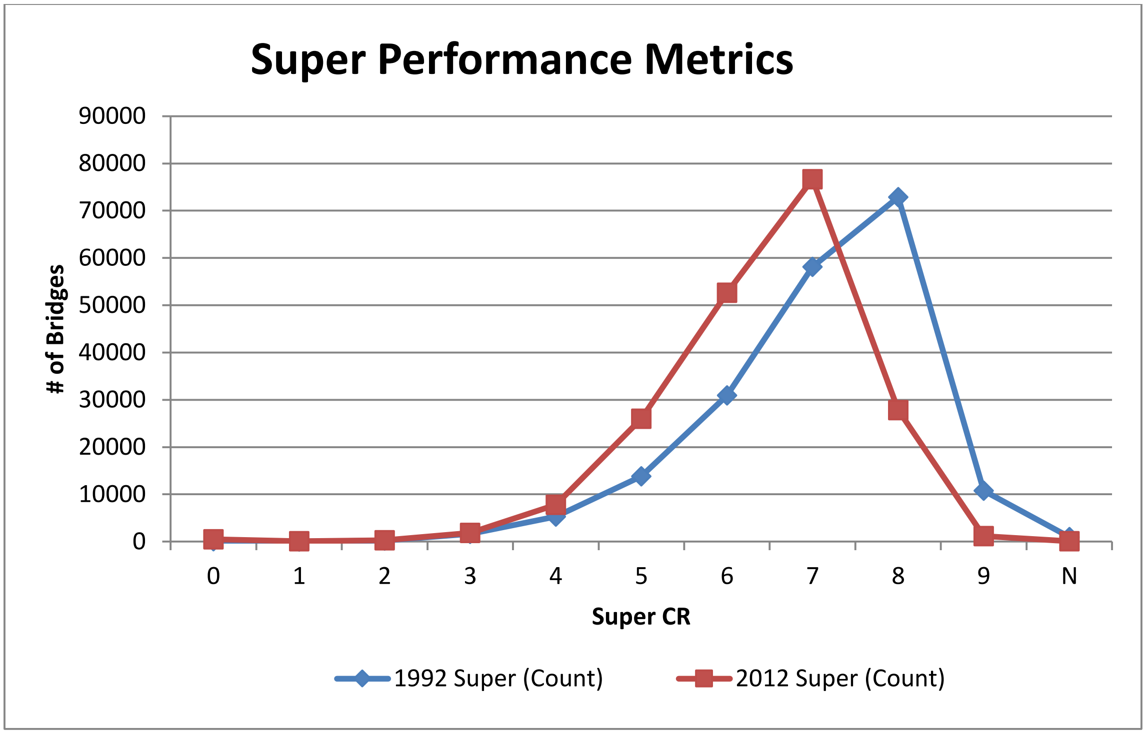

Figure 17 Superstructure Performance 1992 to 2012 (Count)

There was also a gradual change in the overall performance of superstructures for these bridges but the magnitude of the change was larger than that for the decks. The median superstructure condition rating changed from 6.8 to 6.0 in this 20 year period with a larger shift in number of bridges, the total deck area and the total ADT, from the higher (better) condition ratings to lower, but still not deficient, values. The proportion of deficient superstructures, Superstructure Condition Rating 4 or less, increased from 3 percent in 1992 to 5 percent in 2012. It is noted that reconstructed bridges were excluded from the sample. The distribution based upon area is not very different from the distribution based upon the count of bridges. The distribution based upon ADT shows a somewhat more significant change in the proportion of the population in the lower condition ratings.

Table 10 Substructure Performance Metrics

	1992 NBI			2012 NBI		
Sub_CR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	96	18,444	50,568	464	80,218	372,748
1	66	27,568	72,966	134	29,196	52,651
2	408	67,894	159,864	682	137,234	492,594
3	2300	1,006,465	4,349,551	2,991	1,148,930	2,790,364
4	7505	4,151,032	37,780,150	10,015	3,150,825	20,038,368
5	16238	7,826,454	79,656,819	27,485	14,099,818	134,994,277
6	33474	19,152,143	177,354,351	53,578	35,795,478	385,988,821
7	60700	43,745,490	361,300,060	78,089	60,577,841	753,003,517
8	63276	44,391,130	363,250,285	20,450	10,541,735	88,082,960
9	10055	5,801,534	26,741,437	879	287,365	2,121,653
N	712	145,970	3,520,708	63	14,161	246,760

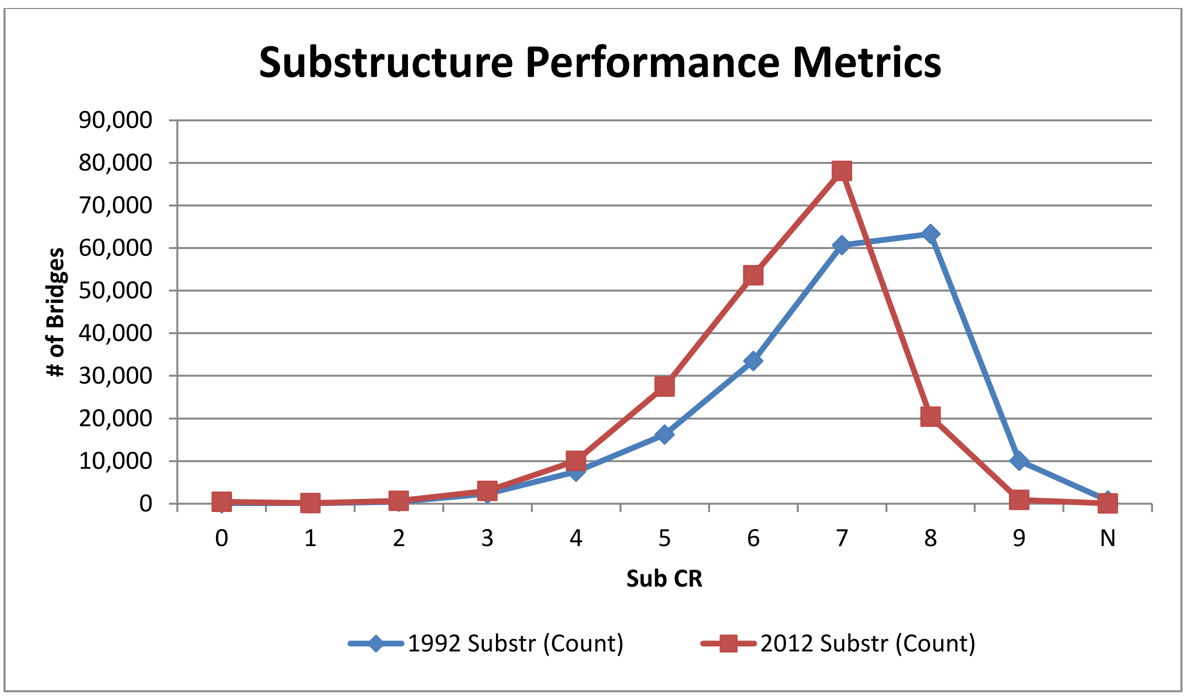

Figure 18 Substructure Performance Metrics (Count)

There was also a gradual change in the overall performance of substructures for these bridges. The median substructure condition rating changed from 6.7 to 6.1 in this 20 year period with a larger shift in number of bridges, the total deck area and the total ADT, from the higher (better) condition ratings to lower, but still not deficient, values. The proportion of deficient superstructures, Substructure Condition Rating 4 or less, remained constant at 4 percent.

Table 11 Structural Appraisal Performance Metrics

	1992 NBI			2012 NBI		
SE_AR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	384	96,737	253,341	1,627	406,871	1,143,601
2	9182	1,681,202	6,203,771	8,296	1,406,157	7,800,955
3	4635	2,187,106	15,430,064	5,215	2,434,261	12,241,645
4	22399	9,383,833	74,097,268	20,970	7,870,430	60,048,579
5	33220	16,238,963	143,891,132	39,944	24,275,207	242,236,393
6	45959	28,446,906	212,811,857	58,345	41,847,949	446,928,913
7	37877	34,740,407	309,245,403	49,931	42,248,423	571,217,763
8	39351	32,631,448	285,591,357	10,286	5,292,764	46,097,864
9	1822	927,523	6,712,176	216	80,739	469,000
N	1	0	390	0	0	0

Reconstructed bridges were excluded from the sample. The distribution based upon area is not very different from the distribution based upon the count of bridges. The distribution based upon ADT shows a somewhat more significant change in the proportion of the population in the lower condition ratings.

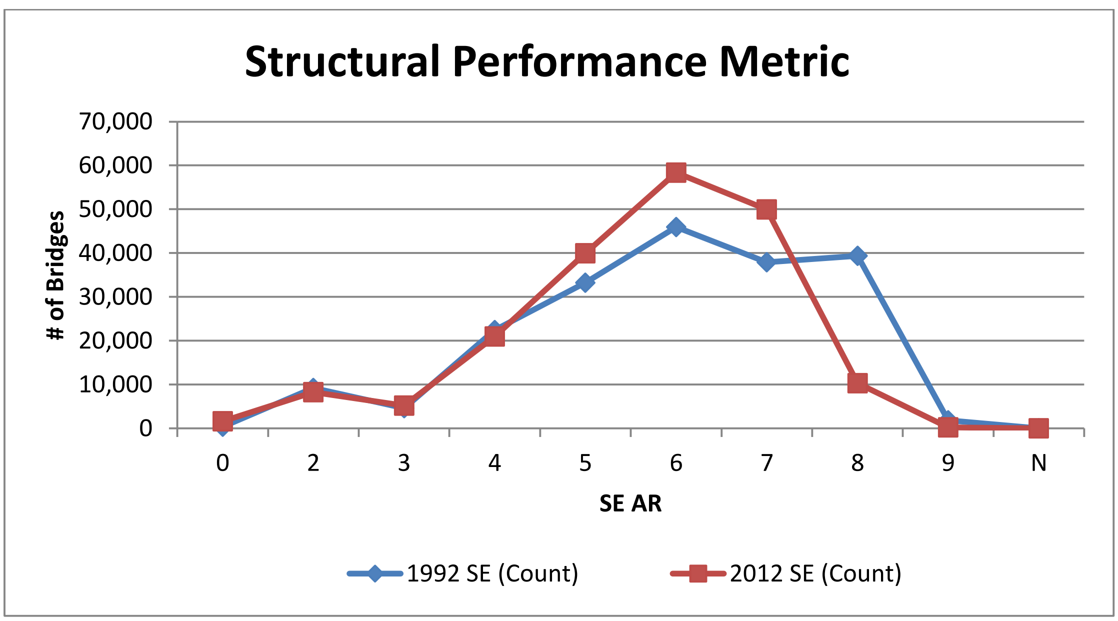

Figure 19 Structural Evaluation Metric

The distribution of the Structural Evaluation Appraisal Ratings, as is the case with several of the appraisal ratings, shows a different pattern than the condition ratings. They are generally lower and more broadly distributed. There was also a gradual reduction in the overall structural appraisal rating for these bridges. The median structural evaluation appraisal rating changed from 6.1 to 5.6 in this 20 year period with a larger shift in number of bridges, the total deck area and the total ADT, from the higher (better) condition ratings to lower, but still not deficient, values. The proportion of deficient structures (based upon deck area), Structural Appraisal Rating of 3 or less, remained constant at 3 percent. Reconstructed bridges were excluded from

Table 12Deck Geometry Performance Metrics

	1992 NBI			2012 NBI		
DG_AR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	88	140,811	289,918	259	105,660	692,405
2	14702	10,266,718	127,158,767	16,685	10,274,609	159,747,529
3	13852	5,412,237	45,130,120	14,639	6,812,971	66,674,965
4	35834	21,373,783	161,989,088	38,905	23,010,747	222,045,626
5	45042	20,993,742	125,229,551	45,883	22,841,392	180,073,501
6	43487	22,102,710	151,900,040	41,124	21,396,120	225,685,803
7	23619	18,720,141	123,694,911	21,049	17,826,648	175,214,947
8	4580	4,545,108	37,529,607	4,631	3,122,857	32,761,351
9	12435	22,270,473	276,147,499	11,211	20,408,409	324,770,792
N	1191	508,402	5,167,258	444	63,386	517,794

the sample. The distribution based upon area is not very different from the distribution based upon the count of bridges. The distribution based upon ADT shows a somewhat more significant change in the proportion of the population in the lower condition ratings.

The distribution of the Deck Geometry Appraisal Ratings is generally lower and more broadly distributed than the other NBI performance metrics. There was also almost no change in the overall deck geometry appraisal rating for these bridges. The median deck geometry appraisal rating changed from 5.2 to 5.0 in this 20 year period. There was no significant change in the total deck area distribution and a gradual shift the ADT , from the higher (better) appraisal ratings to lower, but still not deficient, values. The proportion of deficient structures (based upon deck area), Deck Geometry Appraisal Rating of 3 or less, changed from 13 percent to 14 percent. This is a significantly greater proportion of deficient bridges than for any of the condition metrics. Reconstructed bridges were excluded from the sample.

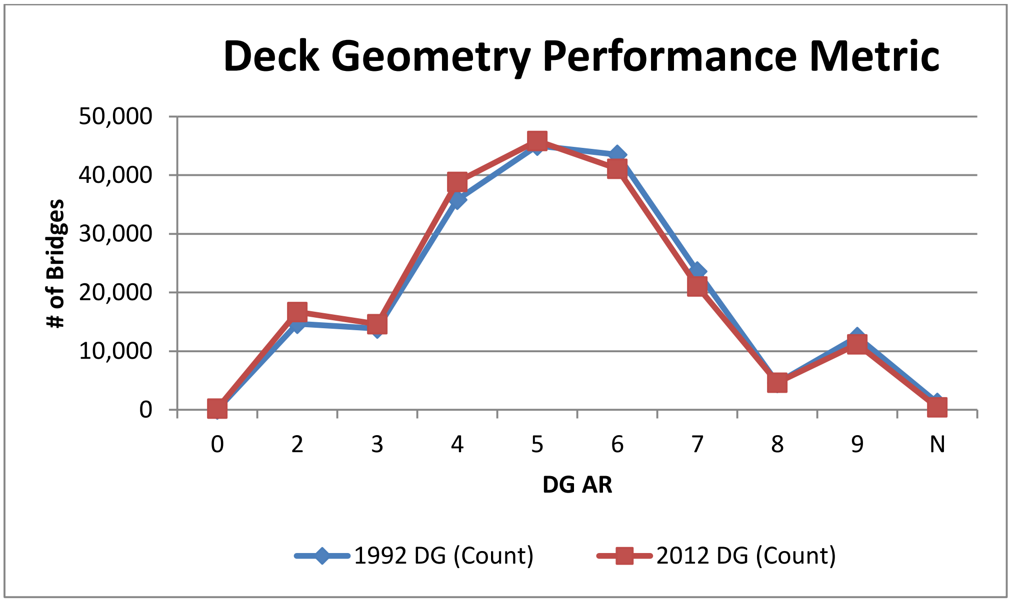

Figure 20 Deck Geometry Performance Metric (Count)

Table 13 Approach Alignment Performance Metrics

	1992 NBI			2012 NBI		
AA_AR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	71	41,293	47,843	198	44,868	358,447
2	876	137,246	753,910	357	58,848	373,995
3	3,971	1,038,294	5,837,770	3,065	715,763	3,954,145
4	9,865	2,754,828	19,149,485	6,571	1,763,889	16,208,629
5	11,955	3,687,743	21,383,475	8,805	2,725,614	17,568,849
6	34,535	16,430,435	113,417,213	31,756	12,526,598	86,636,106
7	28,755	14,439,026	108,890,793	27,305	13,566,853	114,666,076
8	98,587	81,784,447	698,840,957	112,698	90,485,094	1,066,955,602
9	6,025	5,909,806	84,124,815	4,075	3,975,274	81,462,864
N	190	111,005	1,790,498	444	63,386	517,794

The distribution based upon area shows a different than that based upon the count of bridges. The distribution based upon ADT shows a somewhat more significant change in the proportion of the population in the lower condition ratings.

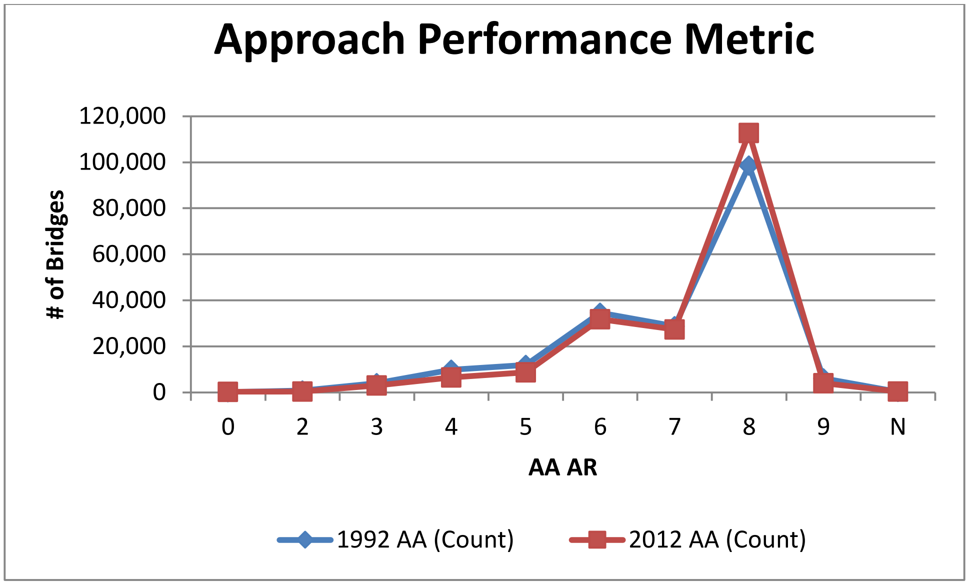

Figure 21 Approach Alignment Performance Metric (Count)

The distribution of the Approach Alignment Appraisal Ratings is quite different than the other NBI performance metrics. The distribution is very peaked at an appraisal rating of 8 and there was also almost no change in the overall approach alignment appraisal rating for these bridges. The median approach alignment appraisal rating remained constant at 7.3 in this 20 year period. There was no significant change in the total deck area distribution and only a gradual increase in the ADT distributed across all bridges. The proportion of deficient structures (based upon deck area), Approach Alignment Appraisal Rating of 3 or less, remained constant at 1 percent. Reconstructed bridges were excluded from the sample.

Table 14 Underclearance Performance Metrics

	1992 NBI			2012 NBI		
UC_AR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	22	123,637	242,953	55	161,540	1,005,055
2	805	1,676,366	12,219,609	1,243	1,919,092	24,784,797
3	9232	14,573,695	182,975,276	8,056	13,149,377	179,551,011
4	6066	8,399,047	123,765,274	8,890	12,903,002	225,517,266
5	6294	8,671,261	110,154,075	7,498	9,897,559	151,369,572
6	6921	9,735,350	122,099,595	7,631	11,061,481	171,053,681
7	4020	5,455,172	53,794,211	3,804	5,390,051	75,258,893
8	1118	1,651,919	14,841,730	800	1,239,259	16,894,048
9	4333	7,408,487	56,156,579	3,590	5,935,163	76,547,087
N	156019	68,639,191	377,987,457	153,263	64,206,276	466,203,303

The next two performance metrics are slightly different from the preceding metrics in that they do not apply to all of the bridges in the sample. As can be appreciated, vertical and lateral clearance appraisals are only meaningful if there is traffic under the bridge. Also, waterway appraisal is only meaningful if the bridge is over a waterway. The distribution presentations are adjusted to present the data accordingly

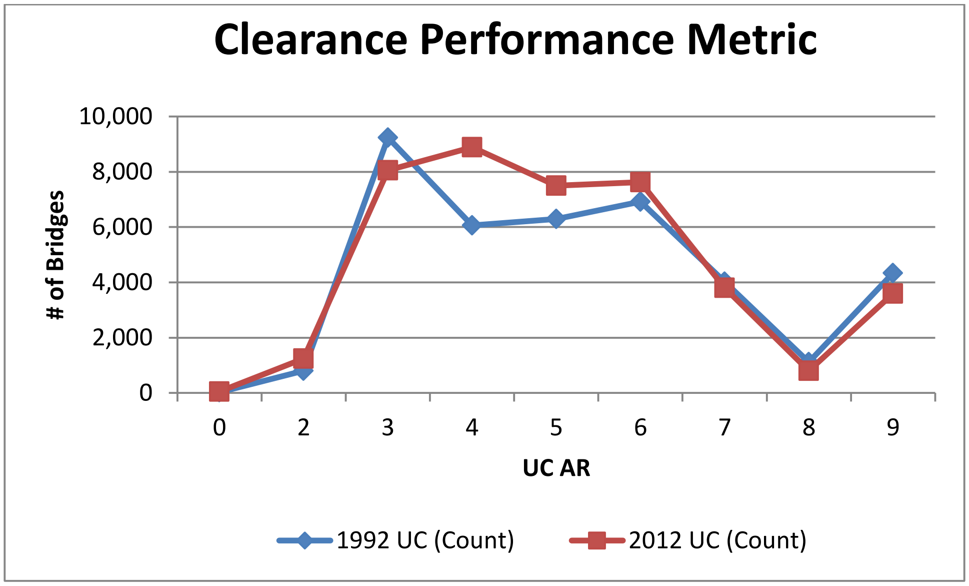

Figure 22 Underclearance Performance Metric (Count)

The distribution of the Underclearance Appraisal Ratings is generally lower and more broadly distributed than most of the other NBI performance metrics. There was a slight flattening of the distribution in the overall underclearance appraisal rating for these bridges. The median underclearance appraisal rating changed from 4.5 to 4.3 in this 20 year period. There was no significant change in the total deck area distribution and a gradual increase the ADT across the board. The proportion of deficient structures (based upon deck area), Underclearance Appraisal Rating of 3 or less, changed from 28 percent to 25 percent. This was the only performance metric which showed an improvement in the 20 year period. It is also noted that there is significantly greater proportion of deficient bridges for this metric than for any of the other performance metrics. Reconstructed bridges were excluded from the sample.

The distribution of the Waterway Appraisal Ratings is also different than most of the other NBI performance metrics. The distribution is very peaked at an appraisal rating of 8 and there was also almost no change in the overall approach alignment appraisal rating for these bridges. The median waterway appraisal rating remained constant at 7.4 in this 20 year period. There was no significant change in the total deck area distribution and only a gradual increase in the ADT distributed across all bridges. The proportion of deficient structures (based upon deck area), Waterway Appraisal Rating of 3 or less, remained constant at 1 percent. Reconstructed bridges were excluded from the sample.

Table 15 Waterway Appraisal Performance Metrics

	1992 NBI			2012 NBI		
WW_AR	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0	62	29,719	117,452	209	32,287	58,619
2	510	84,160	328,724	193	29,391	198,212
3	1799	267,172	1,105,780	1,168	164,442	1,140,958
4	6568	1,205,533	5,702,527	6,869	1,005,059	7,383,382
5	9662	2,319,368	13,596,126	9,480	2,215,366	15,383,167
6	28610	8,504,856	50,631,997	33,476	11,031,470	76,303,928
7	30037	10,393,648	50,876,684	35,006	10,665,433	65,035,317
8	62987	38,423,860	184,365,296	54,256	35,388,343	219,301,927
9	13396	13,716,291	59,764,191	13,106	15,492,535	105,258,930
N	41199	51,389,517	687,747,982	41,067	49,838,475	898,120,273

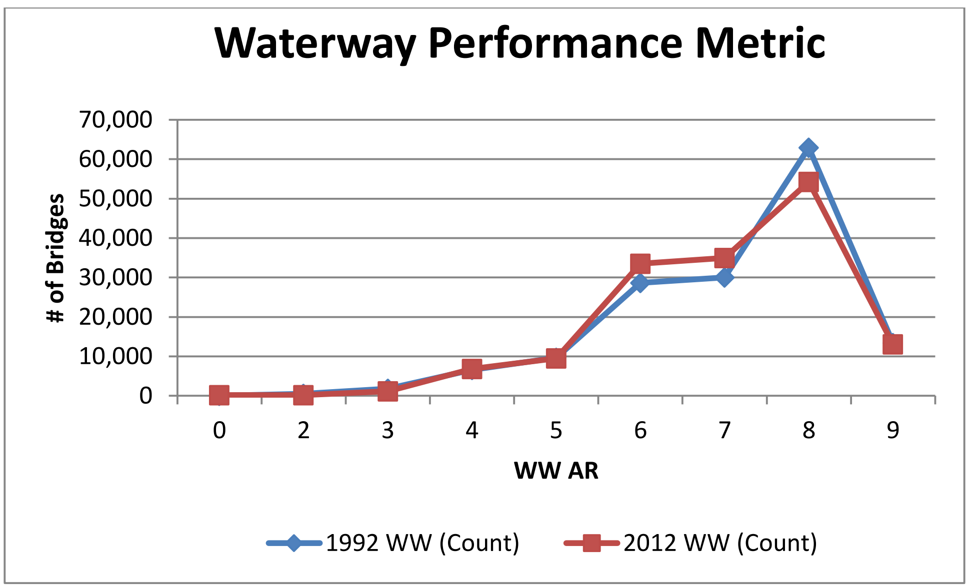

Figure 23 Waterway Appraisal Performance Metric (Count)

The last NBI performance metric analyzed is sufficiency rating. This metric is defined in the Recording and Coding Guide and is a number between 100 and 0. A value of 100 is reduced by four factors, each of which is based upon different combinations of data fields in the NBI record.

Table 16 Sufficiency Rating Definition

The sufficiency rating formula is a method of evaluating highway bridge data by calculating four separate factors to obtain a numeric value which is indicative of bridge sufficiency to remain in service. The result of this method is a percentage in which 100 percent would represent an entirely sufficient bridge and zero percent would represent an entirely insufficient or deficient bridge.

The sixteen different NBI data fields contribute to the final sufficiency rating as shown in Figure 24. Frequency distributions of sufficiency rating for these bridges in this sample for 1992 and 2012 are presented in Table 18 and Figure 25. There is a very slight shift in the distributions when based upon count of bridge associated with each of the 11 bins. The overall increase in ADT between 1992 and 2012 is captured in the ADT distribution but there is no significant shift noted. The median sufficiency rating changed slightly from 82.7 to 80.0 in this 20 year period. There was no significant change in the total deck area distribution and only a gradual increase in the ADT distributed across all bridges.

Table 18 Sufficiency Rating Metrics

	1992 NBI			2012 NBI		
SR_Bin	# of Bridges	Deck Area (m^2)	∑ ADT	# of Bridges	Deck Area (m^2)	∑ ADT
0: 9	500	463,088	2,647,113	592	476,615	3,011,237
10: 19	1,446	520,049	3,783,090	1,767	777,093	3,654,442
20: 29	4,275	1,436,793	7,519,608	5,233	1,200,026	5,847,274
30: 39	5,080	1,803,577	14,776,232	7,196	2,049,168	11,958,991
40: 49	9,269	3,957,773	27,720,500	10,601	4,205,655	29,702,699
50: 59	12,095	5,295,013	46,749,531	12,671	6,552,670	56,101,720
60: 69	19,578	9,825,266	90,935,795	20,050	12,133,612	129,755,670
70: 79	29,569	19,502,606	161,419,298	30,509	21,306,171	244,752,814
80: 89	37,107	26,337,778	297,042,304	38,008	28,324,048	425,115,062
90: 99	65,438	51,468,609	386,015,128	61,321	45,840,426	466,783,095
100:100	10,440	5,688,890	15,490,587	6,849	2,961,092	11,142,165

Overall, he change in performance metrics for these bridges over a 20 year period was gradual at most. The changes for the NBI condition ratings were more pronounced than those for the appraisal metrics. The Structural Evaluation Appraisal Metric is changed more than the other appraisal metrics but the Structural Evaluation Appraisal is actually a composite. The SE appraisal is the lower of the Superstructure Condition Rating. The Substructure Condition Rating and a rating based upon the inventory rating of the bridge. In order to examine the change in the inventory rating (load rating) of bridges over this 20 year period, another analysis was performed on the Inventory Rating of these bridges.

A comparison of the distribution of inventory ratings for the years 1992 and 2012 for these bridges is shown in Figure 26. Surprisingly, the overall distribution of these inventory ratings shifted from lower to higher values, with a shift in the number of bridges with inventory ratings from values lower than 3 to values higher than 33 metric tons

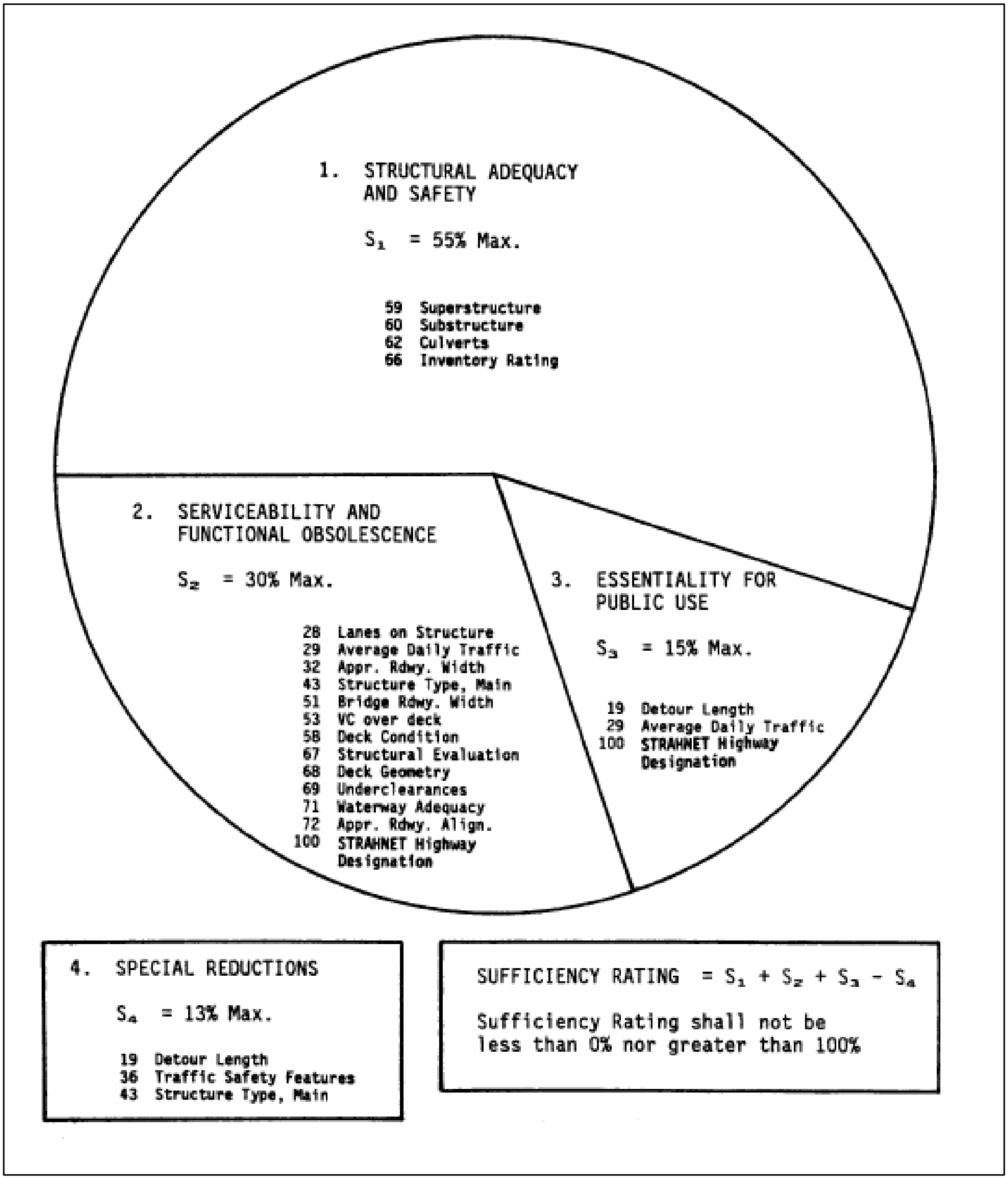

Figure 24 Items Contributing to Sufficiency Rating (from FHWA Recording and Coding Guide)

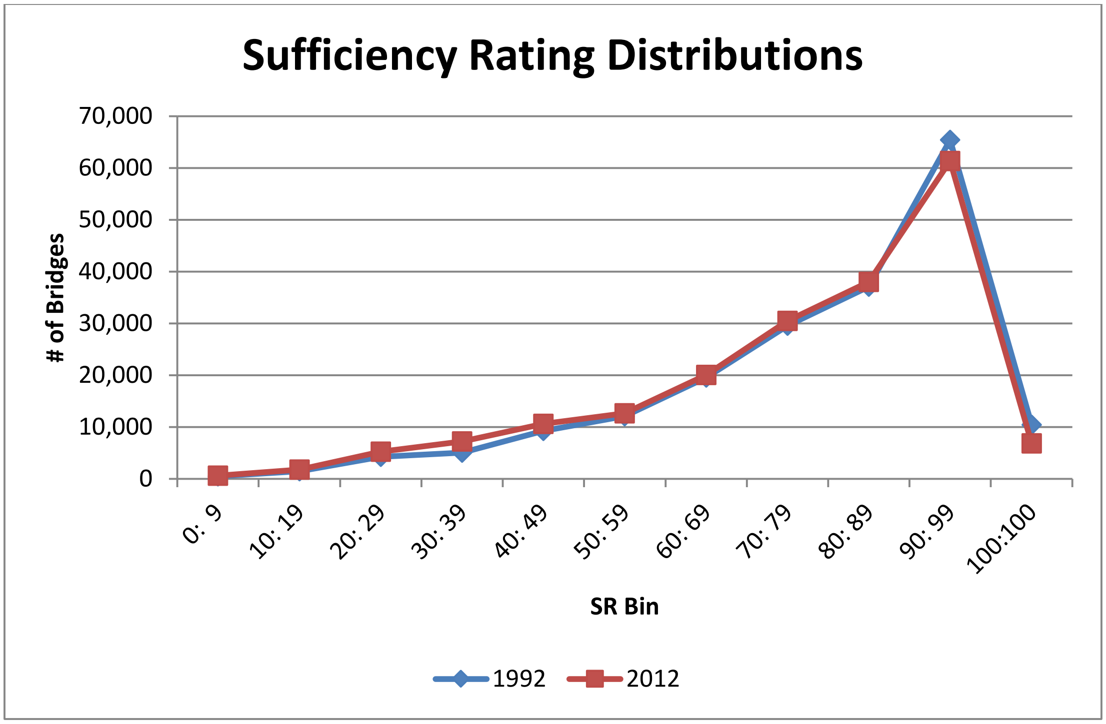

Figure 25 Sufficiency Rating Metric (Count)

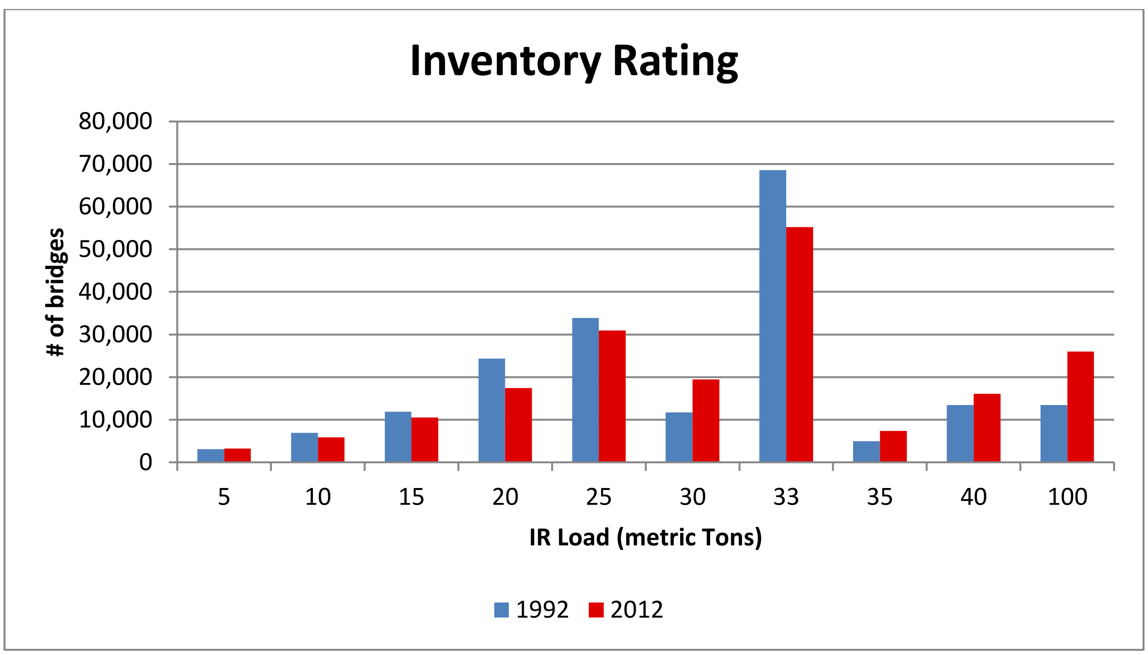

Figure 26 Inventory Rating Distribution

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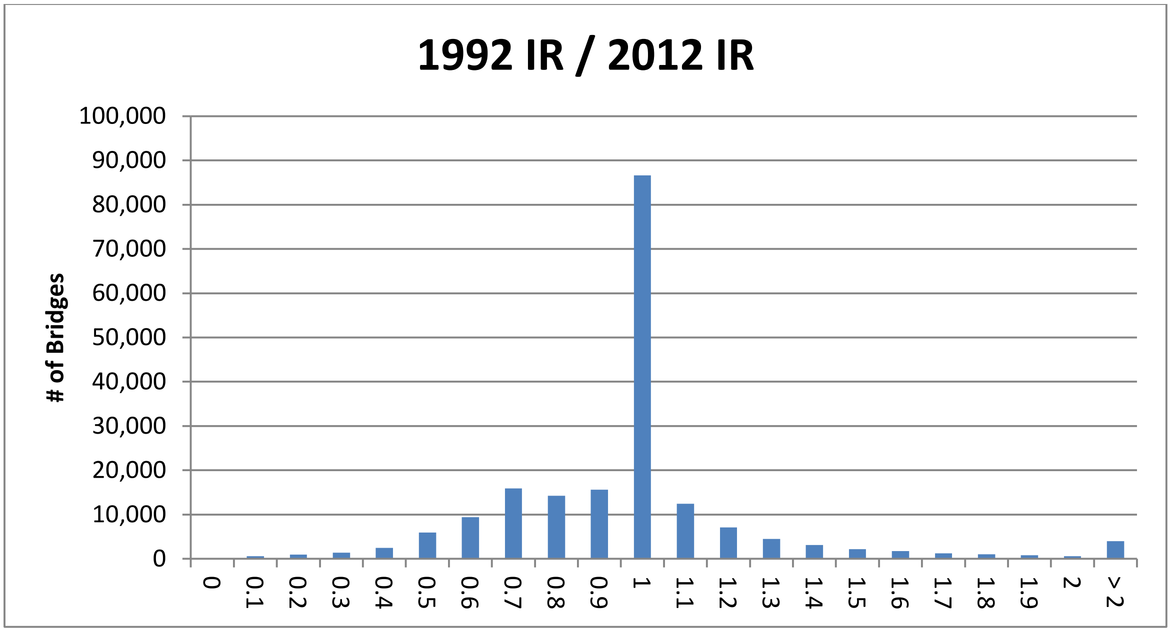

Figure 27 1992 IR 2012 Ratio Distribution

This counterintuitive result was examined in more detail. The ratio of the inventory rating in 1992 and the inventory rating in 2012 was computed for each bridge and the results are summarized in Figure 27. For the majority of bridges, the inventory rating did not change more than +/- 10 percent. However, the inventory rating ratio was less than1 for many bridges. A ratio of less than 1 means that the inventory rating increased in 2012 relative to the 1992 inventory rating. This is unexplained but it is noted that the data field for Item 65, the method used to calculate the inventory rating, was blank for all of the 1992 records and was populated for most of the 2012 records. This suggests that the load ratings were revised at some time in the 20 year period between 1992 and 2012 and it is possible that the more recent load rating resulted in a higher inventory rating than that which was recorded in 1992. This is also likely if the method used to calculate the newer load rating was the load factor or load and resistance factor method. It is likely that the earlier load rating would have been based on the allowable stress method.

Analysis of Condition State Transition Data

The condition state distributions for 194,830 bridges for 1992 and 2012 were presented earlier in this report. The change in condition over this 20 year period was less than expected. The data was examined in more detail with some surprising results. The number of bridges in each of the condition state bins 0 thru 9 and N in 1992 were determined for the Deck, Superstructure and Substructure elements. This resulted in 11 categories for each element. Then, the condition state distributions for these bridges in 2012 were determined. The results are presented in Tables 19, 20 and 21.

Table 17 Deck Condition Rating Transitions (count)

	2012 CR										
1992 CR	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**N**
0	0	0	0	1	0	3	1	2	2	0	0
1	0	0	0	1	2	2	3	7	0	0	0
2	0	0	6	6	7	17	22	21	12	0	0
3	6	1	13	158	169	207	225	240	85	15	3
4	4	6	21	223	1243	1564	1090	884	271	49	24
5	9	12	38	298	1652	5613	4136	3018	617	67	65
6	22	12	37	379	2172	7719	14837	8277	1077	116	149
7	13	16	58	373	2088	8388	20960	29045	2174	73	338
8	2	6	14	150	782	4586	12667	28896	9986	146	385
9	0	0	1	4	53	503	1225	4274	3341	499	43
N	0	0	5	13	124	520	806	1095	254	30	1230

Table 20 Superstructure Condition Rating Transitions (count)

	2012 CR										
1992 CR	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**N**
0	0	0	0	1	0	1	4	4	3	2	0
1	0	0	0	0	1	1	0	3	3	0	0
2	1	0	10	19	32	31	26	22	35	0	0
3	3	1	20	233	258	306	243	210	133	18	0
4	10	3	32	264	1299	1570	974	586	231	31	3
5	4	3	34	337	1689	5060	3514	2156	478	53	8
6	11	0	54	339	1896	7184	13013	6499	1208	85	8
7	10	1	39	236	1381	7067	18922	27186	2618	73	10
8	12	0	11	134	796	3906	14219	35307	18003	220	18
9	0	0	0	9	24	198	946	4024	4889	658	0
N	0	0	2	22	55	127	248	354	107	6	6

Table 18 Substructure Condition Rating Transitions (count)

	2012 CR										
1992 CR	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**N**
0	0	0	0	0	2	2	2	8	1	0	0
1	1	1	4	3	7	2	1	0	0	2	1
2	2	1	14	25	53	63	42	35	29	2	0
3	5	2	32	286	390	514	364	295	148	17	1
4	10	3	82	421	1767	2161	1512	841	247	31	9
5	7	1	81	501	2136	5652	4456	2381	459	26	6
6	14	2	97	623	2450	7638	14152	6966	873	37	7
7	11	3	101	529	1882	7248	19480	29464	1525	36	10
8	7	2	30	199	789	3473	12141	33581	12735	120	1
9	0	0	3	7	48	214	921	4015	4229	596	0
N	0	0	1	21	50	95	178	248	96	4	7

It was noted that there was significant improvement in 2012 for most of the bridges which were coded as having condition ratings of 4 or less in 1992. This was somewhat surprising, given that bridges which were coded as having had significant rehabilitation or reconstruction were excluded from the sample. The conclusion was that these improvements were the result of maintenance, repair, rehabilitation or reconstruction which were considered as not eligible for Federal funding and therefore did not meet the criteria for coding Item 106 as reconstructed. This significant level of improvement for many thousands of bridges skewed the condition rating distributions for 2012 for the better. In order to obtain a better understanding of bridge deterioration without improvement, another sample of bridges was identified which consisted of bridges which existed in the 1992 inventory and the 2012 inventory but which did not show improvement in condition ratings between 1992 and 2012. This resulted in a new, smaller, sample of approximately 160,000 bridges.

The condition rating distributions for 1992 and 2012 are presented for the Deck, Superstructure and Substructure elements for these bridges in Figures 28, 29 and 30.

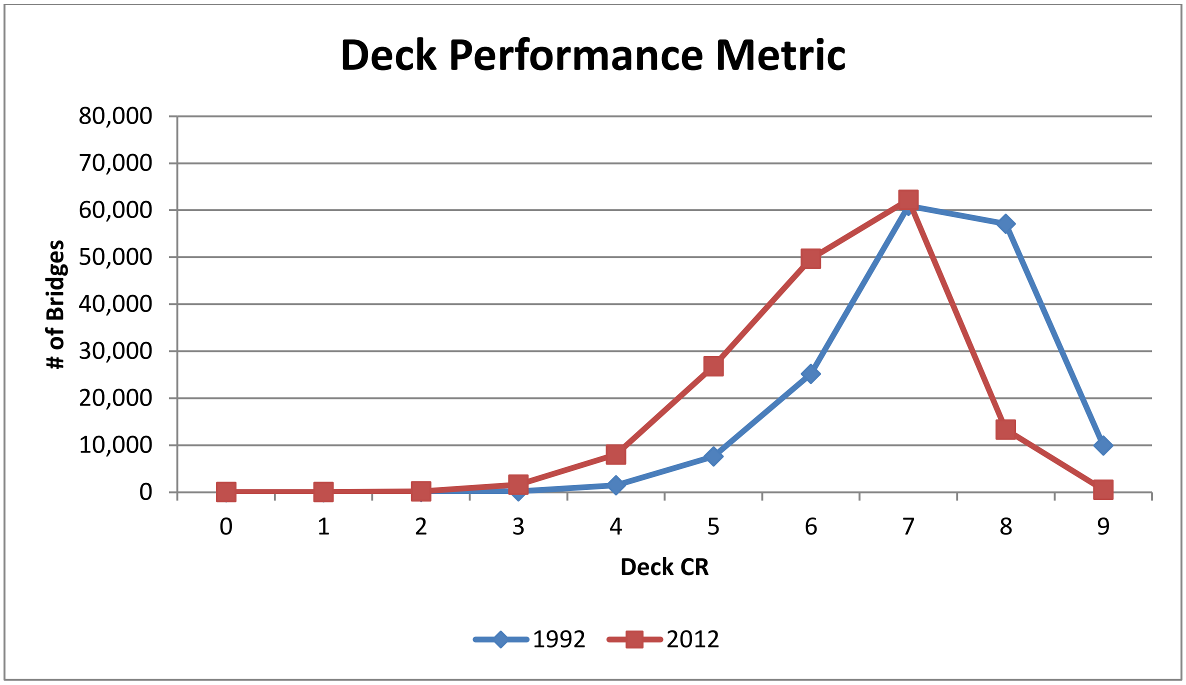

Figure 28 Deck Performance Metrics (without improvements)

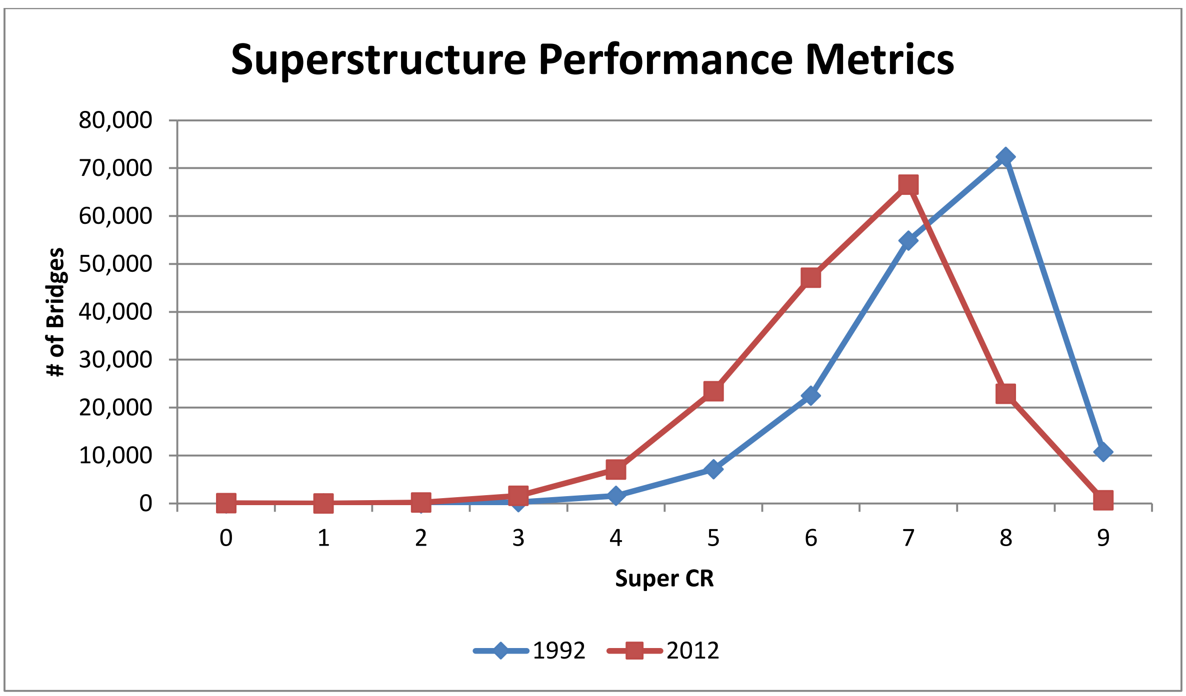

Figure 29 Superstructure Performance Metrics (without improvements)

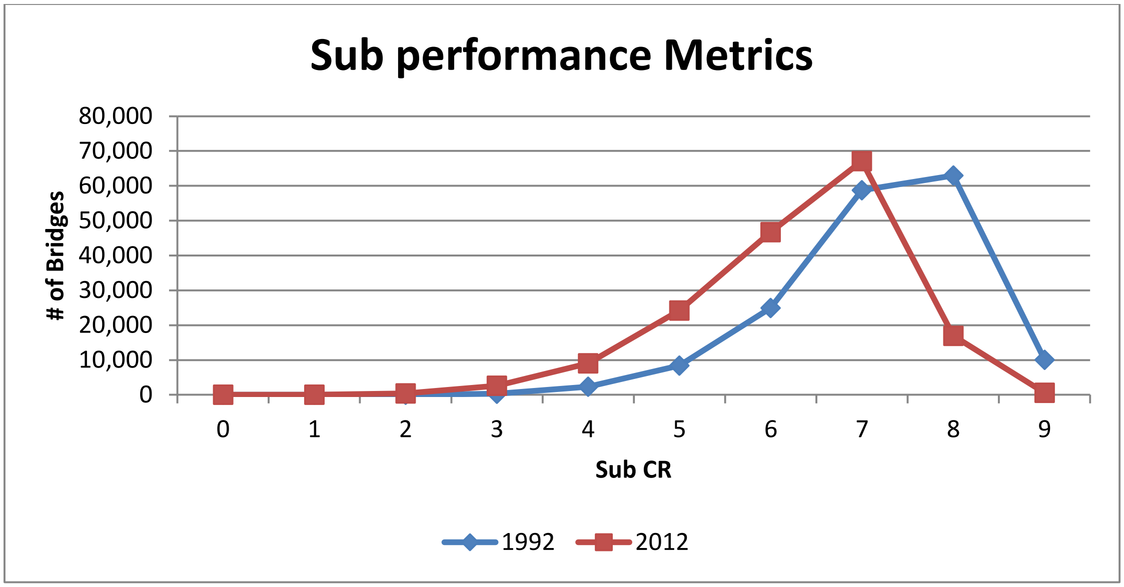

Figure 30 Substructure Performance Metrics (without improvements)

The effect of the unknown improvements can be judged by comparing Figure 16 and Figure 28, Figure 17 and Figure 29, and Figure 18 and Figure 30.

Markov Models

Several Markov Chain models were fit to the observed condition rating data. This provided a compact quantification of the observed behavior and also provides forecasting capabilities. It is assumed the reader is familiar with the theory behind Markov Chain models and only the final transition probability matrices are presented. Markov models were developed for the observed condition rating transitions for Deck, Superstructure and Substructure elements. Separate models were developed for the data with and without the improvements described in the previous section. The Deck data is presented first.

Table 19 Deck Transition Probabilities (with Imp.)

	9	8	7	6	5	4	3	2	1	0
9	0.8814	0.1186	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.9310	0.0690	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.9750	0.0250	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.9819	0.0181	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.9932	0.0068	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.9969	0.0031	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0068	0.9932	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9900	0.0100	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9834	0.0166
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

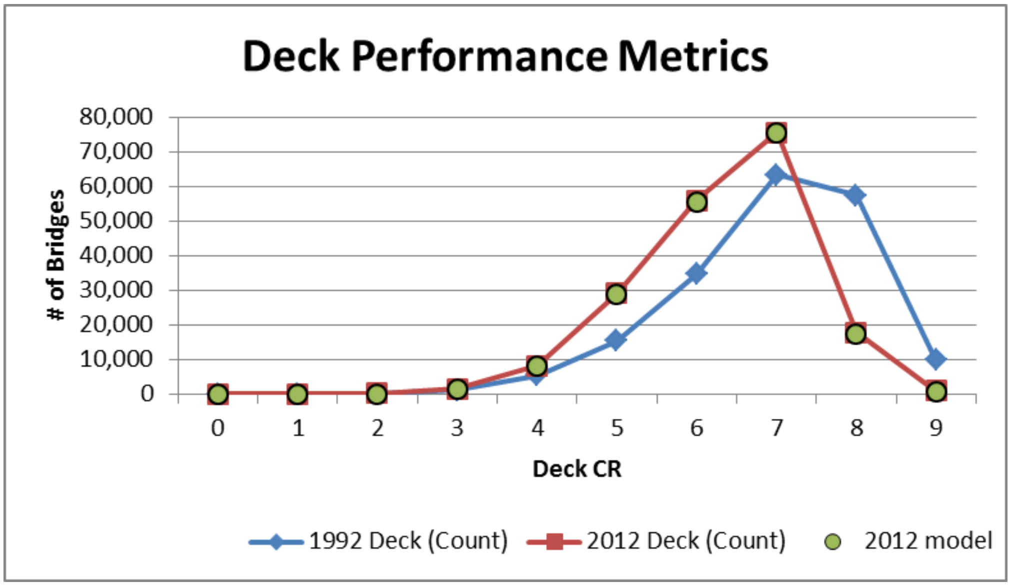

Figure 31 Deck Condition Prediction (with imp.)

Table 20 Deck Condition Transition Probabilities (without improvement)

	9	8	7	6	5	4	3	2	1	0
9	0.8611	0.1389	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.9175	0.0825	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.9617	0.0383	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.9643	0.0357	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.9744	0.0256	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.9786	0.0214	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9779	0.0221	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9162	0.0838	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8176	0.1824
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

It is observed that the Markov models for Deck Condition fit the observed data very well. It is noted that the model with improvement only has one instance where the probability of improvement in greater than zero. That is for bridges with a Deck Condition Rating of 3. There is a slight probability (0.0068) that the Deck Condition Rating will become a 4 after one year. The major difference between the Markov models with and without improvement is that the transition probabilities for a reduction in Deck Condition Rating are higher for the model without improvement, as would be expected.

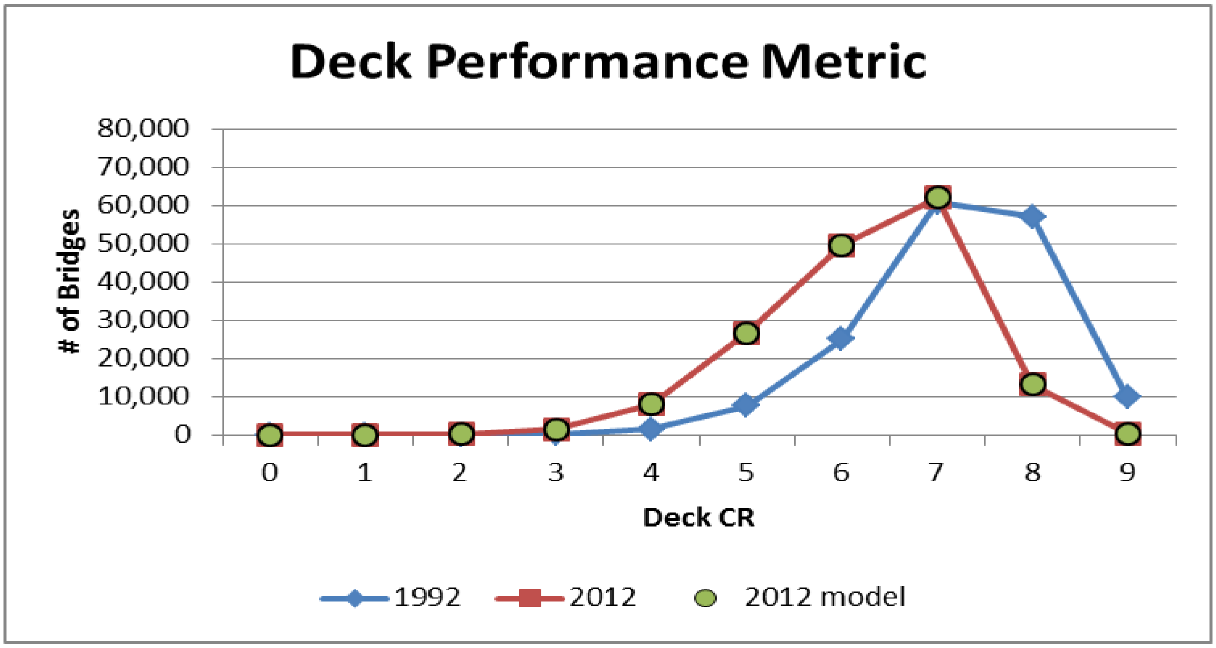

Figure 32 Deck Condition Prediction (without imp.)

The data for Superstructures is presented below.

Table 21 Superstructure Condition Transition Probabilities (with improvement)

	9	8	7	6	5	4	3	2	1	0
9	0.8889	0.1111	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.9437	0.0563	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.9748	0.0252	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.9822	0.0178	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.9934	0.0066	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0003	0.9990	0.0007	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9990	0.0010	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9164	0.0836	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8166	0.1834
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

It is observed that the Markov models for Superstructure Condition are very similar to the Deck Condition models and also fit the observed data very well. The model for Superstructure Condition with improvement only has one instance where the probability of improvement in greater than zero. That is for bridges with a Superstructure Condition Rating of 4. There is a very slight probability (0.0003) that the Superstructure Condition Rating will become a 5 after one year. The major difference between the Markov models with and without improvement is that the transition probabilities for a reduction in Superstructure Condition Rating are higher for the model without improvement, as would be expected.

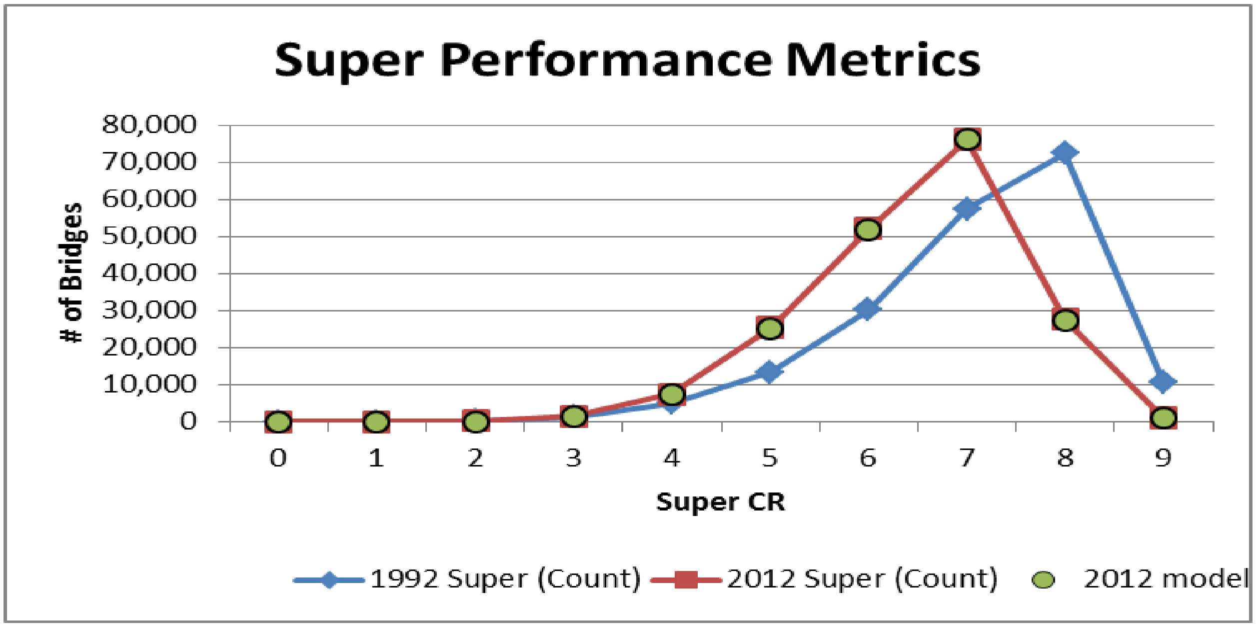

Figure 33 Superstructure Prediction (with improvement)

Table 22 Superstructure Condition Transition Probabilities (without improvement)

	9	8	7	6	5	4	3	2	1	0
9	0.8697	0.1303	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.9344	0.0656	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.9640	0.0360	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.9666	0.0334	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.9751	0.0249	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.9793	0.0207	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9830	0.0170	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9745	0.0255	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7800	0.2200
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

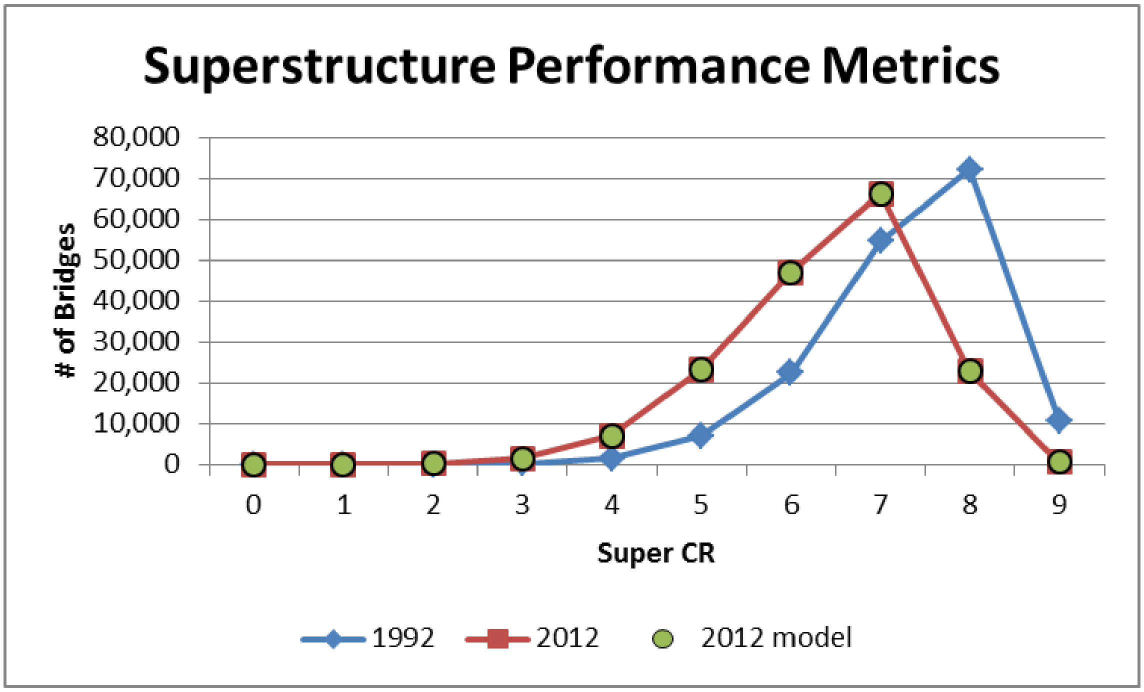

Figure 34 Superstructure Prediction (without improvement)

The Substructure data is now presented.

Table 23 Substructure Condition Transition Probabilities (with improvement)

	9	8	7	6	5	4	3	2	1	0
9	0.8788	0.1212	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.9328	0.0672	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0007	0.9742	0.0251	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0029	0.9798	0.0172	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0005	0.9918	0.0077	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.9952	0.0048	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9926	0.0074	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.9990	0.0000	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9774	0.0226
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

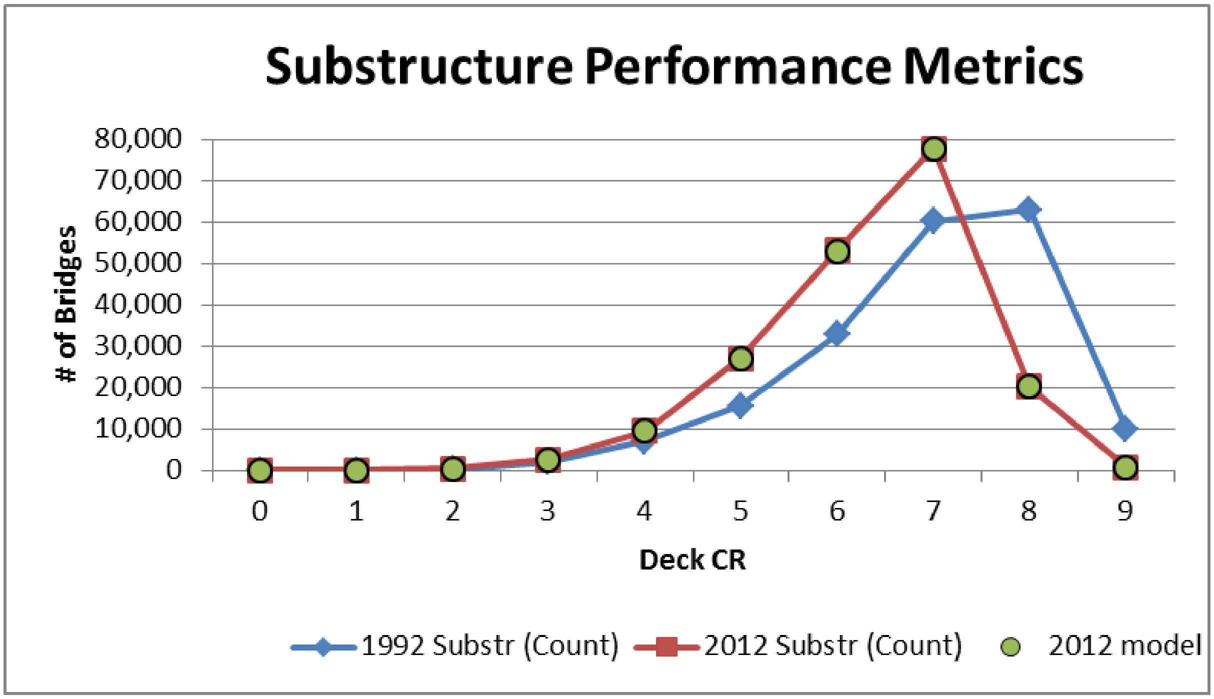

Figure 35 Substructure Condition Prediction (with improvement)

Table 24 Substructure Condition Transition Probabilities (without improvement)

	9	8	7	6	5	4	3	2	1	0
9	0.8682	0.1318	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.9256	0.0744	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.9659	0.0341	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0000	0.9649	0.0351	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.9690	0.0310	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.9725	0.0275	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9783	0.0217	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9775	0.0225	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

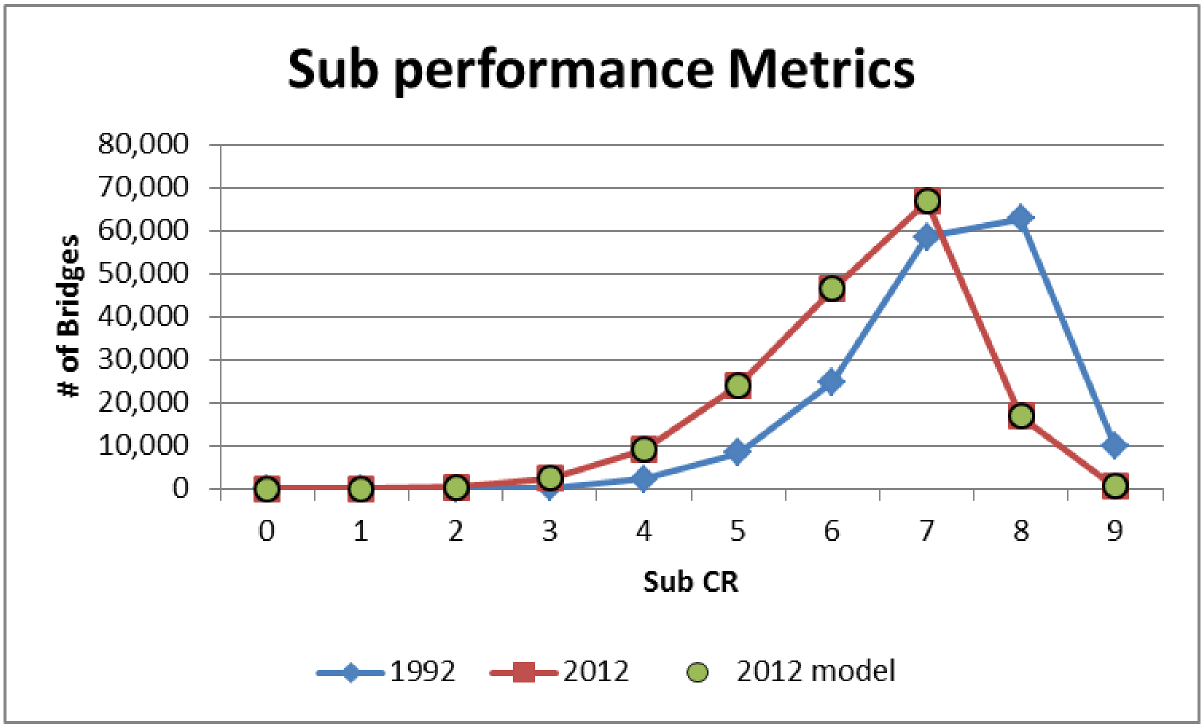

Figure 36 Substructure Condition Prediction (without improvement)

The Markov models for Substructure Condition are very similar to the prior models and also fit the observed data very well. The model for Substructure Condition with improvement only has several instances where the probability of improvement in greater than zero. That is for bridges with a Superstructure Condition Rating of 7, 6, 5 or 2, there is a slight probability (0.0007, 0.0029, 0.0005 and 0.0010 respectively) that the Substructure Condition Rating will increase by 1 after one year. The major difference between the Markov models with and without improvement is that the transition probabilities for a reduction in Superstructure Condition Rating are higher for the model without improvement.

Prediction of Condition Distributions

The models described above were used to predict the distribution of Condition Ratings for the final sample of bridges twenty years into the future. The predictions were made with and without the effect of improvements included. The results are presented in Figures 37, 38 and 39.

With the current level of improvement, the condition rating distributions for Deck, Superstructure and Substructure Elements are forecast to shift toward lower overall condition ratings. The shift is much more significant when the effects of improvements are eliminated. The percentage of Structurally Deficient bridges is forecasted to be much higher when improvements are not included. The difference is most pronounced for forecast Deck Condition, with the percentage of Structurally Deficient, more than triple that forecast with improvements included.

It is concluded that the effect of improvements in the NBI data must be removed to provide an accurate assessment of bridge deterioration. As demonstrated, the effects of improvements can be included separately.

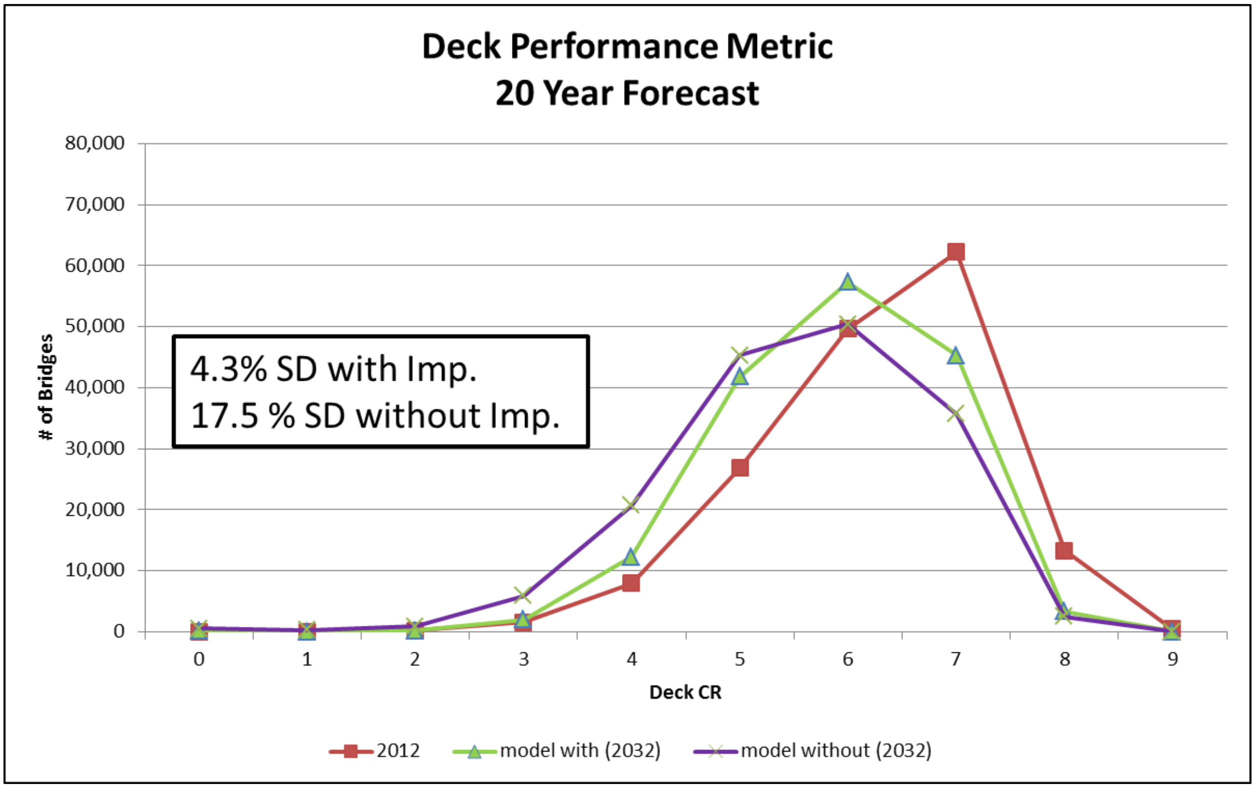

Figure 37 20 Year Deck Condition Distribution Forecast

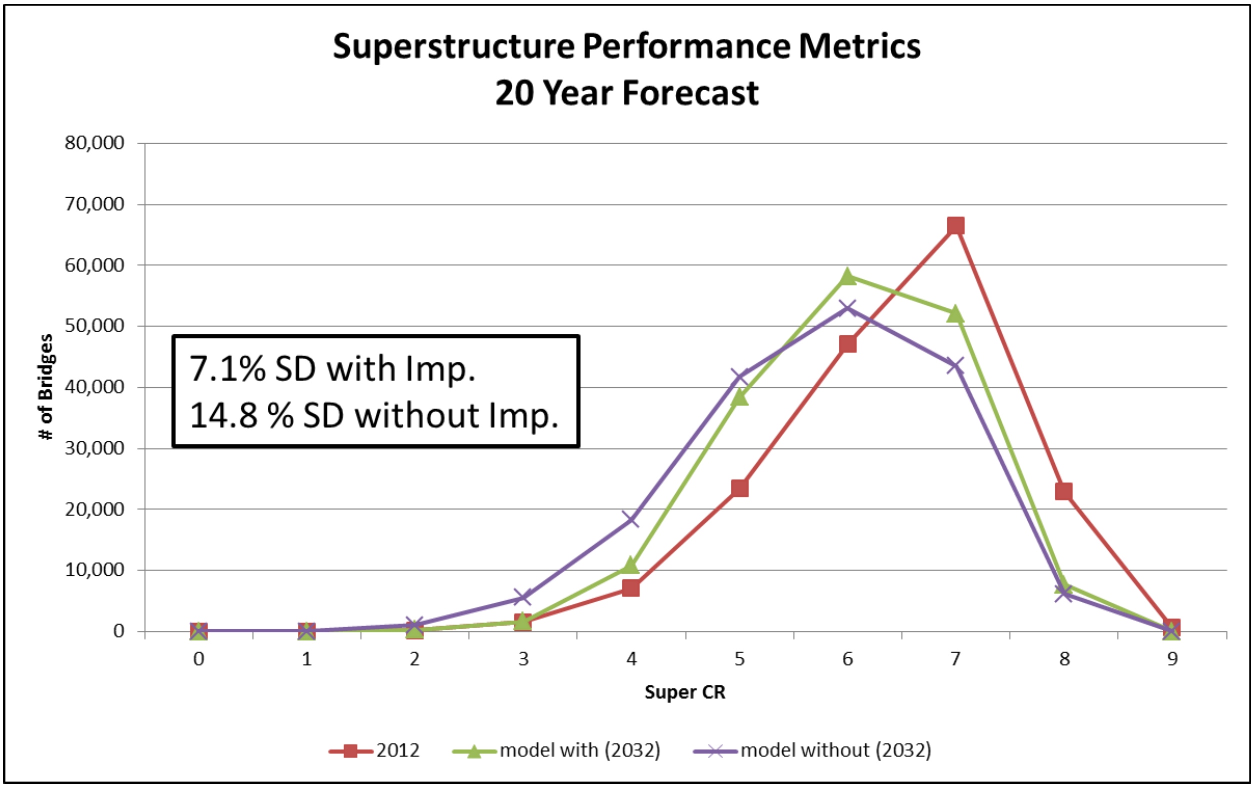

Figure 38 20 Year Superstructure Condition Distribution Forecast

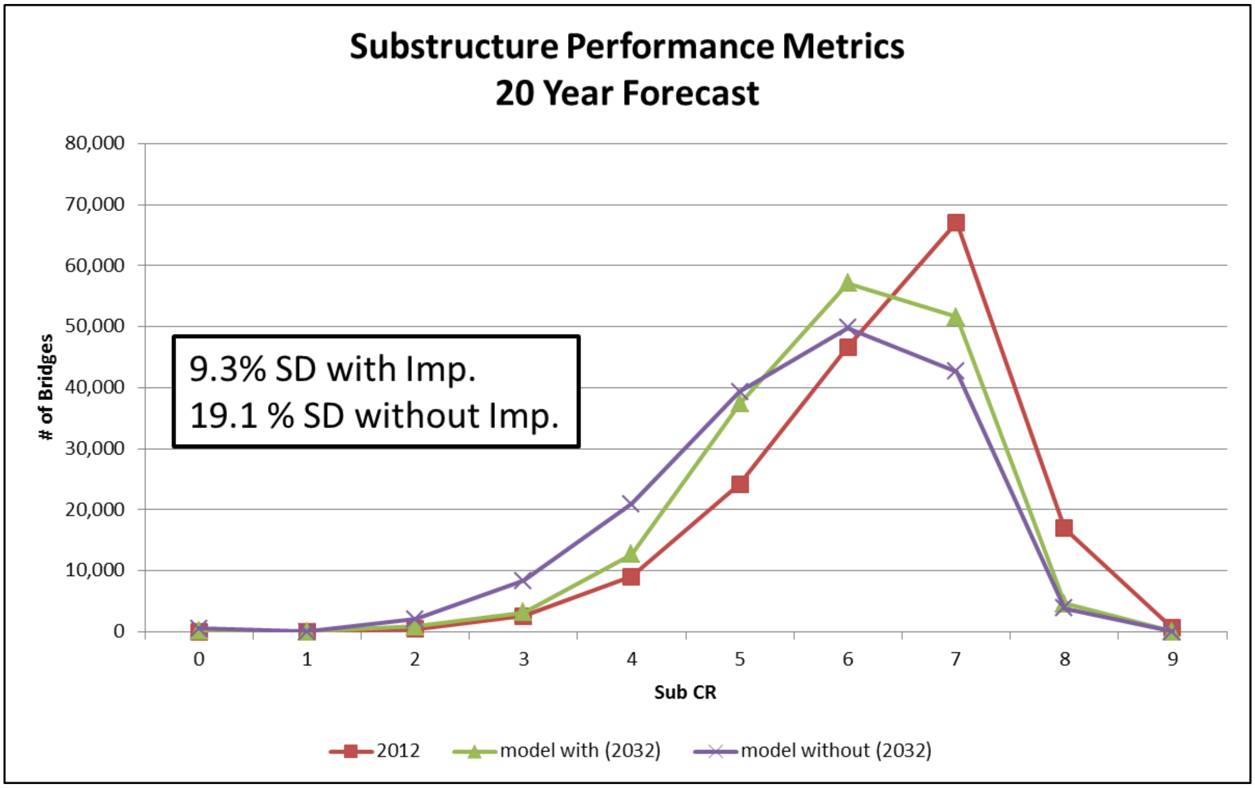

Figure 39 20 Year Substructure Condition Distribution Forecast

Service Life of Bridges Estimation Using 20 Years of NBI Data

The service file of existing highway bridges is difficult to determine. The Condition and Performance Report published by the Federal Highway Administration does not provide specific data on this important performance indicator. Therefore, a detailed analysis of the data in the FHWA National Bridge Inventory was performed under this project to identify, to the extent possible, the service life existing bridges and to identify the factors which limit that service life.

The data available includes the National Bridge Inventories from 1992 to 2012. However, a separate database of bridges which have reached their service lives is not available. A sample of bridges was created by identifying specific bridges which were in service in 1992 and which were replaced between the years 1993 and 2012. Because many jurisdictions assign new structure identification numbers to these replacement bridges it was not possible to simply identify bridges with the same structure number. The method used was to select bridges which were built after 1992 but carried the same route and facility, intersected the same feature and had the same location as bridges which were in service in 1992. This procedure resulted in a sample of 11,753 bridges. It is recognized that this is not a complete sample of all of the bridges which have been replaced in this twenty year period because some bridges would have been simply removed from service and others might have been constructed in new locations. However, it is assumed that this sample is large enough to help identify the factors which resulted in these bridges being taken out of service and replaced.

Service Life Statistics

The age at which each of the sample bridges was replaced was determined and the distribution of these ages (service lives) is presented in Figure 40. Current bridge design practice is to obtain a service life of 75 to 100 years. Clearly, this is a significant increase from existing practice and helps to emphasize the significance of research which will help identify those factors which limit bridge service life.

Current bridge management and inspection practice is to assign subjective condition ratings to major bridge components and to rate the functional performance of bridges and to classify bridges as structurally deficient or functionally obsolete based upon these ratings. The FHWA definitions of these classifications are provided in Table 27. The item numbers referenced are defined in the FHWA Bridge Inspection Coding Guide.

The median service life is 53 years for this sample. This means that almost half of current highway bridges have service lives of less than 50 years. The quartile statistics for service life are 40 years for the first quartile, 53 years for the median and 69 years for the third quartile.

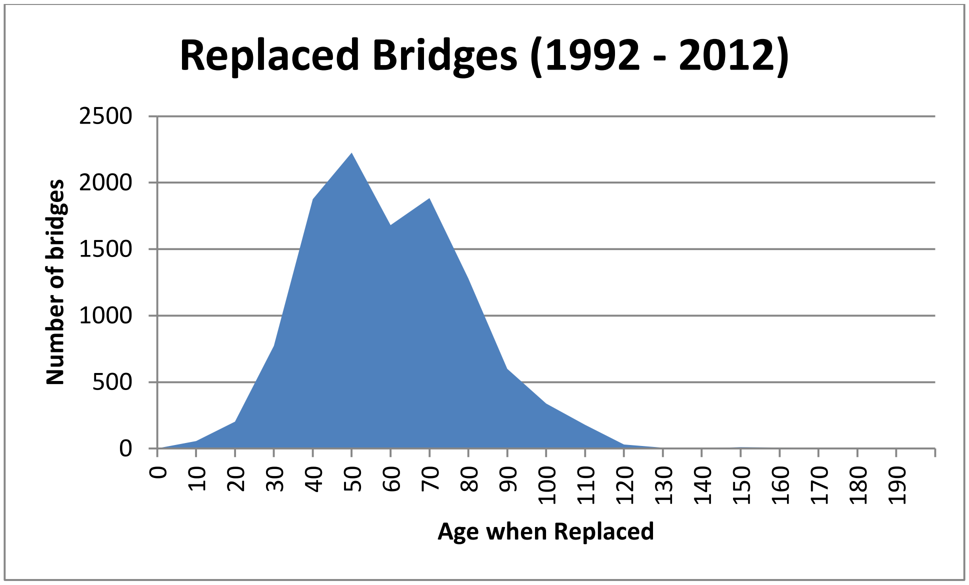

Figure 40. Service Life Distribution

Table 27 SD and FO Definitions

General Qualifications: In order to be considered for either the structurally deficient or functionally obsolete classification a highway bridge must meet the following:

Structurally Deficient -

1. A condition rating of 4 or less for
   - Item 58 - Deck; or
   - Item 59 - Superstructures; or
   - Item 60 - Substructures; or
   - Item 62 - Culvert and Retaining Walls. or
2. An appraisal rating of 2 or less for
   - Item 67 - Structural Condition; or
   - Item 71 - Waterway Adequacy.

Functionally Obsolete -

3. An appraisal rating of 3 or less for
   - Item 68 - Deck Geometry; or
   - Item 69 - Underclearances; or
   - Item 72 - Approach Roadway Alignment. or
4. An appraisal rating of 3 for
   - Item 67 - Structural Condition; or
   - Item 71 - Waterway Adequacy.

Any bridge classified as structurally deficient is excluded from the functionally obsolete category.

An initial look at the proportion of classification of the sample bridges helps to begin to examine the factors limiting bridge service life. The proportions of these replaced bridges as classified are presented in Figure 41.

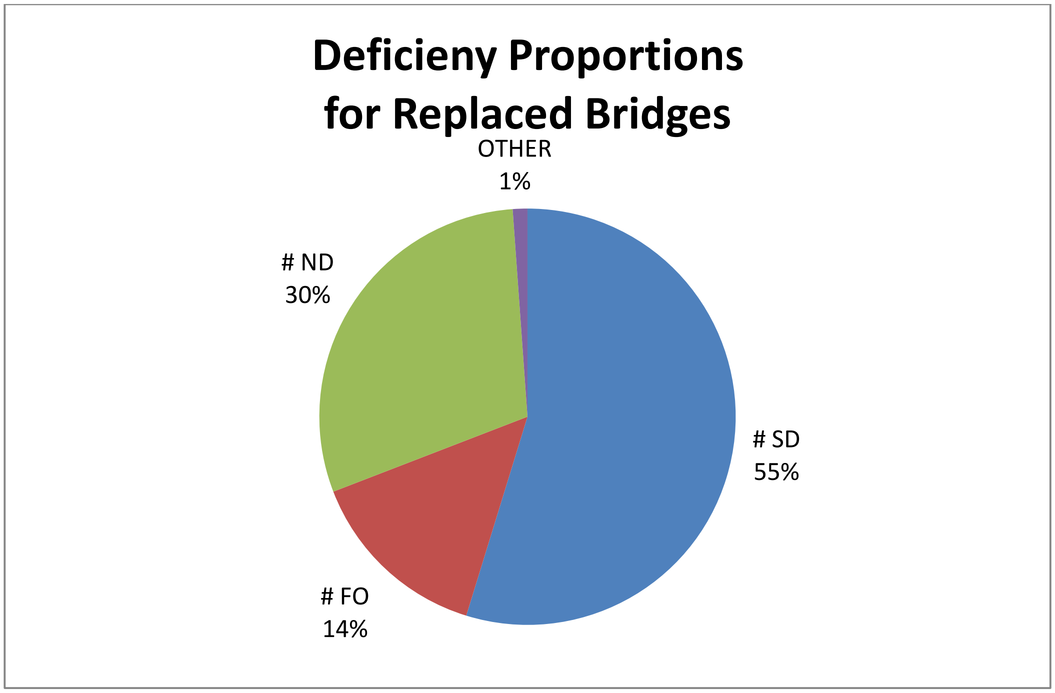

Figure 41 Deficiency Proportions for Replaced Bridges

More than half of the replaced bridges were classified as structurally deficient prior to replacement. Only 14 percent of the replaced bridges were classified as functionally obsolete and, somewhat surprisingly, 30 percent (or almost 1 in 3) of the replaced bridges were not classified as deficient using the above definitions and were therefore assumed to have been replaced for some other reason.

As noted in the definitions for these deficiency classifications, there are a number of ratings which can result in a bridge being classified as deficient. A more detailed analysis of these contributory factors was performed to try to better identify what factors were most significant in limiting bridge service life. A closer look at the structurally deficient bridges which were replaced is provided in Figure 42.

Two factors were most common for these structurally deficient bridges, low load capacity and a substructure in poor condition. Multiple deficiencies are very common. Additional insight into those factors limiting bridge service life was obtained by identifying which combinations of deficiencies exist on the sample. This information is presented in Figure 43. By far the most common deficiency on these structurally deficient bridges is solely a low load capacity. The second most common was solely a poor substructure condition. These two deficiencies account for almost half of the structurally deficient bridges replaced.

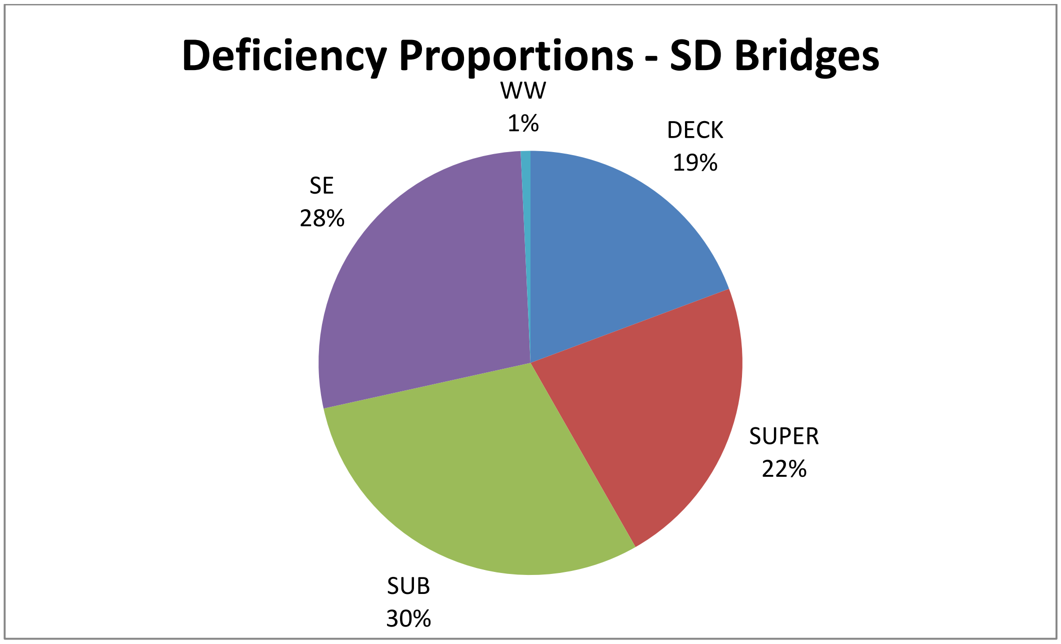

Figure 42 Deficiency Propositions for Structurally Deficient Bridges

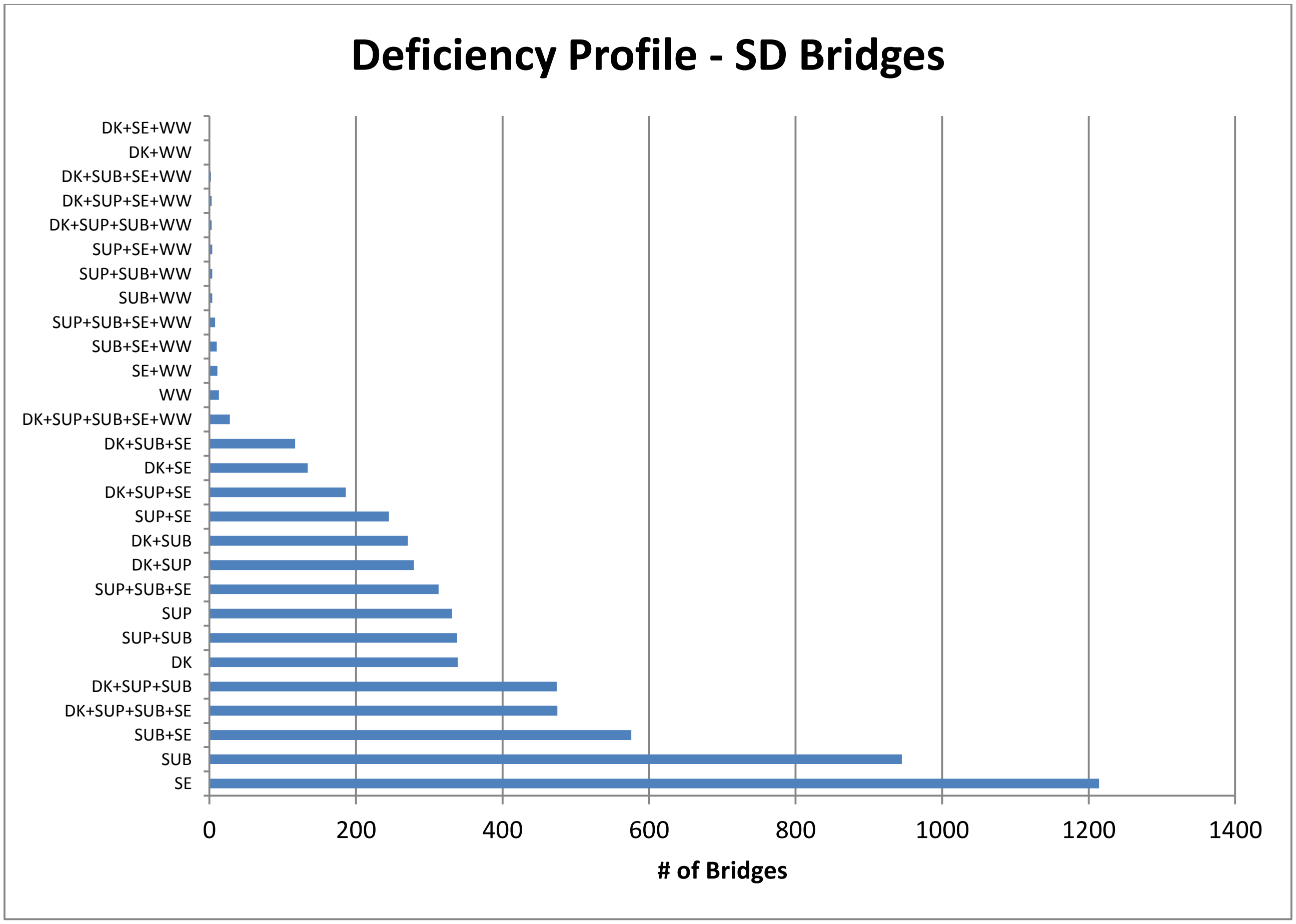

Figure 43 Singular Deficiencies for SD Bridges

A similar analysis was performed on the sample bridges which were classified as functionally obsolete. The deficiency distribution for these bridges is presented in Figure 44. By far, the most frequent deficiency in these replaced bridges was a low deck geometry appraisal rating. This means that the roadway width on the bridge is substandard for the system and average daily traffic present on the bridge.

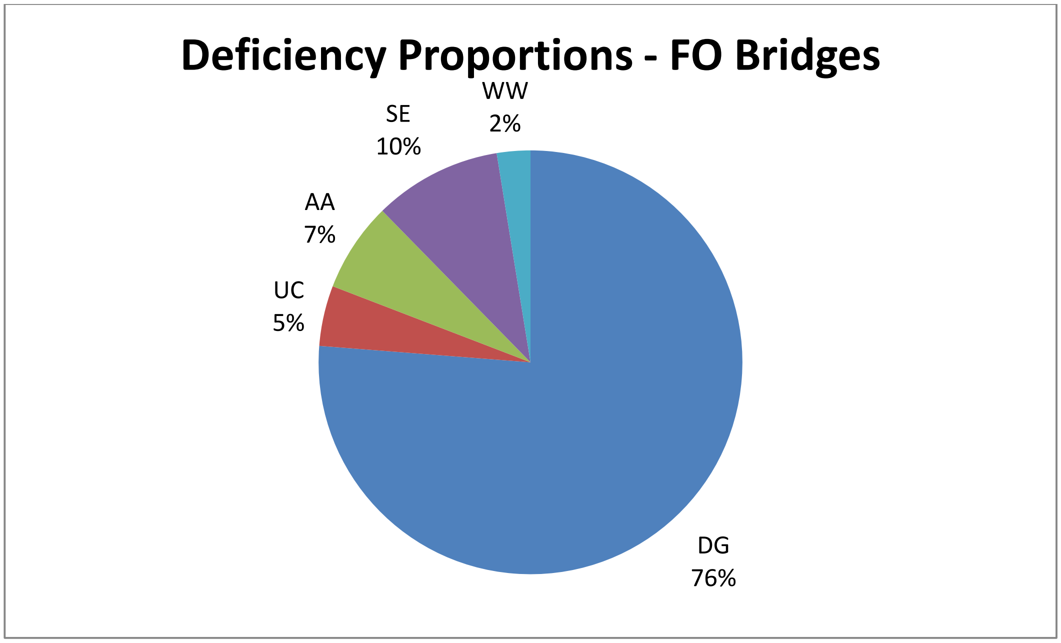

Figure 44 Deficiency Proportions for Functionally Obsolete Bridges

The above analysis provides insight into the factors limiting bridge service life but further information was provided by looking more closely into the distribution of deficiencies with age at bridge replacement. Figure 45 shows the temporal distribution of deficiency classification for these sample bridges.

The most significant observation is that there are bridges which are replaced with less than twenty years of service and that most of these are not deficient. Another observation is that a 100 year service life, the currently desired design objective, is not attained by 98 percent of the bridges in this sample. Clearly, if the current bridge population falls so far short of the desired objective, then a fuller understanding of those factors which limit service life is essential if the desired goal is to be achieved. A detailed analysis of the age distribution of the sample bridges classified as structurally deficient or functionally obsolete was performed to determine if there were patterns which might provide this additional insight.

The number of structurally deficient bridges replaced in each of the ten year age bins with specific deficiencies is shown in Figure 46. The predominance of substructure and load capacity deficiencies is reiterated but there is a fairly uniform distribution of all deficiencies across all age bins, with the exception of low waterway appraisal rating (i.e. flooding. The number of functionally obsolete bridges replaced in each age bin is shown in Figure 48. The very dominant contribution of substandard roadway width is obvious. This is discussed more fully in the findings section of this report.

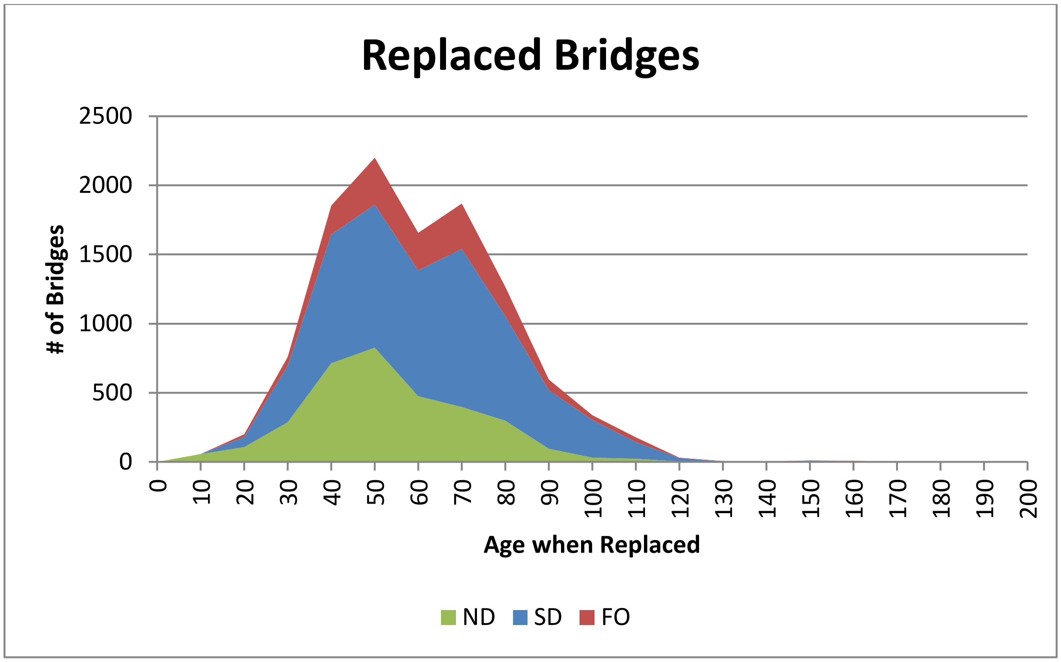

Figure 45 Deficiency Classification By Age at Replacement

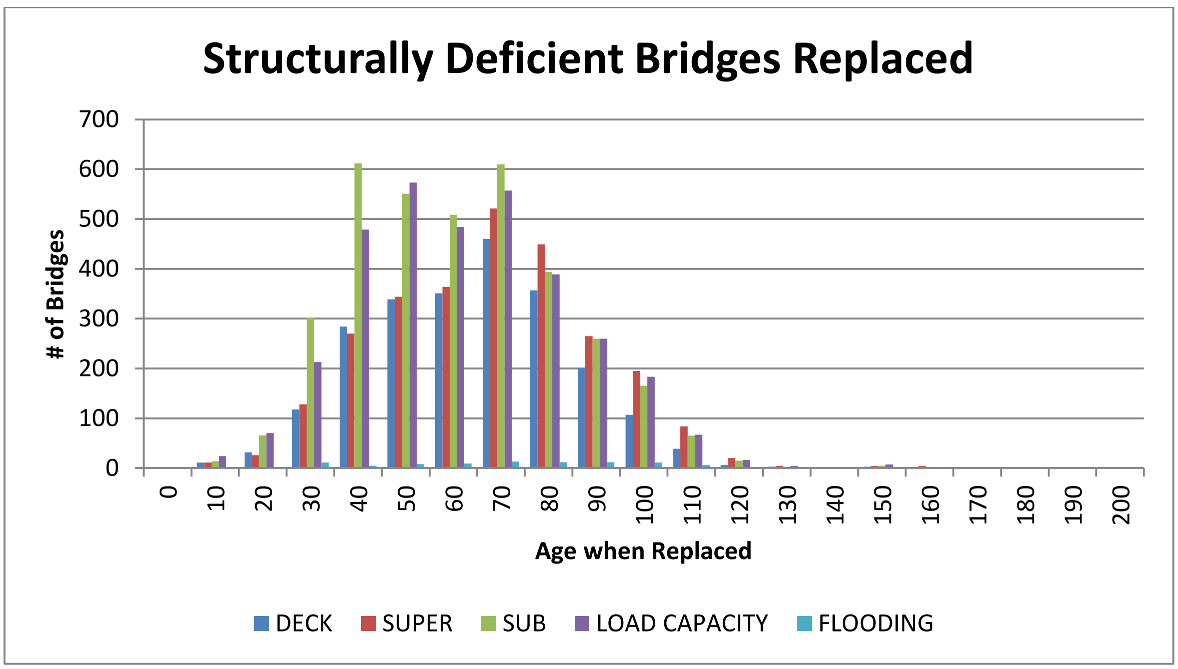

Figure 46 Age Distribution of SD Deficiencies

A very significant proportion of the bridges which have been replaced in the last twenty years were not characterized as having any deficiencies. It was assumed that these bridges were replaced for other reasons. The most likely reason considered was that the bridges were replaced as part of a roadway widening project or other improvement. If this was the case, then it was hypothesized that the new bridges would be longer or wider than the existing brides. To test this hypothesis, an analysis of the bridge length, width and total deck area was performed for these replaced non-deficient bridges. The results are presented in Figures 48, 49 and 50.

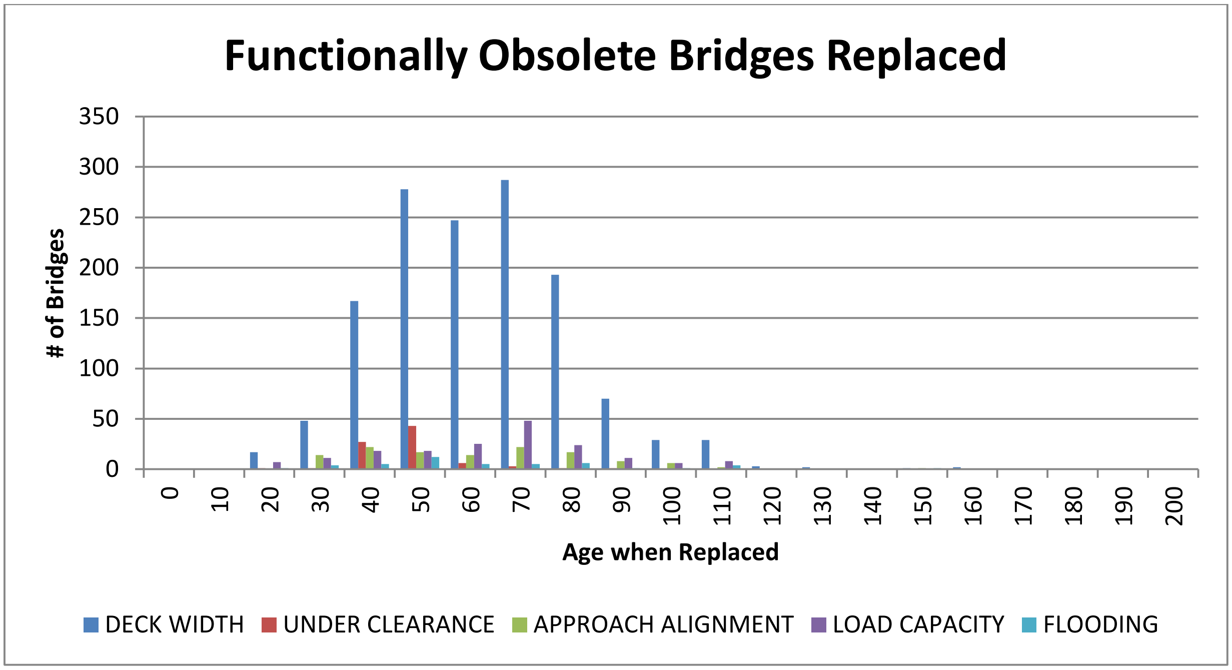

Figure 47 Age Distribution of FO Deficiencies

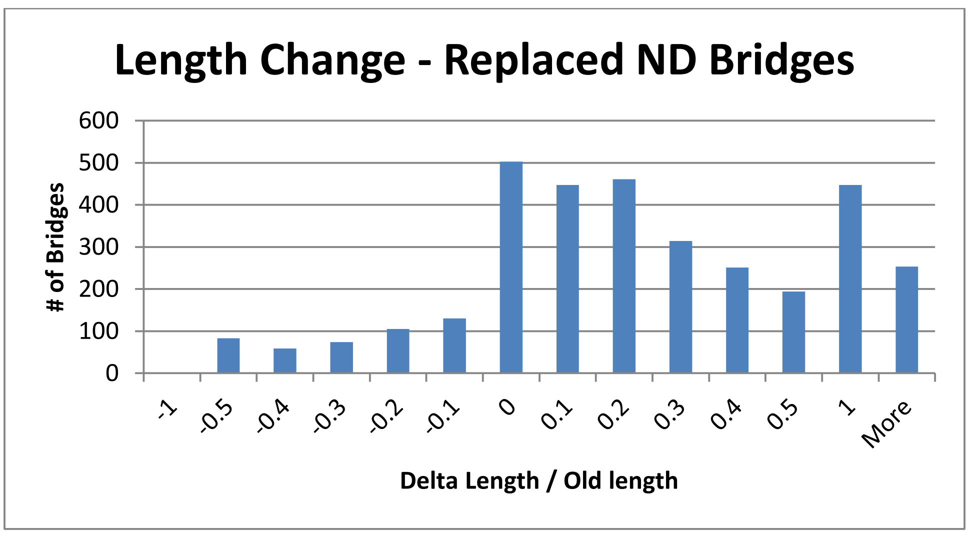

Figure 48 Length Change of ND Replaced Bridges

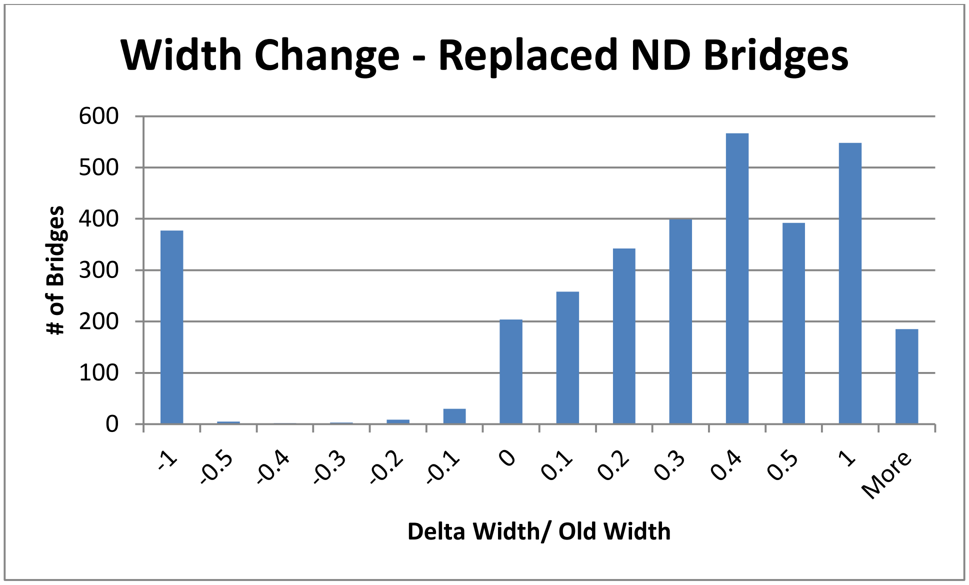

Figure 49 Width Change - ND Replaced Bridges

These results confirm the hypothesis that in the majority of instances the new bridges are longer and wider than the bridges which were replaced. The large numbers of bridges with a significant reduction in width are instances where the new bridge is a culvert with no deck.

It is concluded that the service life of thirty percent of the bridges replaced was limited by the obsolete traffic capacity of the associated roadway.

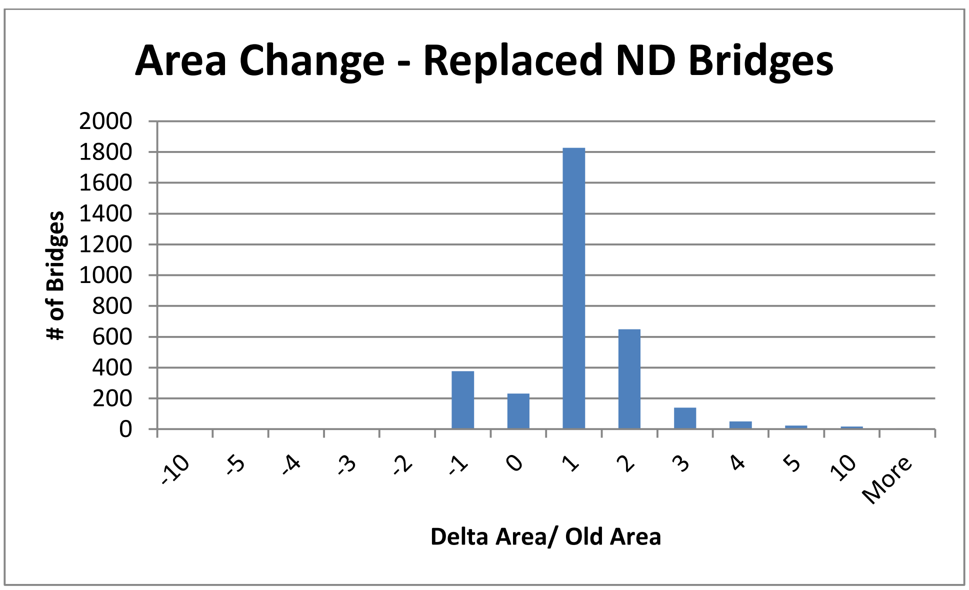

Figure 50 Area Change ND Replaced bridges

Load Capacity Analysis

The statistics for bridge service life support the view that bridge service life is limited by physical deterioration, functional obsolescence and other factors external to the bridge itself. In this section we consider the bridge as a physical system of systems and identify deterioration processes which need to be better understood in order to more fully understand the physical factors which limit bridge service life.

A schematic representation of a typical highway bridge is presented in Figure 51.

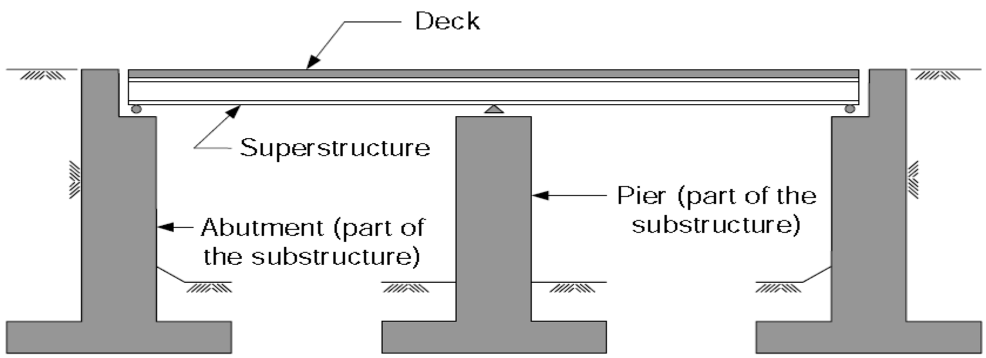

Figure 51 Bridge Schematic

The bridge consists of a substructure, most commonly of reinforced concrete, upon which rests the superstructure and deck. The superstructure transfers the load from the deck to the substructure. The deck is the riding surface and is the component of the bridge system with which the travelling public is most familiar. A variety of materials and structural systems are common on highway bridges and these have changed significantly over time.

As shown in Figure 43, the load capacity of the bridge system is the most frequent factor in limiting bridge service life. Load capacity is usually determined by an engineering calculation based upon the guidance provided in the AASHTO Bridge Evaluation Manual. In summary, the bridge is modeled as a single moment carrying beam element with span lengths and boundary conditions determined by bridge. The effective width of the beam is determined by formulas prescribed in the AASHTO manual. The stresses and deflections associated with special rating vehicles positioned as to produce maximum effects on the beam are determined. These are adjusted for dead load effects and safety factors and are compared against limiting values to determine the load capacity of the bridge. If the calculated load capacity is lower than a certain value the bridge is classified as having an inadequate structural evaluation appraisal. The load capacity of the bridge is very much determined by the initial design of the bridge and many older bridges were designed for loads which are lower than today’s standards. Degradation and deterioration of the load carrying components of the bridge also result in reduced load capacity.

The proportions of the recorded original design load for the replaced bridges are shown in Figure 52.

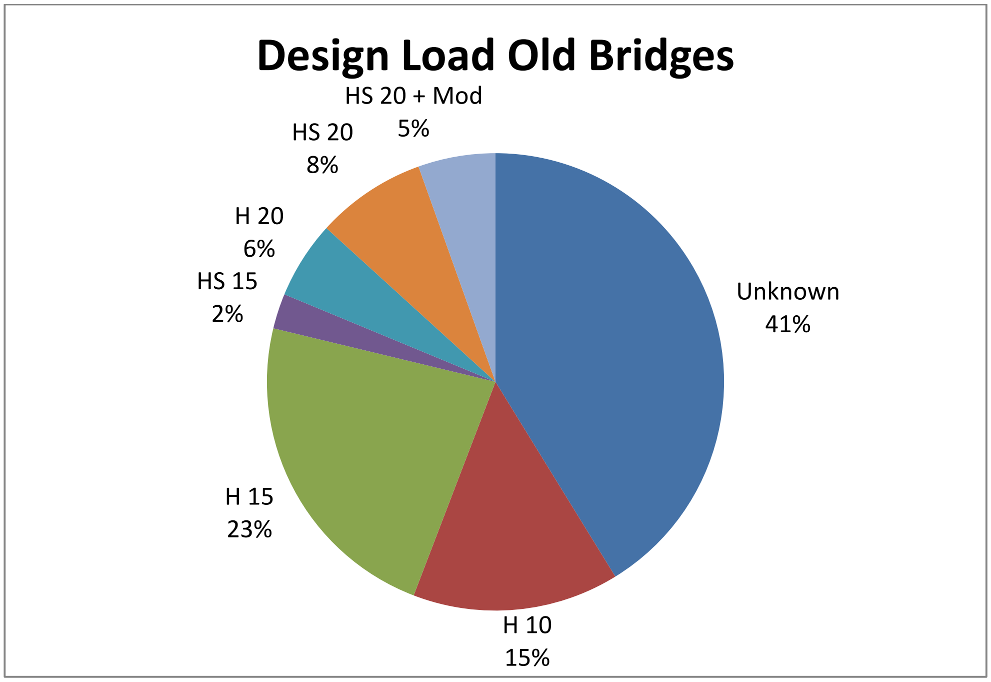

Figure 52. Design Load of Old Bridges

Very significantly, 41% of these old bridges had an unknown design load. In addition, design loads of H 10 and H 15 are well below today's standards and these bridges are classified as deficient. This draws attention to the fact that the service life of highway bridges is often determined by the original design standards which become obsolete with time and with the changing expectations of the owners and the public. It also demonstrates that important information necessary for predicting service life is often not available and that alternate methods, such as field measurement, are needed to help manage the inventory of existing infrastructure. While deterioration is certainly an important limiting factor for bridge service life, changing standards and expectations are also very important.

A closer look at the load capacity of this sample of bridges supports this conclusion. The load capacities, of the old and new bridges, as determined by the methods described above are presented in Figures 53 and 54.

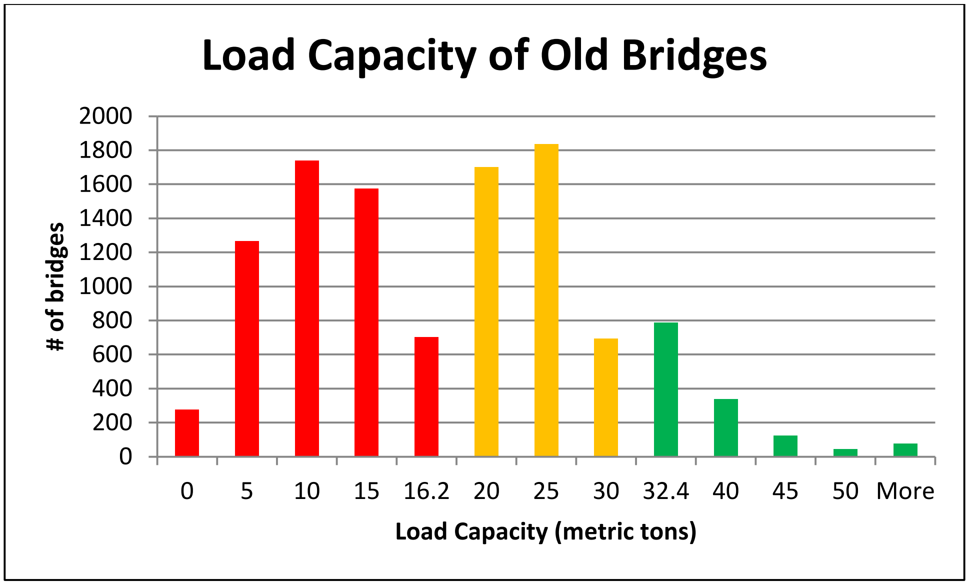

Figure 53 Load Capacity of Old Bridges

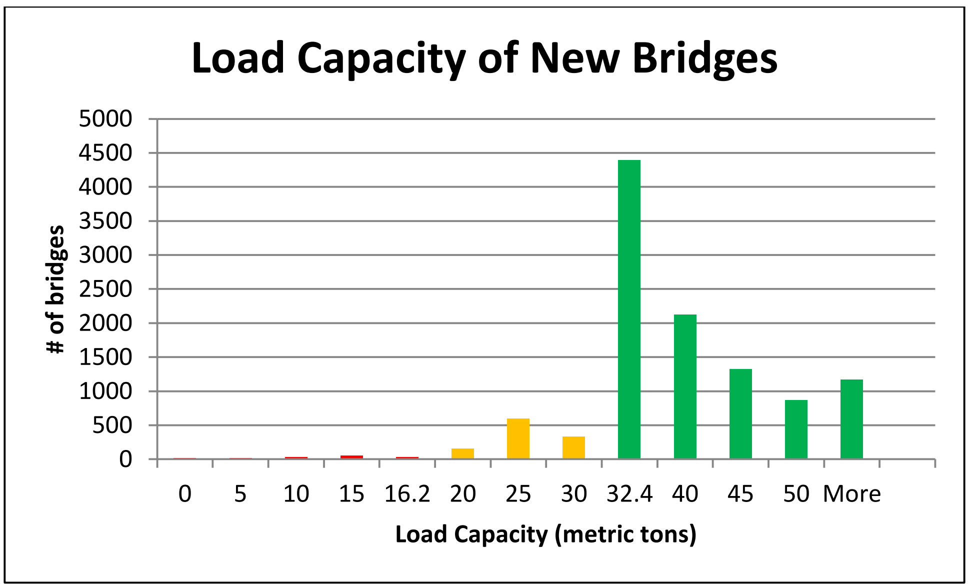

Figure 54 Load Capacity of New Bridges

Half of the old bridges had load capacities below the deficient level of 16.2 metric tons and ninety-five percent below current load capacity standard of 32.4 metric tons for new bridges. Eighty-nine percent of the replacement bridges have load capacities above 32.4 metric tons, as is to be expected, given the large proportion of bridges with unknown design loads, it is not possible to compare the calculated load capacity with the design load and determine if the low load capacity is due to an old design or deterioration. However, the significant number of structurally deficient bridges with deficiencies other than low load capacity clearly demonstrates that deterioration is a major factor in limiting service life. The predominant materials utilized in highway bridges are steel and Portland cement concrete. This is illustrated in Figure 55, showing the bridge types of the old bridges which were replaced.

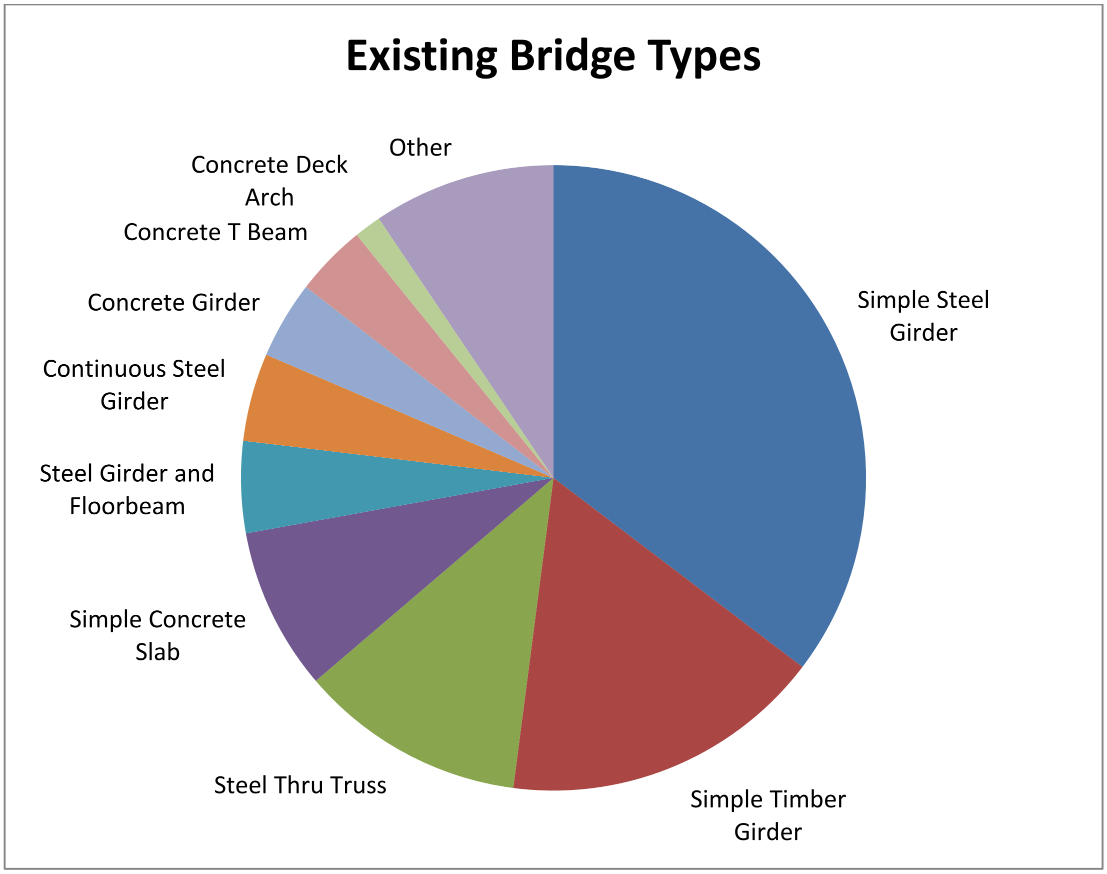

Figure 55 Existing Bridge Types

The predominance of steel superstructures in noted but most bridge decks and most substructures are made of reinforced concrete. The predominant deterioration mechanisms affecting bridges are corrosion, overloads, fatigue, other environmental attack and impact.

A bridge is an interconnected system of subsystems with the performance of each subsystem often dependent upon the performance of other subsystems. A good example is the effect of leaking joints (a superstructure element) on substructure corrosion. Bridge bearings, often located under joints and corrode if the joints leak. This in turn leads to bearings which not function as designed and lead to very large thermal overloads with temperature extremes.

The performance and service life of a highway bridge is very dependent upon the initial design, but it is also very much dependent upon the bridge being constructed as designed. The fact that the service life distribution in Figure 45 has a large proportion of fairly new bridges might be attributable to substandard materials of details which were not constructed properly. A very common example of this is insufficient cover in reinforced concrete elements.

Findings

Interstate Deterioration Models

Several models were developed which provided the Virginia Department of Transportation forecasting capabilities to assist them in developing a new bridge maintenance initiative for interstate bridges in Virginia. In the process it was found that there is a significant difference between the forecasts developed using element level data from the Pontis database and models developed using general condition ratings. In particular, the models for prestressed concrete superstructures were very different. While the element level data for these prestressed concrete bridges shows very low levels of deterioration, the GCR data shown bridges with superstructure condition ratings as low as 5. The relationship between the element condition state data and superstructure condition ratings for prestressd concrete bridges in Virginia was examined more closely.

The quantity averaged condition state and the superstructure condition rating data was extracted from the Pontis database. The data for 4861 inspections was analyzed and is summarized in the Figure 56 below. Figure 56 shows a scatter plot of the quantity averaged condition state for Element 109 is plotted against the superstructure condition rating reported for each inspection.

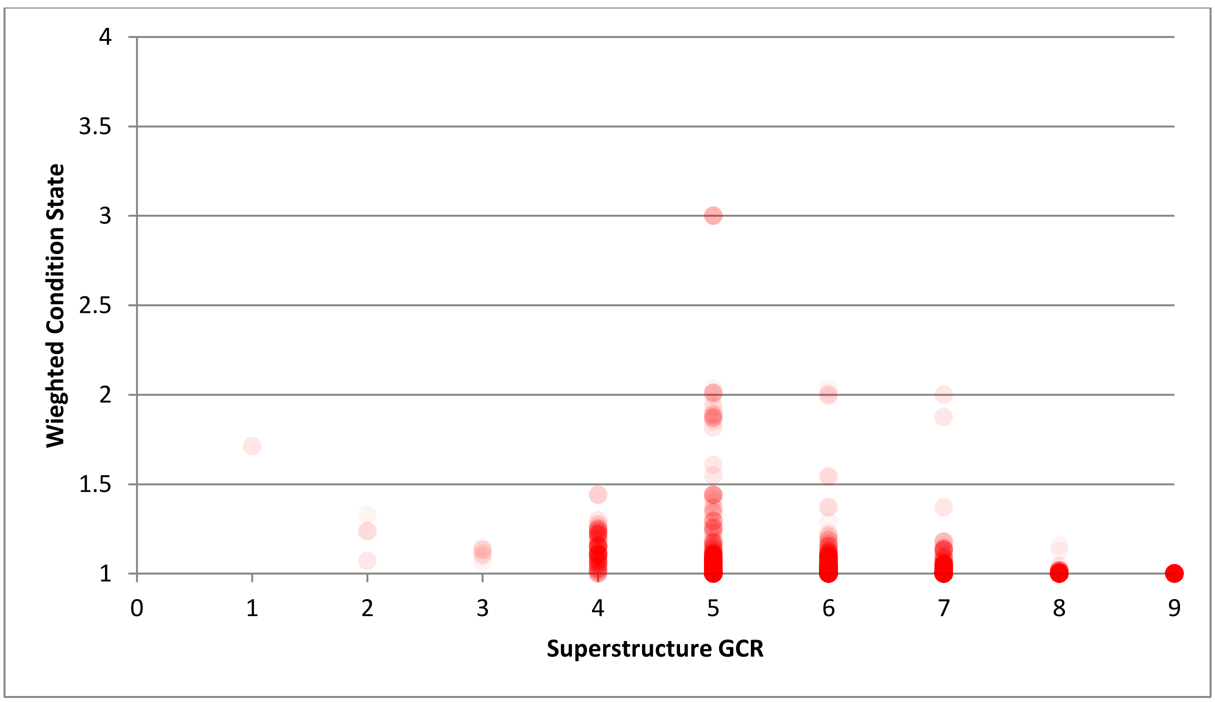

Figure 56 Weighted Condition State vs Condition Rating

The data points are plotted with 99% transparency to provide a visual indication of the number of inspections represented. The discrepancy between the condition state data and the condition rating data is further examined in Figures 57 and 58.

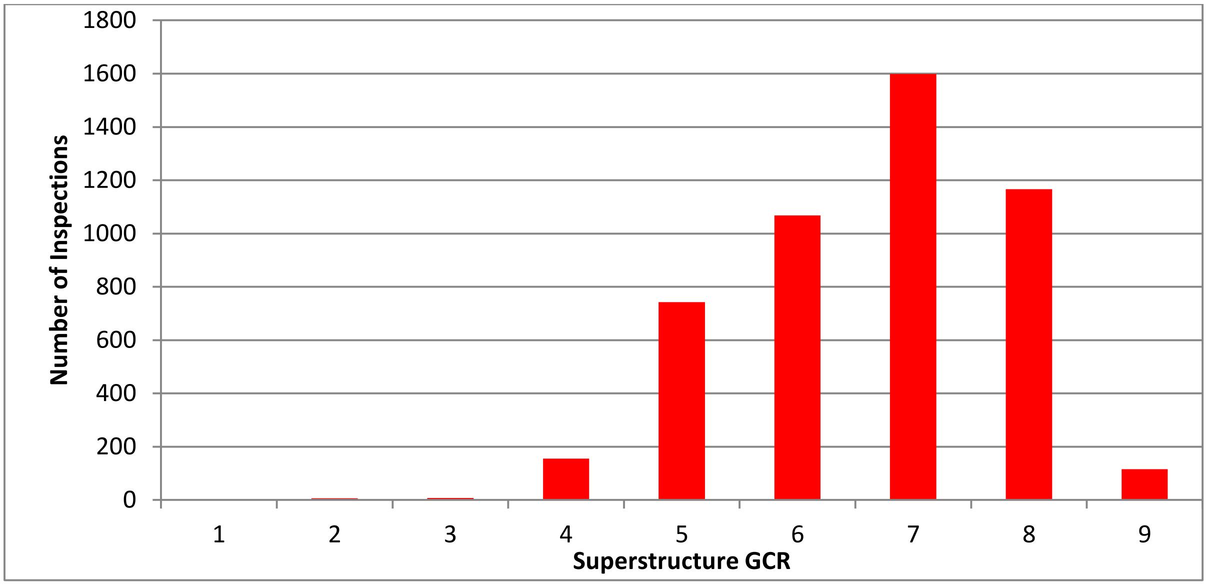

Figure 57 Condition Rating Histogram for Prestressed Concrete Bridges

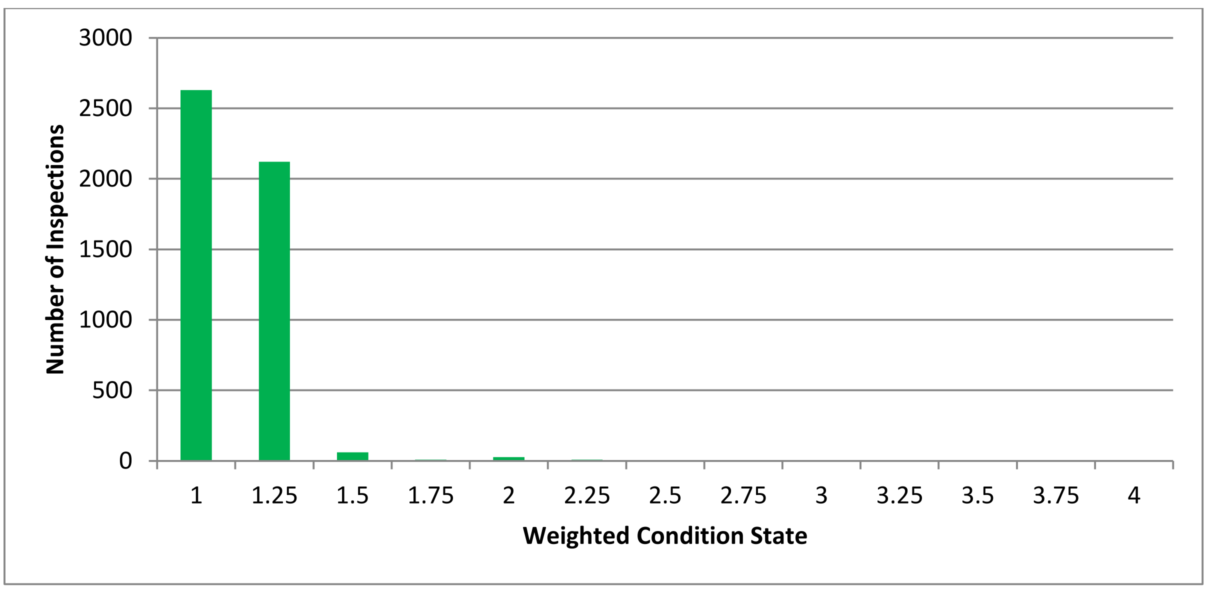

Figure 58 Condition State Histogram for Prestressed Concrete Bridges

A Temporal Analysis of Twenty Yeats of NBI Data

Using the twenty years of data which has recently become available, a new approach to examining bridge performance metrics was possible. A sample of bridges which existed both in 1992 and in 2012 was identified and by removing culverts, tunnels, and bridges which were coded as having been reconstructed or built after 1992, a consistent sample was used to examine bridge deterioration. The change in the distributions of several common bridge performance metrics was analyzed. The metrics examined were

- Deck Condition Rating
- Superstructure Condition Rating
- Substructure Condition Rating
- Deck Geometry Appraisal rating
- Approach Alignment Appraisal Rating
- Under-clearance Appraisal Rating
- Waterway Adequacy Appraisal Rating
- Structural Evaluation Appraisal Rating
    - Inventory Rating
- Sufficiency Rating

The changes in condition rating distributions were more significant than the changes in the appraisal rating distributions over the twenty year analysis period. The unexpectedly small changes led the authors to examine the condition rating transition data more closely. The change in individual condition ratings for the 194,830 bridges in the initial sample was analyzed. It was discovered that many of the lower condition ratings which existed in 1992 were greatly improved by 2012. This was true even though Item 106 was coded as there having been no significant reconstruction.

A new sample was identified which excluded those bridges which showed condition rating improvements over the twenty year analysis period. This second sample, of approximately 160,000 bridges, was analyzed for changes in condition ratings. The authors consider the results to be more representative of bridge deterioration with the absence of significant intervention or maintenance actions. The results were used to develop deterioration models for both situations, with and without improvement. These models were used to forecast the condition state distributions twenty years into the future. The number of structurally deficient bridges, those bridges with condition ratings of 4 or less, was estimated both with and without improvement. It was noted that the number of structurally deficient bridges more than doubled without improvement.

Service Life of Bridges Estimation Using 20 Years of NBI Data.

The median service life for the sample of bridges identified in this study was 53 years. Almost half of the bridges which were taken out of service were less than 50 years old. This is much less than the 75 to 100 years which is specified for current practice. Many of these bridges were replaced, even though they were not deficient

Conclusions

Interstate Deterioration Models

It was possible to develop reasonable deterioration models for the most significant elements present in the Interstate Highway Bridge population in Virginia. Markov Chain models and weighted least squares regression models were developed and are provided in this paper.

The data used for these models did have several characteristics which should be appreciated. The age of the bridges used was limited to sixty five years or less. Therefore, any extrapolation beyond this limit must be regarded with skepticism. The data had many episodes of missing values. This reflects bridge engineering practice and policies over the sixty five years examined and the resulting models should be used with this knowledge.

The models were found to be useful by the Technical Advisory Group.

It is recommended to extend the modeling to the entire bridge population in Virginia, with specific models developed for the different system classifications of Primary, NHS, secondary and local.

This disparity between the condition state and condition ratings for prestressed concrete superstructures should be investigated further.

A Temporal Analysis of Twenty Yeats of NBI Data

The analysis of the difference in bridge condition and performance over a twenty year period was useful and informative. Unexpected improvements were noted and assumed to be attributable to bridge maintenance activities. This was an assumption however, and further investigation of this is warranted. In particular the importance of accounting for this improvement in the historic record and modifying statistical deterioration models is essential for accurate results.

Service Life of Bridges Estimation Using 20 Years of NBI Data

The analysis of the service life of this sample of bridges has demonstrated that the service life of existing bridges is less than what is desired. The factors which limit service life have been examined as far as possible, given the subjective and non-quantitative nature of the data available in the National Bridge Inventory. The specific reasons for bridges being replaced can only be conjectured and assumed based upon this data. To better understand the factors which limit bridge service life will require a different approach.

Recommendations

The presence of unexplained improvement in the NBI data was the most significant finding of this study. It is recommended that this be studied more closely to determine what actions or factors led to this improvement. It can be hypothesized that this was due to unrecorded maintenance actions but without further study, the true cause is in fact unknown. In particular, the TAG requested that a similar analysis be performed, specifically for Virginia's bridges. A more detailed study of the historic bridge record for Virginia's bridges is planned for the next reporting period. This study will look at the condition rating transition date for each year, from 1992 to 2013. It is expected that this will help better define the lower condition rating portion of the sample data and also provide a more complete picture of the amount and effect of bridge maintenance activities.

It is also planned to conduct a study to provide a complete valuation of Virginia's bridge inventory as a potentially more useful performance metric and management tool.

BENEFITS AND IMPLEMENTATION PROSPECTS

There are several benefits to this research. First, new tools in the form of deterioration models have been developed and delivered to VDOT. Second, this research has discovered new knowledge about bridge performance and bridge deterioration in Virginia as well as discovering some unexpected patterns in bridge inspection data that suggests follow up actions regarding bridge inspection practice and procedures. Additionally, new insight into long term bridge performance was provided by mining 20 years of legacy data, Previously unknown patterns of improvement were discovered which emphasize the importance of collecting and recording bridge maintenance activities to better understand and model bridge performance for bridge management and perform reliable life cycle cost estimating.

Because of the close interaction between the Technical Advisory Group and the research team, the implementation of these research results has been continual and immediate.

ACKNOWLEDGEMENTS

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