Identifying Performance Patterns on New Mexico Bridges

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IDENTIFYING BRIDGE PERFORMANCE PATTERNS IN NEW MEXICO BRIDGES: INVENTORY DATABASE

by

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PREFACE

This research investigates the possible analysis a bridge inventory database to recognize patterns of performance and how these patterns relate to different bridge attributes. One major challenge in performing this analysis is to determine a set of bridge performance features with minimum uncertainties and consistent records in the database.

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DISCLAIMER

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ABSTRACT

Optimal choices for new bridge designs and existing bridge maintenance strategies necessitate understanding how bridge attributes and their interactions affect the performance of bridges in different environments. This research investigates the possible analysis a bridge inventory database to recognize patterns of performance and how these patterns relate to different bridge attributes. One major challenge in performing this analysis is to determine a set of bridge performance features with minimum uncertainties and consistent records in the database.

This report describes the analytical investigations performed in searching for bridge performance features and their patterns as observed from the bridge inventory database of the State of New Mexico. The use of hierarchical clustering combined with soft computing techniques made it possible to classify the data while also creating a knowledge base to reveal the underlying attributes that significantly affect bridge performance. The analysis showed that certain material and structure types were prevalent in either high performing or low performing bridges. The analysis also showed that the method of defining bridge performance have a significant influence on the findings. The report describes these findings and shows that it is possible to develop a simulation tool based on the identified knowledge base that can be used thereafter for predicting the bridge performance for known bridge attributes. A plan for completing the study and developing this tool is proposed.
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LITERATURE REVIEW

Management of infrastructure is a complex and multi-criteria based problem that is becoming more and more demanding. Without a fundamental change in current methods, it is likely that there will be an upcoming wave of limited infrastructure efficiency that cannot be dealt with the limited available resources (1). Moreover, infrastructure systems already have to surpass their design service lives and performance expectations (2). With new challenges arising in infrastructure management, there is an increasing need to employ means of artificial intelligence for modeling such complex information environments. The development of a comprehensive strategy for efficient infrastructure maintenance can help in handling the significantly large amount of information to enhance effective decision-making. Meanwhile, many researchers demonstrated the value of using of soft-computing methods in data mining and for developing tools for infrastructure management (2-4). Some advantages of using fuzzy systems as a soft computing paradigm, for example, over classical methods as outlined by Flintsch et al. (2) are their abilities to effectively address imprecision and uncertainty in evaluation databases as a result of subjectivity of the evaluation process. The ability of soft computing techniques to establish sophisticated knowledge base that can relate a significantly large number of parameters while considering a noticeably large database has always been reported as an advantage of soft computing paradigms (5-8).

Different types of soft computing methods have been used in the literature to deal with the above issues in infrastructure management research. Such methods included artificial neural networks (ANN), fuzzy systems (FS) and genetic algorithms (GA). Artificial neural networks, for example, were used effectively to recognize data patterns and detect
relationships between bridge condition rating data and bridge parameters (9). Artificial neural networks also were capable of predicting the subjective ratings based on given bridge parameters. A major drawback with ANN is their functionality as a “black box” and therefore the difficulty to establish an interpretable knowledge rule-base that can be used for understanding the underlying behavior (10). Fuzzy systems and fuzzy set theory were applied to numerous infrastructure research projects but has been predominant in pavement infrastructure research (11). In particular, membership functions were used due to their ability to deal with subjectivity and partial truth. The use of fuzzy sets allowed incorporating subjective descriptors such as “poor”, “good”, and “excellent” (12). Fuzzy systems were used to create a universal pavement distress evaluator (13) and a comprehensive index for flexible pavements (14). Finally, in a slightly different approach, fuzzy systems were used to help interpreting image processing techniques for pavement distress evaluation (15).

The objective of this research is to classify and pattern bridges based on their structural performance and identify what characteristics most dictate their level of performance. A case study using the New Mexico bridge inventory database is demonstrated. The subjectivity of existing performance parameters, indicators, and the high dimensionality of the database made this research further challenging. We tackled this challenge by considering soft computing paradigms for data mining. We employed fuzzy set theory to establish a comprehensive structural performance index. We also considered statistical methods and hierarchical clustering methods to identify the underlying bridge performance patterns.

The rest of this report is structured as follows. First we describe the methods used to establish a sensitive performance index for bridges. We then describe the methods used for extracting the
bridge performance patterns. We present the bridge performance patterns identified and we
discuss the fundamental parameters and processes that is believed to result in these patterns.
Representative findings are provided along with a discussion addressing how these findings can
be used in future decision-making to improve overall bridge performance.
METHODS

This section discusses the methods used to enable using the database, the development of the performance index, and techniques employed to analyze the database and to identify bridge performance patterns. We start by outlining some of the fundamental processes that were necessary prior to analysis.

DATA PRE-PROCESSING

The New Mexico National Bridge Inventory (NBI) database describes approximately the records of 4,000 bridges and culverts in New Mexico spanning over 22 years (1983-2004). Each bridge or culvert is described by 132 parameters (attributes) in addition to their corresponding sufficiency rating. Sufficiency rating is the performance criterion used by FHWA to allow decision making for infrastructure maintenance (16). Exemplar bridge attributes include bridge identification values, average daily traffic, detour length, structure kind (material type), structure type, clearance measurements, and structure length along with many others. Data pre-processing was essential to enable computational development. This pre-processing incorporated the removal of un-coded parameters, conversion of non-numeric data to numerical values, and data normalization. Values such as N and other alphabetical coding were transformed into meaningful numerical data that can be handled by the computational algorithms. The normalization process reformatted the data to range between 0 and 1 to prevent numerical bias that can results from numerical weights (17). The pre-processing was carefully documented to allow tracing information back and for future research. Table 1 presents exemplar converted and normalized bridge attributes for
10 exemplar bridges. Description of all bridge attributes and their normalization formulate are provided for reference purposes in Appendix 1.

**TABLE 1: Exemplar conversion and normalization of bridge parameters for 10 bridges.**

<table>
<thead>
<tr>
<th>Bridge #</th>
<th>Parameter # 19: Bypass, Detour Length</th>
<th>Parameter # 29: Average Daily Traffic</th>
<th>Parameter # 58: Condition rating for deck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Normalized</td>
<td>Original</td>
</tr>
<tr>
<td>4269</td>
<td>5</td>
<td>0.0251</td>
<td>685</td>
</tr>
<tr>
<td>6974</td>
<td>10</td>
<td>0.0503</td>
<td>1000</td>
</tr>
<tr>
<td>6843</td>
<td>0</td>
<td>0.0000</td>
<td>25</td>
</tr>
<tr>
<td>7234</td>
<td>82</td>
<td>0.4121</td>
<td>2563</td>
</tr>
<tr>
<td>2647</td>
<td>2</td>
<td>0.0101</td>
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</tr>
<tr>
<td>7858</td>
<td>10</td>
<td>0.0503</td>
<td>100</td>
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<td>646</td>
</tr>
<tr>
<td>6850</td>
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<td>0.0000</td>
<td>1111</td>
</tr>
</tbody>
</table>

**PARAMETER CLASSIFICATION**

Following data conversion and normalization processes, the bridge parameters were then classified into a few major categories. The categorization process aimed at providing an organized perspective of the data that is available to analyze. By identifying parameter

---

1 Unavailable data (N/A) was given the numerical value of (-1) to be excluded from analysis.
categories, the process of identifying the most significant parameters or parameter groups out of the 132 parameters becomes possible. The categorization process also helps a great deal in discovering redundant parameters which might not be needed for initial analysis. The redundancy identification and filtering process is very essential for reducing computational expenses. The bridge parameters are classified into five categories named as bridge parameters, loading parameters, identification parameters, indirect parameters and performance parameters. A brief description of each category follows

1) **Bridge Parameters**: This category includes all physical attributes of the bridge such as geometry, materials and other characteristics used which may affect the bridge performance.

2) **Loading Parameters**: This category includes all parameters describing the nature, type, and intensity of loading on the bridge. Such parameters include Average Daily Traffic (ADT) and percentage of Trucks in Average Daily Traffic.

3) **Identification Parameters**: This category includes all parameters used to index the bridge by number or location. These parameters are very important for the database operation but might have less significance on the bridge performance.

4) **Indirect Parameters**: This category includes miscellaneous parameters that might have indirect effect on the bridge performance. Such parameters include relative humidity exposure from nearby waterways, bridge elevations (weather patterns), and other issues that do not directly relate with bridge characteristics or loading, but might have an affect on the bridge performance.

5) **Performance Parameters**: We consider this category of parameters that represents the bridge performance or in modeling terms what is known as the knowledge rule-base that
relates all bridge attributes to bridge performance. The performance parameters category includes all condition ratings of bridge deck, super and sub structures, appraisal rating and sufficiency rating as well. Condition ratings are defined by the US Federal Highway Administration (FHWA) (16).

Table 2 summarizes the major five categories of the bridge parameters and the bridge parameters falling under each category. A detailed categorization of all the inventory database parameters and explanations for the choice of one category for each parameter is presented in Appendix 2. Figure 1 illustrates an intuitively perceived relationship between the five parametric categories.

FIGURE 1: Schematic representation of parameter categories and bridge knowledge base.
### TABLE 2: Major categories for all parameters of the bridge inventory database

<table>
<thead>
<tr>
<th>Bridge parameters</th>
<th>Loading parameters</th>
<th>Identification parameters</th>
<th>Indirect parameters</th>
<th>Performance parameters</th>
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<tr>
<td>27</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>28a</td>
<td>26</td>
<td>2</td>
<td>3</td>
<td>59</td>
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<td>32</td>
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<td>3</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>33</td>
<td>30</td>
<td>5d</td>
<td>5b</td>
<td>61</td>
</tr>
<tr>
<td>34</td>
<td>31</td>
<td>4</td>
<td>5c</td>
<td>62</td>
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</table>
The four major categories shown to the left represent the knowledge base, while the performance category represents the result of the interaction of these four categories in the knowledge base and thus lies to the right. This schematic representation describes how the independent attributes of bridges are assumed to interact in an unknown mode of aggregation (blue circle) to form the observed performance. A few methods in the literature were reported to be capable of extracting the rules that govern the knowledge base (18-23). Here, we implement statistical and clustering methods to identify the major patterns and components essential for understanding this knowledge base. We also recommend using other group of methods for identifying the bridge parameters-performance knowledge base in future research.

**ESTABLISHING A NEW PERFORMANCE INDEX**

It is evident that the system shown in Figure 1 cannot be established unless a comprehensive performance index (metric) that can accurately represent the bridge performance exists. While the FHWA (16) recommends using the sufficiency rating (SR) for decision making, it is obvious that SR does not accurately represent structural performance, but represents a decision making index that allows considering other issues that does not directly relate to performance but to the decision making. Such issues include the importance of the bridge and its significance on the economy and essentiality for public use during the time of reconstruction or repair. The breakdown of sufficiency rating is represented schematically in Figure 2. The FHWA reports the ability to compute the SR using equations (1) to (10)

\[
SR = S_1 + S_2 + S_3 - S_4
\]  

(1)
Where $S_1$ is the structural adequacy, $S_2$ represents the serviceability and structural obsolescence, $S_3$ represents the essentiality for public use and $S_4$ is a reduction factor to represent the influence of detour length, the traffic safety features on the bridge sufficiency.

Figure 2: Schematic representation of sufficiency rating and factors affecting on it showing the influence of many “non-performance” parameters on SR as a tool for decision making.

The structural adequacy $S_1$ can be computed as

$$S_1 = 55 - (A + B)$$  \hspace{1cm} (2)

$A$ is a function of the minimum of substructure and superstructure rating while $B$ is evaluated according to the Inventory Rating (IR). $B$ shall range between 0 and 55 can be computed as

$$B = (32.4 - IR)^{1.5} \times 0.3254$$  \hspace{1cm} (3)
the serviceability and structural obsolescence, can be computed as

\[ S_2 = 30 - [J + (G + H) + I] \]  

(4)

where

\[ J = (A + B + C + D + E + F) \quad (0 \leq J \leq 13) \]  

(5)

A is a function of deck condition, B is a function of structural evaluation, C is a function of deck geometry, D is a function of under-clearance, E is a function of waterway adequacy and F is a function of approach roadway width. \( G = 5 \), if bridge roadway width < approach roadway width. H is a function of ADT, roadway width, and number of lanes on the structure. I is a function of STRAHNET designation and vertical clearance.

Finally, the essentiality for public use \( S_3 \) can be computed as

\[ S_3 = 15 - (A + B) \]  

(6)

While

\[ A = 15 \left[ \frac{ADT \times Detour\_Length}{320,000 \times K} \right] \]  

(7)

and

\[ K = \frac{S_1 + S_2}{85} \]  

(8)

B is a function of STRAHNET designation. The special reduction parameter \( S_4 \) shall be used when \( S_1 + S_2 + S_3 + S_4 \geq 50 \) and can be computed as

\[ S_4 = A + B + C \]  

(9)

\[ A = (Detour\_Length)^4 \times \left(7.9 \times 10^{-18}\right) \quad (0 \leq A \leq 15) \]  

(10)
B is a function of main structure Type and C is a function of traffic safety structures. Detailed descriptions of all these functions are provided by FHWA guidelines (16).

The above presentation of the SR computation method demonstrates the fact that SR is influenced by many parameters that are not related to performance. Thus, SR might be misleading if used to identify the significance of the various bridge parameters on bridge performance.

Another alternative is to use the structural adequacy (SA) denoted by $S_1$ in equation (2). However, a major drawback in using SA for describing the structural performance of the bridge is its obvious lack of representation of bridge deck condition as shown in Equation (5). It is well known that bridge decks usually represent critical elements in bridge performance (24-26) and therefore bridge deck conditions shall be included in any comprehensive index that describing bridge performance.

Therefore, we suggest developing a comprehensive performance index denoted (PI) that is designed to represent the combined effect of the structural adequacy, the bridge deck condition, and the structural evaluation. The new performance index was developed using fuzzy-set theory to incorporate the uncertainty in the bridge evaluation process for its human dependence and to account for the vagueness and ambiguity in the definitions describing many of the modeling parameters. Therefore, a group of fuzzy sets were first defined over the modeling domains. Three fuzzy sets were defined over each modeling parameters including the structural adequacy, the deck condition and the structural evaluation. The three fuzzy sets represent poor, good and excellent performances for each index independently. The mean and spread of these fuzzy sets were extracted from the inventory database and the definitions of these performance indices by
FHWA (16). The three fuzzy sets for each performance index are shown in Figure 3. Right and left shouldered fuzzy sets were used to represent the fact that performances beyond certain limit will equally represent a performance state (e.g. bridges with SA equal or higher than 50 can all be categorized as “Adequate”. The domain of the proposed performance index (PI) was defined by five uniformly distributed fuzzy sets. The PI domain ranges between 0 and 100 with zero representing the lowest possible performance (low performance) and 100 presenting the highest possible performance (high performance). The level of overlap of the membership functions represents the level of vagueness of these fuzzy sets. Fuzzy sets overlap is an intrinsic advantage in fuzzy set theory to handle ambiguity and vagueness in modeling parameters. The membership values represented by the membership functions describing the different fuzzy sets shall not be considered from the probabilistic (chance) point of view but rather used for scaling hardness (27).

A rule-base that relates the fuzzy sets defined over the modeling parameters to the proposed performance index (PI) was then established using Mamdani fuzzy inference system (10, 18, 28). The Mamdani system is established by considering a linguistic rule-base that relates all the premise parameters to the consequent parameter (the PI). The reason for preferring the Mamdani-based fuzzy inference system over other fuzzy inference-systems (e.g. TSK system (10, 18) for evaluating the performance index (PI)) is attributed to the absence of validation data for this index. TSK-based fuzzy systems are based on combining linguistic and numerical values and are commonly used when numerical validation data is available (18, 29).

The linguistic rule-base combining the premise and consequence parameters are shown in Figure 4. The rule-base was established to express the significance of some parameters (e.g.
structural adequacy) over other parameters (e.g. deck condition) in affecting the overall bridge performance.
FIGURE 3 Graphical representation of fuzzy sets defined over the domains of the parameters influencing bridge performance including [a] Structural Adequacy [b] Deck Condition [c] Structural Evaluation and [d] Performance Index
<table>
<thead>
<tr>
<th>Rule #</th>
<th>Linguistic rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule # 1:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Not Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 2:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 3:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Not Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 4:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Not Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 5:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Not Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 6:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 7:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Superior” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 8:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 9:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Superior” then Performance Index is “Medium Low”</td>
</tr>
<tr>
<td>Rule # 10:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 11:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 12:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Superior” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 13:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Not Tolerable” then Performance Index is “Medium Low”</td>
</tr>
<tr>
<td>Rule # 14:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Not Tolerable” then Performance Index is “Medium Low”</td>
</tr>
<tr>
<td>Rule # 15:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Tolerable” then Performance Index is “Medium”</td>
</tr>
</tbody>
</table>
Table 3 (Continue): Linguistic rules describing the knowledge rule-base relating the structural adequacy, the deck condition and
the structural evaluation to the comprehensive performance index (PI)

<table>
<thead>
<tr>
<th>Rule #</th>
<th>Linguistic rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule # 16:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Superior” then Performance Index is “Medium”</td>
</tr>
<tr>
<td>Rule # 17:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Tolerable” then Performance Index is “Medium”</td>
</tr>
<tr>
<td>Rule # 18:</td>
<td>If Structural Adequacy is “Moderately Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Superior” then Performance Index is “Medium High”</td>
</tr>
<tr>
<td>Rule # 19:</td>
<td>If Structural Adequacy is Adequate and Deck Condition is “Serious Condition” and Structural Evaluation is “Not Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 20:</td>
<td>If Structural Adequacy is “Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Tolerable” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 21:</td>
<td>If Structural Adequacy is “Adequate” and Deck Condition is “Serious Condition” and Structural Evaluation is “Superior” then Performance Index is “Low”</td>
</tr>
<tr>
<td>Rule # 22:</td>
<td>If Structural Adequacy is “Adequate” and Deck Condition is “Fair” and Structural Evaluation is “Not Tolerable” then Performance Index is “Medium Low”</td>
</tr>
<tr>
<td>Rule # 23:</td>
<td>If Structural Adequacy is Adequate and Deck Condition is “Excellent” and Structural Evaluation is “Not Tolerable” then Performance Index is “Medium”</td>
</tr>
<tr>
<td>Rule # 24:</td>
<td>If Structural Adequacy is Adequate and Deck Condition is “Fair” and Structural Evaluation is “Tolerable” then Performance Index is “Medium High”</td>
</tr>
<tr>
<td>Rule # 25:</td>
<td>If Structural Adequacy is Adequate and Deck Condition is “Fair” and Structural Evaluation is “Superior” then Performance Index is “Medium High”</td>
</tr>
<tr>
<td>Rule # 26:</td>
<td>If Structural Adequacy is “Not Adequate” and Deck Condition is “Excellent” and Structural Evaluation is “Tolerable” then Performance Index is “High”</td>
</tr>
<tr>
<td>Rule # 27:</td>
<td>If Structural Adequacy is Adequate and Deck Condition is “Excellent” and Structural Evaluation is “Superior” then Performance Index is “High”</td>
</tr>
</tbody>
</table>
The high significance of the structural adequacy on the overall performance is represented in the rule-base by limiting the overall performance of bridges not to exceed “Medium Low” fuzzy set if the SA is “Not Adequate”. However, it is important to realize that the deck condition effect on the overall performance was also considered as the deck condition can act as a limiting factor in the overall structural performance. This is represented, for example, by rule 21 which limits the overall performance of bridges with serious condition deck even if its structural adequacy and structural evaluation are high.

A total of 26 rules were developed to describe the system. The number of rules is dependent on the number of fuzzy sets defined over each parameter and the number of input parameters considered in the model. Therefore, the number of rules will be exponentially increasing with further increase in input parameters. Methods for rule reduction without significantly affecting the model predictability have been reported elsewhere (30). It can be observed that the linguistic assignments for each input value are constructed conservatively such that fuzzy sets describing high performance bridges have a narrower range than the fuzzy sets describing low performance bridges. For example, under the structural evaluation domain, the “Not Tolerable” fuzzy set ranges between 0 and 4, the “Tolerable” fuzzy set ranges from 0 to 7, while the “Superior” fuzzy set has a smaller range of 6 – 9. This is to limit the number of bridges that have a high membership to the fuzzy sets with high performance expectations.

The fuzzy system operates by relating the premise parameters to the consequence parameters (the PI) using the fuzzy rule-base. The final result of the PI is computed by aggregating the membership values of the different possible rules using the T-norm operator (18, 28) and by defuzzification of the final output. The defuzzification process targets finding a
logical scalar representation of the aggregated rules (18, 21). Many fuzzification methods can be used to find the output (31). Here, the centroid defuzzification method was used to obtain the scalar output. This process takes the centroid of the output resulting aggregated membership function as defined on the PI domain. The resultant $PI^*$ based on centroid defuzzification can be computed as

$$PI^* = \frac{\int \mu_T(PI) \cdot PI \, dPI}{\int \mu_T(PI) \, dPI}$$  \hspace{1cm} (11)$$

The new performance metric (PI) ranges between zero and 100 with zero indicating poor performance and 100 indicating excellent performance. Similar metrics have been developed in the area of infrastructure management for providing a meaningful solution to complex modeling of pavement damage assessment (13). Pictorial representations of the complex relationship relating the new performance index (PI) to the structural adequacy, the deck condition and the structural evaluations are shown in Figures 4 and 56 respectively. The relations shown are established on the basis of the fuzzy rule-base described in Table 3.
FIGURE 4 Complex relationships between the new performance index (PI), the structural adequacy and the deck condition based on the fuzzy sets defined in Figure 3 and the linguistic rule-base defined in Table 3.
FIGURE 5 Complex relationships between the new performance index (PI), the structural adequacy and the structural evaluation based on the fuzzy sets defined in Figure 3 and the linguistic rule-base defined in Table 3.
Comparison between the new performance index and the structural adequacy for a few bridges from the database is shown in Figure 6. Two random sets are shown in which the SA is normalized for comparison against PI which ranges from 0 - 100. It is evident from Figure 4 that the fuzzy-based performance index usually agrees with the structural adequacy defined in the bridge inventory database. Most of the discrepancies are due to the conservative nature of the new performance index, therefore making the PI slightly lower than SA as it takes the deck condition and the structural evaluations into account.

FIGURE 6 Comparison between SA and the new performance index (PI) for two randomized sets of data.
Preliminary Statistical Analysis

Once the comprehensive performance index (PI) was established, preliminary statistical analysis was performed to explore the database. The statistical analysis was conducted on random datasets of the ten different material types, and the thirteen different structure types. The analysis considered the sufficiency rating (SR), the structural adequacy (SA) and the performance index (PI) as possible metrics to describe bridge performance. Two cases of analysis were considered. First we isolated certain parameters like ADT, material type, and structure type to find which cases had high performance and which cases had low performance. Second, we considered an average values for material type and structure type for each year to find general performance trends.

To reveal deterioration rates for several material types and structure types, we studied the change in structural adequacy over time by quantifying the loss in structural adequacy (LSA) for different types of materials. LSA is defined as

\[ LSA = SA_{\text{max}} - SA \]  \hfill (12)

where \( SA \) is the structural adequacy defined by FHWA (12) that has a maximum value of \( SA_{\text{max}} \) reported by FHWA to be 55 and \( LSA \) is the loss in structural adequacy. Based on Equation (12), LSA ranges between 0 and 55 with zero representing a very adequate bridge and 55 representing a very poor bridge. Each set of data was randomly selected for each type of analysis.

All statistical analysis was performed on groups of several sets of data randomly selected from the inventory database. Randomized analysis provides the confidence to generalize the results as that drawn from the whole population. Randomized sampling was performed using the boot-strap technique (32).
Hierarchical Clustering

The preliminary analysis was followed by performing hierarchical clustering, which serves as our main tool for a multidimensional classification to group similar datasets based on a multitude of attributes. Clustering techniques are used for performance pattern recognition (23, 33). As an unsupervised method, clustering can provide an efficient and computationally inexpensive technique for feature extraction with the advantage of being reversible for inference. Through classification, data can be grouped and analyzed. Clustering techniques are comparable in performance to Hidden Markov Models (maximum likelihood estimations) (18, 23, 32). An in-depth level of classification is achieved by including many parameters in the classification process.

Hierarchical clustering is well equipped to deal with multiple parameters by creating clusters at each stage of the classification process with regard to a different parameter. In essence, each cluster is sub-clustered, which creates a “dendogram”, or tree-like structure, that summarizes the hierarchy format. This classification process not only classifies data in steps, but also creates a path that can be followed to establish a knowledge rule-base that describes the complex relationships between bridge attributes and bridge performance patterns. The objective of the hierarchical clustering was to find the commonalities between the different bridges. Random datasets were sub-clustered into sub-sets with common attributes and so on. This allowed inferring which bridge attributes helped to enhance bridge performance and which attributes might have resulted in a reduced bridge performance. Thus, the hierarchical clustering established a hierarchical tree structure that resulted in a knowledge rule-base, which relates
bridge attributes to bridge performance patterns. Figure 7, shows an example case of the hierarchical clustering to infer bridge performance patterns.

K-means clustering method was used to provide the main and sub clusters in each cycle of analysis. K-means clustering has the advantage of quick convergence and being computationally inexpensive (23,33). This method is also referred to as nearest neighborhood clustering. For a sample set of n data samples with m features such that

\[
X = \{x_1, x_2, x_3, x_4, \ldots, x_n\}
\]

\[
x_i = \{x_{i1}, x_{i2}, x_{i3}, x_{i4}, \ldots, x_{im}\}
\]

\[
X = \{x_1, x_2, x_3, x_4, \ldots, x_n\}
\]

\[
x_i = \{x_{i1}, x_{i2}, x_{i3}, x_{i4}, \ldots, x_{im}\}
\]

**FIGURE 7** Tree structure based on hierarchical clustering

The K-means technique creates k clusters such that \(2 < k < n\) by minimizing an objective function \(J\) based on the Euclidean distance between the data samples \(x_i\) in the cluster and clusters centers \(v_j\). The objective function is thus defined as
\[ J(U,v) = \sum_{j=1}^{n} \sum_{i=1}^{k} \chi_{ij}(d_{ij})^2 \]  (15)

Where \( d_{ij} \) is the Euclidean distance measure of \( m \) dimensional feature space between the \( j^{th} \) data sample \( x_{ij} \) and the \( i^{th} \) cluster and \( \chi_{Ai}(x_j) \) is a characteristic function deciding on the belonging of the data sample \( x_j \) to the \( i^{th} \) cluster \( A_i \) as

\[
\chi_{A_i}(x_j) = \begin{cases} 
1, & x_j \in A_i \\
0, & x_j \notin A_i 
\end{cases}
\]  (16)

Each set of data for the clustering analysis was randomly selected using bootstrapping, a method of Monte Carlo simulation, in which each probability mass has the same likelihood of being selected (31).

**RESULTS AND DISCUSSION**

Exemplar results of the statistical analysis of a two random data sets are shown in Figure 8. The plots in Figure 8 can be divided into three categories by age: young (0-15 years), middle-aged (15-30 years), and old bridges (over 30 years). Figure 9 shows age versus normalized sufficiency rating for different material types for two random datasets considering young and middle age bridges. The preliminary statistical analysis showed continuous steel bridges to have a significantly good performance while performance of masonry bridges tend to fluctuate significantly. The level of ADT is also considered in this analysis. Figure 10 shows ADT levels in four random sets: two for young bridges and two for old bridges. It can be observed that bridges experiencing medium level of ADT (max of 137- vehicles per day) were capable of maintaining good performance over age. Moreover, bridges exposed to high level of ADT (above 23000 vehicles per day) observed significant performance deterioration with age.
FIGURE 8 Age versus normalized sufficiency rating [a] material type [b] structure type
Figure 9 Age versus Normalized Sufficiency Rating for material type
[a] Random set 1 of young bridges, [b] random set 2 of young bridges,
[c] random set 1 of middle-aged bridges, and [d] random set 2 for middle-aged bridges
FIGURE 10 Age versus Normalized Sufficiency Rating for ADT levels
[a] Random set 1 of young bridges, [b] random set 2 of young bridges,
[c] random set 1 of old bridges, and [d] random set 2 for old bridges
The preliminary statistical investigations showed that the rate of performance deteriorations is strongly dependent on the material type. Figure 11 shows an exemplar case for young bridges (younger than 35 years of age). Figure 11 presents the observation that concrete bridges tend to have high performance (low LSA) and its performance is steady for long period of time while steel bridges tend to have performances lower than that of concrete (relatively high LSA) and tend to observe abrupt changes in performance. It was usually observed that steel bridges seemed to start showing minor deficiency after 15-20 year of service life.

FIGURE 11 Age versus loss in structural adequacy (LSA) for young bridges (younger than 35 years of age) [a] concrete [b] steel. Legend identifies bridge numbers.
The previous observation is also evident for old bridges (35 years of age and older). Figure 12 shows the change in the LSA with age for old concrete and steel bridges. While only one deteriorating bridge can be observed in the concrete sample, a few deteriorating steel bridges can be observed in the steel sample. Similar observations were recorded during the analysis of most randomized datasets. Another interesting observation was apparent at the 45 years of age mark for which many concrete bridges begin to start showing deterioration. Figures 11 and 12 are representative of other examples for the effect of age on deterioration rates. Reverse slopes represent repair effects, performance error, and/or subjective evaluation effects. While the information presented represents a general idea on bridge deterioration rates, they also prove the existence of a considerable level of uncertainty in the database records that might not be possible to handle using classical methods.

The analysis using hierarchical clustering represents a cornerstone for our findings. The analysis was performed on the three performance metrics separately (the structural adequacy (SA) and the performance index (PI)). An example of hierarchical clustering is presented in
Figure 13. Each hierarchical plot is distinguished by colors. Cluster 1 of each plot is always blue, cluster 2 is red, and cluster 3 is green. Hierarchical clustering of four more random using SA and four other random sets using the PI are shown in Appendix 3.

FIGURE 13 Hierarchical k-means clustering plots for a group of randomly selected bridges [a] Cluster C1, C2 and C3, [b] Sub-clusters C11, C12 and C13 [c] Sub-clusters C111, C112 and C113
We demonstrate an example of the hierarchical path that can be followed to isolate bridge clusters with similar characteristics. This path allows establishing the knowledge rule-base that relates bridge performance indices to bridge attributes. The hierarchical path can be better understood with the aid of Figure 7 as clusters being divided into k sub-clusters in the m dimensional feature space. Figure 13 [a] presents the three major clusters that can be found in a set of bridges randomly selected from the inventory database. The first clustering feature here is age. The next step in the hierarchical process is to isolate cluster 1 from Figure 13 [a], denoted C1, which in this case represents old bridges with good performance (bridges older than 40 years of age and with high structural adequacy). The isolation of C1 is one of three possible paths as shown in Figure 13 [a]. The data samples in cluster 1 are then sub-clustered with respect to the second feature space, which is the average daily traffic (ADT). Figure 13 [b] shows three new sub-clusters: C11, C12 and C13. By observing sub-cluster C11, this sub-cluster represents a group of bridges that are characterized by having a high structural adequacy, older than 40 years of age, and with low ADT. Going one step further and sub-clustering this group of bridges (C11) with respect to maximum span length leads to Figure 13 [c]. This figure shows three more clusters with the sub-cluster C111 representing bridges that are have high structural adequacy, older than 40 years of age, low ADT and short spans.

Analysis of these clusters and sub-clusters can reveal the fundamental bridge characteristics that might have lead to such performance. For example, analysis of material type distributions within the major clusters and sub-clusters can allow us to understand if specific types of materials dictated low or high performances in bridges. Figure 14 [a] illustrates the material type distribution within the entire randomized dataset. Moreover Figure 14 [b] the material type
distribution within sub-cluster C111 [b]. It is evident that concrete and continuous concrete bridges represent the majority of bridges in the randomized set. This was found to be true for all randomized sets in the analysis. This fact is represented in the composition the dataset (Figure 14 [a]) with concrete bridge forming (52%) of the bridges in the random set. Observing the sub-cluster C111, concrete bridges represent 80% of this sub-cluster. This means other types of materials have dropped from this cluster that presents those bridges which have high structural adequacy, older than 40 years of age and experiencing low ADT and short spans. Considering this cluster description, it becomes evident that concrete contributes to the structural performance of this class of bridges. The analysis was repeated for six times on randomized datasets to guarantee coming to general conclusions. All the results of the sub-analysis of material and structural type distributions of the sub-clusters for all the random datasets are presented in Appendix 4.

FIGURE 14 Material type distribution [a] Randomized dataset  [b] Sub-cluster C111

However, it is important to put caution in coming to general conclusions, realizing that some of these observations/findings may also be dictated by interactions with other bridge parameters.
This seems to be the case shown in Figure 15. Since most concrete continuous structures in the inventory database represent culverts (79%), the observed performance might not be attributed to the bridge being a concrete continuous bridge but to the bridge serving as a culvert. Figure 15 [a] shows the material type distribution of the same random dataset of bridges after excluding culverts. Figure 15 [b] shows the material type distribution of sub-cluster C11 after excluding culverts. It is evident that little change in the material type distribution with respect to concrete can be observed considering the whole random dataset and the sub-cluster C11. Although the results still show concrete bridges to perform well the magnitude of this finding is not as significant as it is from the original analysis shown in Figure 14. Given the fact that the preliminary statistical analysis of the database always showed culverts to have a high performance, it appears that the structural type here rather than the material type might be dictating the performance. It is also obvious that analysis of the sub-clusters can provide much detailed information that can help establishing the knowledge-base that relates bridge performance and bridge attributes.

![FIGURE 15 Material type distribution without culverts](image)

[a] Randomized dataset  [b] Sub-cluster C11
Another example of the hierarchical clustering is shown here. In this example, we start in Figure 16 [a] by considering cluster 3 (green), which indicates an old set of bridges that have a wide range in structural adequacy ranging between medium low to high. Upon sub-clustering of this set, we reach the clusters shown in Figure 16 [b]. Consider those bridges with moderate level of ADT (green cluster).

**FIGURE 16** Hierarchical k-means clustering plots for a group of randomly selected bridges [a] Cluster C1, C2 and C3, [b] Sub-clusters C31, C32 and C33 [c] Sub-clusters C331, C332 and C333
We perform one further clustering step and we reach Figure 16 [c] which shows three clusters. These clusters represent bridges with very high performance and short spans (under 10 m) represented by the blue cluster, bridges with medium to high performance with long spans and finally bridges with low performance with variable spans ranging from low to medium (red cluster).

**FIGURE 17** Material type distribution throughout the hierarchical clusters

[a] Randomized dataset  [b] Sub-cluster C3  
[c] Sub-cluster C33, and [d] Sub-cluster C331
Performing the material and structural type distributions of these clusters, we try to identify the factors that dictate such performance. Figure 17 shows material type distributions throughout this hierarchical step process. Figure 17 [a] simply represents the material type distribution within the whole dataset. Figure 17 [b] represents the material type distribution within high performance and old bridges cluster. Figure 17 [c] represents the material type distribution within high performance and old bridges with medium ADT level. Finally, Figure 17 [d] within high performance and old bridges with medium ADT level and short spans. It is noticeable that the percentage of concrete continuous bridges has increased significantly through the first two steps of the hierarchical analysis. This observation becomes further evident considering Figure 17 [d] where the percentage of concrete continuous bridges took a great jump.

Considering the structural type distribution into the analysis, Figure 18 shows the possible interactions between the structural type and the material type. It is very evident again that culverts are highly present in this high performing cluster. Therefore it is obvious that culverts have high performance and most likely are one reason for observing the significant contribution of concrete continuous to high performing clusters.

A path to a poor performing cluster is shown in Figure 19. We consider sub-cluster 2 (red) in Figure 16 [a]. Upon sub-clustering, Figures 19 [a] and [b] are generated. To explain, the blue cluster in Figure 19 [b], represents bridges with low performance, medium ADT and long span lengths. We then perform the composition analysis of this cluster to reveal its material and structural type distributions.
FIGURE 18 Structural type distribution  
[a] Randomized dataset  
[b] Sub-cluster C3  
[c] Sub-cluster C33, and  
[d] Sub-cluster C331
FIGURE 19 Hierarchical k-means clustering plots for a group of randomly selected bridges [a] Sub-cluster 2  [b] Sub-cluster 21

Figure 20 [a] shows the material type distribution and Figure 20 [b] shows the structural type distribution of the poor performing cluster C21 from Figure 19 [b]. Figure 18 is to be compared to the initial distributions found in Figures 17 [a] and 18 [a].

FIGURE 20 Distributions of C211 [a] Material type [b] Structural Type
It is evident from Figure 20 [a] that pre/post-tensioned concrete is highly prevalent within this low performing cluster. On the other hand, it is evident from Figure 20 [b] that stringers/multiple beam girders represent as much as 79% of the entire low performing cluster. This situation has been found repetitively in analysis of low performing clusters.

FIGURE 21 Hierarchical k-means clustering plots for a group of randomly selected bridges
[a] Cluster C1, C2 and C3, [b] Sub-clusters C11, C12 and C13
[c] Sub-clusters C131, C132 and C133
The hierarchical clustering analysis was repeated the performance index (PI). Figure 21 shows another example of hierarchical clustering, but with respect to the performance index (PI). The analysis is similar to that described above, where a group of distinct paths are followed and the analysis is performed to isolate high and low performing bridges and trace down the bridge characteristics that might have lead to these performances. We demonstrate here an exemplar case considering a high performance cluster while clustering against the new performance index (PI). We start by following the high performing cluster which spans between young and old bridges (Figure 21 [a]). We proceed to consider those high performance bridges with low ADT (blue cluster) and we consider the high performance, low ADT and short span bridges (Figure 21 [c]).

![FIGURE 22 Material Type Distribution](image)

**FIGURE 22 Material Type Distribution**  [a] Randomized data set  [b] Sub-cluster C131
FIGURE 23 Structural Type Distribution  [a] Randomized data set  [b] Sub-cluster C131

Performing materials and structural type analysis of this random set we try to trace the bridge attributes that mostly influence the structural performance. The material and structural types analysis for this random sets considering the PI are shown in Figures 22 and 23 respectively. It can be observed from Figure 22 that pre/post-tensioned concrete jumps from 20% representing the random set to 30% representing the high performance cluster. This shows that considering the overall performance index, the post-tensioned concrete seems to be contributing to high performance bridges. On the other hand, concrete continuous bridges show a significant decrease from 38% in the random set to 24% in the high performance cluster. This observation has been found repetitively in all hierarchical clustering analysis considering the PI as the performance index. While this observation contradicts with the observations shown early considering the structural adequacy (SA) as the performance index, it sheds interesting finding to the analysis.

The change in the evaluation is mainly because of considering the condition of the bridge deck condition in evaluating the PI while neglecting it when considering the SA. It is evident from experience as well as from many sources in the literature that post-tensioned structures will
usually show good crack control of the bridge deck and there for mostly high performing bridge decks. Moreover, it is also evident from the literature that concrete continuous bridges will usually yield significant bridge deck cracking and thus will affect the bridge deck conditions. The analysis showed these two types to contribute adversely to the PI which is affected by the bridge condition. The interesting issue here is that the analysis of what is called “performance” is strongly dependent on our definition of performance. If both the bridge deck condition and the structural evaluation are considered along with the structural adequacy in defining the bridge performance, the final conclusions and recommendations for best practices to enhance performance of bridges might be different than if the structural adequacy solely is considered as the defining factor.

**CONCLUSIONS**

We demonstrated here the possible use of clustering techniques to analyze a high dimensional bridge inventory database to reveal bridge performance patterns and to relate these patterns to the underlying bridge attributes.

While many patterns can be observed in the bridge inventory database, only 8 significantly different patterns were identified considering principles of statistical significance. These patterns can be described as
### Bridges Performing Well

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Material Type</th>
<th>Span</th>
<th>ADT</th>
<th>Pattern Frequency%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Span Multi-girder Bridge</td>
<td>Pre-Post Tensioned Concrete</td>
<td>&gt; 25 m</td>
<td>High &gt; 60,000 veh/day</td>
<td>78%</td>
</tr>
<tr>
<td>Continuous Multi-girder Bridge</td>
<td>Pre-Post Tensioned Concrete</td>
<td>&gt; 25 m</td>
<td>High &gt; 60,000 veh/day</td>
<td>72%</td>
</tr>
<tr>
<td>Continuous Multi-girder Bridge</td>
<td>Steel</td>
<td>&gt; 25 m</td>
<td>High &gt; 60,000 veh/day</td>
<td>69%</td>
</tr>
<tr>
<td>Simple Span Slab Bridge</td>
<td>Reinforced Concrete</td>
<td>&lt; 15 m</td>
<td>Low &lt; 40,000 veh/day</td>
<td>63%</td>
</tr>
</tbody>
</table>

### Bridges Not Performing Well

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Material Type</th>
<th>Span</th>
<th>ADT</th>
<th>Pattern Frequency%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch-Thru</td>
<td>Concrete</td>
<td>&gt; 40 m</td>
<td>Med to High &gt; 45,000 v/day</td>
<td>64%</td>
</tr>
<tr>
<td>Arch-Thru</td>
<td>Steel</td>
<td>&gt; 40 m</td>
<td>Med to High &gt; 45,000 v/day</td>
<td>68%</td>
</tr>
<tr>
<td>Box Beams</td>
<td>Prestressed Concrete</td>
<td>&gt; 25 m</td>
<td>High</td>
<td>77%</td>
</tr>
<tr>
<td>Frames</td>
<td>Steel</td>
<td>&gt; 40 m</td>
<td>Almost All</td>
<td>74%</td>
</tr>
<tr>
<td>Truss-Thru</td>
<td>Steel</td>
<td>Almost All</td>
<td>Almost All</td>
<td>88%</td>
</tr>
</tbody>
</table>

We have also presented a method using fuzzy set theory to develop a comprehensive bridge performance index that is based on multi-performance features that can realistically represent bridge performance.

The investigation results based on unsupervised statistical analysis and hierarchical clustering were presented. The results showed the possible classification of the bridge performance patterns and identify the bridge characteristics (attributes) that strongly affect these patterns. A tree-structure allows building a knowledge base that can relate the different bridge attributes to the performance criteria and their patterns.
We presented many exemplar cases showing the possible identification of bridge attributes and their relation to the performance criteria using the hierarchical clustering technique. The hierarchical clustering process was performed on six randomized sets for both the structural adequacy and the fuzzy-based performance index (PI).

The investigations proved that structural and material types have significant influence on bridge performance. While other important factors such as age, the average daily traffic and the maximum span length have significant affects as well, the material and structural dictates the effects of these other parameters on bridge performance.

Finally, the investigations found that structural and material types have significant influences on bridge performance. Nevertheless, the investigations proved that the method of defining performance has a strong influence on the research findings. When considering the structural adequacy as the bridge performance criterion, it becomes obvious that concrete bridges had better performance records than steel ones. Moreover, multi-girder bridges typically showed poor performance especially when exposed to high average daily traffic. On the other hand, when considering the comprehensive performance index as the bridge performance criterion, concrete continuous bridges showed low performance in general while pre and post-tensioned concrete bridges were usually on the well performing side.

**FUTURE RESEARCH**

The methods described here represent a good start for patterning bridge performance and relating this performance to bridge attributes. The hierarchical clustering was used to identify the significant bridge attributes, the results of this clustering analysis shall be used in developing a complete knowledge base that can be used for predicting performances of bridges to help the
decision making process at the design stage. We thus suggest three major steps are needed to complete this investigation. These steps can be summarized as

1- Extend the inventory database using *PONTIS* software to fill in the information gaps currently existing.

2- Analysis of the complete database to confirm the findings of primary bridge attributes using Bayesian Model Screening (BMS) technique (34). Preliminary investigations of this method showed its efficiency in confirming our findings. The analysis performed using Bayesian statistical rules can help identifying the fundamental factors and processes that affect bridge performance.

3- Using the results of this report and finding from step 1 and 2 to establish an intelligent simulation module that can predict bridge performance based on its attributes using principles of intelligent learning from examples.
REFERENCES


(34) Reda Taha, M.M., J.L., Lucero, T.J. Ross, Examining the significance of mortar and brick unit properties on masonry bond strength using Bayesian model screening. Proc. 10th Canadian Masonry Symposium, Banff, Canada, 10p.
APPENDIX 1:

Key for Data Normalization

Item #2 Highway Agency District (Col 2)
The code represents the highway district number
There is no change made for normalization

Item #3 Country Parish Code (Col 3)
The code represents the FIPS code
There is no change made for normalization

Item #4 Place Code (Col 4)
The code represents the FIPS code
There is no change made for normalization

Item #5b Route Signing Prefix (Col 6)
1 = Interstate highway
2 = U.S. numbered highway
3 = State highway
4 = County highway
5 = City Street
6 = Federal lands road
7 = State lands road
8 = Other
There is no change made for normalization

Item #5c Designated Level of Service (Col 7)
0 = None of the below
1 = Mainline
2 = Alternate
3 = Bypass
4 = Spur
6 = Business
7 = Ramp, Wye, Connector, etc.
8 = Service and/or unclassified frontage road

\[ N_f = \frac{N_i}{8} \]

Item #8 Structure Number (Col 13)
The code represents the structure number
There is no change made for normalization (index)

Item #16 Latitude (Col 20)
The code represents the latitude of the structure

\[ \frac{1}{6} \left( dd - 31 + \frac{mm}{60} + \frac{ssss}{360000} \right) \]
d = degrees  m = minutes  s = seconds

* The latitude is constricted to the bounds of New Mexico with the smallest latitude possible of 31 degrees

One-sixth of the difference in latitude of the bridge and the base latitude of New Mexico

Item #17 Longitude (Col 21)
The code represents the longitude of the structure
\[
\frac{1}{6.19} \left( ddd - 103 + \frac{mm}{60} + \frac{sss}{360000} \right)
\]

* The longitude is constrained the bounds of New Mexico with the western-most longitude possible of 103 degrees

One-sixth of the difference in longitude of the bridge location and the longitude of the western-most boundary of New Mexico

**Item #19 Bypass, Detour Length (Col 22)**
The code represents the length of detour in kilometers

\[ N_f = \frac{N_i}{199} \]

* The max quantity is 199
All values are divided by 199

**Item #20 Toll (Col 23)**
1 = Toll Bridge – tolls specifically to use structure
2 = Toll Road – structure carries toll road
3 = Free Road – toll free structure and road
4 = Interstate Toll Segment – structure is part of toll segment
5 = Toll Bridge is Segment – structure is separate from highway segment

\[ N_f = \frac{N_i - 1}{4} \]

All values are subtracted by 1, then divided by 4

<table>
<thead>
<tr>
<th>Item</th>
<th>#26 Functional Classification of Inventory Route (Col 26)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>Urban</td>
</tr>
<tr>
<td>01</td>
<td>Principal Arterial – Interstate</td>
</tr>
<tr>
<td>02</td>
<td>Principal Arterial – Other</td>
</tr>
<tr>
<td>06</td>
<td>Minor Arterial</td>
</tr>
<tr>
<td>07</td>
<td>Major Arterial</td>
</tr>
<tr>
<td>08</td>
<td>Minor Collector</td>
</tr>
<tr>
<td>09</td>
<td>Local</td>
</tr>
<tr>
<td>11</td>
<td>Principal Arterial – Interstate</td>
</tr>
<tr>
<td>12</td>
<td>Principal Arterial – Other</td>
</tr>
<tr>
<td>14</td>
<td>Other Principal Arterial</td>
</tr>
<tr>
<td>16</td>
<td>Minor Arterial</td>
</tr>
<tr>
<td>17</td>
<td>Collector</td>
</tr>
<tr>
<td>19</td>
<td>Collector</td>
</tr>
</tbody>
</table>

\[ N_f = \frac{N_i - 1}{20} \]

All values are subtracted by 1, then divided by 20

**Item #27 Year Built (Col 27)**
The code represents the year that the structure was constructed

\[ N_f = \frac{YOF - N_i}{120} \]

All values are subtracted from the year of the file, then divided by 120.

**Item #28a Lanes on Structure (Col 28)**
The code represents the number of lanes on a structure

\[ N_f = \frac{N_i}{20} \]

All values are divided by 20
Item #28b Lanes Under Structure (Col 29)
The code represents the number of lanes under a structure
\[ N_f = \frac{N_i}{12} \]
All values are divided by 12

Item #29 Average Daily Traffic (Col 30)
The code represents the volume of vehicles per day
\[ N_f = \frac{N_i}{216000} \]
All values are divided by 216,000

Item #30 Year of Average Daily Traffic (Col 31)
The code represents the year of the Average Daily Traffic
\[ N_f = \frac{YOF - N_i}{70} \]
All values are subtracted from the year of the file, then divided by 70

Item #31 Design Load (Col 32)
1 = M 9 (Metric) or H 10 (English)
2 = M 13.5 or H 15
3 = MS 13.5 or HS 15
4 = M 18 or H 20
5 = MS 18 or HS 20
6 = MS 18+mod or HS 20+mod
7 = Pedestrian
8 = Railroad
9 = MS 22.5 or HS 25
0 = Other or Unknown
\[ N_f = \frac{N_i}{9} \]
All values are divided by 9

Item #32 Approach Roadway Width (Col 33)
The code represents the width if the approach roadway in meters
\[ N_f = \frac{N_i}{190} \]
All values are divided by 190

Item #33 Bridge Median (Col 34)
0 = No Median
1 = Open Median
2 = Closed Median
3 = Closed Median
\[ N_f = \frac{N_i}{3} \]
All values are divided by 3

Item #34 Degrees Skew (Col 35)
The code represents the angle skewed in degrees
\[ N_f = \frac{N_i}{100} \]
All values are divided by 100

**Item #35 Structure Flared (Col 36)**
0 = No Flare  \hspace{1cm} 1 = Yes, Flare

\[ N_f = N_i \]

There is no change needed for normalization

**Item #36a Bridge Railings (Col 37)**
0 = Inspected Feature does not meet acceptable standards
1 = Inspected Feature meets acceptable standards
N = Not applicable, or safety feature is not required

\[ N_f = N_i \hspace{0.5cm} \text{if } N_i = N, \text{ then } N_f = -1 \]

There is no change needed for normalization, except substitution for N with -1

**Item #36b Transitions (Col 38)**
*Uses the same coding and has the same normalization as 36a

**Item #36c Approach Guardrail (Col 39)**
*Uses the same coding and has the same normalization as 36a

**Item #36d Approach Guardrail Ends (Col 40)**
*Uses the same coding and has the same normalization as 36a

**Item #37 Historical Significance (Col 41)**
1 = On National Register of Historic Places
2 = Eligible for National Register of Historic Places
3 = Possibly Eligible for National Register of Historic Places
4 = Historical significance is not determinable at time
5 = Not eligible for National register of Historic Places

\[ N_f = \frac{N_i - 1}{4} \]
All values are subtracted by 1, then divided by 4

**Item #38 Navigation Control (Col 42)**
N = Not Applicable
0 = No Navigation control on waterway
1 = Navigation control on waterway

\[ N_f = N_i \hspace{0.5cm} \text{if } N_i = N, \text{ then } N_f = -1 \]

There is no change needed for normalization, except substitution for N with -1

**Item #41 Structure Open, Posted, or Closed to Traffic (Col 45)**
A = 0 = Open, no restrictions
B = 1 = Open, posting recommended, but not legally implemented
D = 2 = Open, would be posted/closed except for temp. shoring
E = 3 = Open, temp. structure carries load while structure is being replaced/rehabilitated
G = 4 = New structure not yet open to traffic
K = 5 = Bridge closed to all traffic
P = 6 = Posted for load and other restrictions
R = 7 = Posted for other load capacity restrictions: speed, vehicles, etc.

\[ N_j = \frac{N_i}{7} \]

All values are converted, then divided by 7

Item #42a Type of Service on Bridge (Col 46)
1 = Highway
2 = Railroad
3 = Pedestrian-Bicycle
4 = Highway-Railroad
5 = Highway-Pedestrian
6 = Overpass (2nd level of interchange)
7 = Third level of interchange
8 = Fourth level of interchange
9 = Building or plaza
0 = Other

\[ N_j = \frac{N_i}{9} \]

All values are divided by 9

Item #42b Type of Service under Bridge (Col 47)
1 = Highway, with or without pedestrian
2 = Railroad
3 = Pedestrian-Bicycle
4 = Highway-Railroad
5 = Waterway
6 = Highway-Waterway
7 = Railroad-Waterway
8 = Highway-Waterway-Railroad
9 = Relief for waterway
0 = Other

\[ N_j = \frac{N_i}{9} \]

All values are divided by 9

Item #43a Structure Kind, Main: Material and/or Design (Col 48)
1 = Concrete
2 = Concrete continuous
3 = Steel
4 = Steel continuous
5 = Prestressed/Post-tensioned concrete
6 = Prestressed/Post-tensioned concrete continuous
7 = Wood or Timber
8 = Masonry
9 = Aluminum, Wrought Iron, or Cast Iron
0 = Other

\[ N_j = \frac{N_i}{9} \]

All values are divided by 9

Item #43b Structure Type, Main: Design and/or Construction (Col 49)
01 = Slab
02 = Stringer/Multi-Beam or Girder
03 = Girder and Floor beam System
04 = Tee Beam
05 = Box Beam or Girders –Multiple
06 = Box Beam or Girders – Single
07 = Frame (exception – culverts)
08 = Orthotropic
09 = Truss-Deck
10 = Truss-Thru
11 = Arch-Deck
12 = Arch-Thru
13 = Suspension
14 = Stayed Girder
15 = Movable-Lift
16 = Movable-Bascule
17 = Movable-Swing
18 = Tunnel
19 = Culvert (Includes Frame)
20 = Mixed Types (approach spans)
21 = Segmental Box Girder
22 = Channel Beam
00 = Other

All values are divided by 22

Item #44a Approach Material and/or Design (Col 50)
Refer to Item 43a for coding values

\[ N_f = \frac{N_i}{9} \]

All values are divided by 9

Item #44b Approach Type of Design and/or Construction (Col 51)
Refer to Item 43b for coding values

\[ N_f = \frac{N_i}{22} \]

All values are divided by 22

Item #45 Number of Spans in Main Unit (Col 52)
The code represents the number of spans in the main unit

\[ N_f = \frac{N_i}{120} \]

All values are divided by 120

Item #46 Number of Approach Spans (Col 53)
The code represents the number of spans in the approach

\[ N_f = \frac{N_i}{8000} \quad \text{* Max = 7000} \]

All values are divided by 8000

Item #48 Length of Maximum Span (Col 55)
The code represents the length of the maximum span in meters

\[ N_f = \frac{N_i}{280} \quad \text{* Max = 251} \]

All values are divided by 280

Item #49 Structure Length (Col 56)
The code represents the length of the structure from abutments/paving notches in meters

\[ N_f = \frac{N_i}{800} \quad \text{* Max = 705} \]
Item #50a Left Curb/Sidewalk Width (Col 57)
The code represents the width of the left curb/sidewalk in meters
\[ N_f = \frac{N_i}{32} \quad \text{if } N_i = N \]
\[ * \text{ Max } = 30.2 \]
All values are divided by 32

Item #50b Right Curb/Sidewalk Width (Col 58)
The code represents the width of the right curb/sidewalk in meters
\[ N_f = \frac{N_i}{32} \quad \text{if } N_i = N \]
\[ * \text{ Max } = 27.6 \]
All values are divided by 32

Item #51 Bridge Roadway Width, Curb to Curb (Col 59)
The code represents the bridge roadway width from curb to curb
\[ N_f = \frac{N_i}{150} \]
All values are divided by 150

Item #52 Deck Width, Out to Out (Col 60)
The code represents the out to out width of the deck in meters
\[ N_f = \frac{N_i}{150} \]
All values are divided by 150

Item #58 Condition Rating: Deck (Col 67)
N = Not Applicable
9 = Excellent Condition
8 = Very Good Condition – no problems noted
7 = Good Condition – some minor problems
6 = Satisfactory Condition – structural elements show minor deterioration
5 = Fair Condition – S.E. are sound, but have minor section loss, cracking, etc.
4 = Poor Condition – advanced section loss, deterioration, spalling, or scour
3 = Serious Condition – loss of section, deterioration, spalling, local failures possible
2 = Critical Condition – advanced deterioration of primary element; fatigue cracks; closure may be necessary if corrective action is not taken
1 = “Imminent Failure Condition” – major deterioration or section loss in critical structural members; horizontal movement affecting stability; Bridge closed
0 = Failed Condition – out of service; beyond corrective action
\[ N_f = \frac{N_i}{9} \quad \text{if } N_i = N, \quad N_f = -1 \]
All numerical codes are divided by 9 and N is converted to -1

Item #59 Condition Rating: Superstructure (Col 68)
*Uses same coding and has same normalization as Item 58
Item #60 Condition Rating: Substructure (Col 69)
*Uses same coding and has same normalization as Item 58

Item #61 Condition Rating: Channel and Channel Protection (Col 70)
N = Not applicable: Bridge is not over a waterway
9 = There are no noteworthy deficiencies which affect the condition of channel
8 = Banks are protected or well vegetated; River control devices are sufficient if present
7 = Bank protection needs minor repairs; River control devices have minor damage;
   Banks/Channels have minor amounts of drift
6 = Bank is beginning to slump; River control devices have widespread minor damage;
   Minor stream bed movement; Debris is restricting channel
5 = Bank protection is being eroded; River control devices have major damage; Tress and
   brush restrict the channel
4 = Bank and embankment protection is severely undetermined; River control devices
   have severe damage; Large deposits of debris are in the channel
3 = Bank protection has failed; River control devices have been destroyed; Steam bed
   aggradation/degradation/lateral movement changed to threaten bridge/roadway
2 = The channel has changed to the extent the bridge is near collapse
1 = Bridge closed to channel failure; Corrective action may put back in light of service
0 = Bridge closed to channel failure; Replacement necessary

\[
N_f = \frac{N_i}{9} \quad \text{if } N_i = N, \quad N_f = -1
\]

All numerical codes are divided by 9 and N is converted to -1

Item #62 Condition Rating: Culverts (Col 71)
N = Not applicable: Structure is not a culvert
9 = No deficiencies
8 = No noteworthy deficiencies which affect the condition of culvert; scrapes from drift
7 = Shrinkage cracks, light scaling, insignificant spalling; no corrective action needed
   small damage from drift; minor scouring at curtain walls/wing walls/pipes; metal
   culverts have superficial corrosion or moderate pitting;
6 = Deterioration, minor chloride contamination, cracking/leaching/spalls on masonry
   walls or concrete; local minor scouring at curtain walls/wing walls/pipes; metal
   culverts have significant corrosion or moderate pitting
5 = Moderate to major deterioration; extreme cracking and leaching/spalls on concrete or
   masonry walls; minor settlements/misalignments; noticeable scouring/erosion at
   curtain walls/wingwalls/pipes; metal culverts have significant distortion and
   deflection in section and significant corrosion or deep pitting
4 = Large spalls, heavy scaling, wide cracks, considerable efflorescence or open
   construction joint permitting loss of backfill; considerable settlement or
   misalignment and scour/erosion at curtain walls/wingwalls/pipes; metal culverts have significant
   distortion and deflection; extensive corrosion or deep pitting
3 = Any condition described in code 4, but with an excessive scope; severe movement of
   segments; holes in walls; integral wingwalls severed from culvert; metal culverts
   have extreme distortion and deflection with scattered perforations and deep pitting
2 = Integral wingwalls collapsed; severe settlement or roadway; section of culvert may
   have collapsed; complete undermining at curtain walls or pipes; corrective action
   required to maintain traffic; metal culverts have extreme distortion from corrosion
1 = Bridge closed; corrective action may put back in light of service
0 = Bridge closed; replacement necessary

\[
N_f = \frac{N_i}{9} \quad \text{if } N_i = N, \quad N_f = -1
\]
All numerical codes are divided by 9 and N is converted to -1

**Item #63 Method Used to Determine Operating Rating (Col 72)**
1 = Load Factor (LF)
2 = Allowable Stress (AS)
3 = Load and Resistance Factor (LRFR)
4 = Load Testing
5 = No rating analysis performed

\[ N_f = \frac{N_i - 1}{5} \]

All values are subtracted by 1 and divided by 5

**Item #64 Operating Rating (Col 73)**
The code represents the operating rating in metric tons

\[ N_f = \frac{N_i}{100} \]

All values are divided by 100

**Item #65 Method Used to Determine Inventory Rating (Col 74)**
Refer to Item 63 for coding values

\[ N_f = \frac{N_i - 1}{5} \]

All values are subtracted by 1 and divided by 5

**Item #66 Inventory Rating (Col 75)**
The code represents the inventory rating in metric tons

\[ N_f = \frac{N_i}{100} \quad * \text{Max} = 77.4 \]

All values are divided by 100

**Item #67 Structural Evaluation (Col 76)**
N = Not applicable
9 = Superior to present desirable criteria
8 = Equal to present desirable criteria
7 = Better than present minimum criteria
6 = Equal to present minimum criteria
5 = Somewhat better than minimum adequacy to tolerate
4 = Meets minimum tolerable limits
3 = Basically intolerable requiring high priority of corrective action
2 = Basically intolerable requiring high priority of replacement
1 = This value of rating code not used
0 = Bridge is closed

\[ N_f = \frac{N_i}{9} \quad \text{if} \ N_i = N, \ N_f = -1 \]

All numerical codes are divided by 9 and N is converted to -1

**Item #68 Deck Geometry (Col 77)**
*Uses the same coding and has the same normalization as Item 68*
Item #69 Underclearance, Vertical and Horizontal (Col 78)
*Uses the same coding and has the same normalization as Item 68

Item #70 Bridge Posting (Col 79)
5 = Operating Rating is equal/above legal loads
4 = 0.1 – 9.9% below legal loads
3 = 10.0 – 19.9% below legal loads
2 = 20.0 – 29.9% below legal loads
1 = 30.0 – 39.9% below legal loads
0 = > 39.9% below legal loads

\[ N_f = \frac{N_i}{5} \]

All values are divided by 5

Item #71 Waterway Adequacy (Col 80)
*Uses the same coding and has the same normalization as Item 68

Item #72 Approach Roadway Alignment (Col 81)
*Uses the same coding and has the same normalization as Item 68

Item #75a Type of Work Proposed (Col 82)
31 = Replacement of structure due to substantial load carrying capacity or substandard road geometry
32 = Replacement of structure due to relocation of road
33 = Widening of structure without deck rehabilitation or replacement
34 = Widening of existing bridge with deck rehabilitation/replacement
35 = Bridge rehabilitation because of general structure deterioration/inadequate strength
36 = Bridge deck rehabilitation with only incidental widening
37 = Bridge deck replacement with only incidental widening
38 = Other structural work, including hydraulic replacements

\[ N_f = \frac{N_i - 31}{8} \]

All values are subtracted by 31, then divided by 8

Item #75b Work to be Done by (Col 83)
1 = Work to be done by contract
2 = Work to be done by owner’s forces

\[ N_f = N_i - 1 \]

All values are subtracted by 1

Item #76 Length of Structure Improvement (Col 84)
The code represents the length of the proposed bridge improvement in meters

\[ N_f = \frac{N_i}{500} \]

All values are divided by 500

Item #90 Inspection Date (Col 85)
The code represents the 2 digit month and 2-digit year of the last inspection date
where: \( XX = 2 \) digit Year of File \( N_f = \frac{(12XX - MMYY)}{5.5} \)

\( MM = 1 \) digit month \( YY = 2 \) digit year

All values are divided subtracted from the year of the file, then divided by 5.5

**Item #91 Designated Inspection Frequency (Col 86)**
The code represents the frequency of scheduled inspection in months

\[ N_f = \frac{N_i - 1}{50} \]

All values are divided by 50

**Item #92a Critical Feature Inspection: Fracture Details (Col 87)**
The code represents if the inspection is needed and specifies how often in months

If 1\(^{st}\) field is Y, then \( N_f = \frac{MM - 1}{30} \)  Else \( N_f = -1 \)

Values beginning with Y are subtracted by 1, then divided by 30, while values signified with N are substituted with -1

**Item #92b Critical Feature Inspection: Underwater (Col 88)**
The code represents if the inspection is needed and specifies how often in months

If 1\(^{st}\) field is Y, then \( N_f = \frac{MM - 1}{60} \)  Else \( N_f = -1 \)

Values beginning with Y are subtracted by 1, then divided by 60, while values signified with N are substituted with -1

**Item #92c Critical Feature Inspection: Other (Col 89)**
The code represents if the inspection is needed and specifies how often in months

If 1\(^{st}\) field is Y, then \( N_f = \frac{MM - 1}{24} \)  Else \( N_f = -1 \)

Values beginning with Y are subtracted by 1, then divided by 24, while values signified with N are substituted with -1

**Item #93a Critical Feature Inspection Date: Fracture Details (Col 90)**
The code represents the date of the last inspection

where: \( XX = 2 \) digit Year of File \( N_f = \frac{(12XX - MMYY)}{1.25} \)

\( MM = 1 \) digit month \( YY = 2 \) digit year

All values are divided subtracted from the year of the file, then divided by 1.25

**Item #93b Critical Feature Inspection Date: Underwater (Col 91)**
The code represents the date of the last inspection

where: \( XX = 2 \) digit Year of File \( N_f = \frac{(12XX - MMYY)}{8} \)

\( MM = 1 \) digit month \( YY = 2 \) digit year

All values are divided subtracted from the year of the file, then divided by 8

**Item #93c Critical Feature Inspection Date: Other (Col 92)**
The code represents the date of the last inspection
where: $XX = 2$ digit Year of File  

$$N_f = \frac{12XX - MMYY}{6}$$

$MM = 1$ digit month  
$YY = 2$ digit year

All values are divided subtracted from the year of the file, then divided by 6

**Item #94 Bridge Improvement Cost (Col 93)**  
The code represents the cost of the proposed bridge improvement in thousands of dollars  

$$N_f = \frac{N_i}{11000}$$

All values are divided by 11,000

**Item #95 Roadway Improvement Cost (Col 94)**  
The code represents the cost of the proposed road improvement in thousands of dollars  

$$N_f = \frac{N_i}{4000}$$

All values are divided by 4,000

**Item #96 Total Project Cost (Col 95)**  
The code represents the total proposed project cost in thousands of dollars  

$$N_f = \frac{N_i}{30000}$$

All values are divided by 30,000

**Item #97 Year of Improvement Cost Estimate (Col 96)**  
The code represents the year that the improvement cost was taken  

$$N_f = \frac{N_i - YOF}{3}$$

All values are subtracted from the year of file and divided by 3

**Item #100 STRAHNET Highway Designation (Col 100)**  
0 = Inventory route is not a STRAHNET route  
1 = Inventory route is on Interstate STRAHNET  
2 = Inventory route is on a Non-Interstate STRAHNET route  
3 = Inventory route is on a STRAHNET connector route  

$$N_f = \frac{N_i}{3}$$

All values are divided by 3

**Item #101 Parallel Structure Designation (Col 101)**  
R = 1 Right structure carries roadway in direction of inventory  
L = 0 Left structure carries roadway in direction of inventory  
N = -1 No parallel structure exists  

$$N_f = N_i$$

All values are converted as above

**Item #102 Direction of Traffic (Col 102)**  
0 = Highway traffic not carried  
1 = 1-way traffic  
2 = 2-way traffic  
3 = One-lane bridge for 2-way traffic
\[ N_f = \frac{N_i}{3} \]
All values are divided by 3

**Item #103 Temporary Structure Designation (Col 103)**

T = 1 = Temporary structure exists
\[ N_f = N_i \quad N_f = 0 \text{ for blanks} \]

T’s are converted to 1’s and blanks are changed to 0

**Item #105 Highway System of the Inventory Route (Col 105)**

0 = Not applicable
1 = Indian Reservation Road (IRR)
2 = Forest Highway (FH)
3 = Land Management Highway System (LMHS)
4 = Both IRR and FH
5 = Both IRR and LMHS
6 = Both FH and LMHS
9 = Combined IRR, FH, and LMHS

\[ N_f = \frac{N_i}{10} \]
All values are divided by 10

**Item #106 Year Reconstructed (Col 106)**

The code represents the year of reconstruction
\[ N_f = \frac{YOF - N_i}{100} \]
All values are subtracted from the year of file, then divided by 100

**Item #107 Deck Structure Type (Col 107)**

1 = Concrete Cast-in-Place
2 = Concrete Precast Panels
3 = Open Grating
4 = Closed Grating
5 = Steel plate (orthotropic)
6 = Corrugated Steel
7 = Aluminum
8 = Wood or Timber
9 = Other
N = Not Applicable

\[ N_f = \frac{N_i - 1}{10} \quad \text{if } N_i = N, \quad N_f = -1 \]
All numeric values are subtracted by 1, then divided by 10 and N is converted to -1

**Item #108a Type of Wearing Surface (Col 108)**

1 = Monolithic Concrete
2 = Integral Concrete
3 = Latex Concrete or similar additive
4 = Low Slump Concrete
5 = Epoxy Overlay
6 = Bituminous
7 = Wood or Timber
8 = Gravel
9 = Other
N = Not Applicable

\[ N_f = \frac{N_i}{10} \quad \text{if } N_i = N, \quad N_f = -1 \]
All numeric values are divided by 10 and N is converted to -1
Item #108b Type of Membrane (Col 109)

1 = Built-up
2 = Preformed Fabric
3 = Epoxy
8 = Unknown
9 = Other
0 = None
N = Not Applicable (No deck)

\[ N_f = \frac{N_i}{10} \quad \text{if} \quad N_i = N, \quad N_f = -1 \]

All numeric values are divided by 10 and N is converted to -1

Item #108c Deck Protection (Col 110)
1 = Epoxy Coated Reinforcing
2 = Galvanized Reinforcing
3 = Other Coated Reinforcing
4 = Cathodic Protection
6 = Polymer Impregnated
7 = Internally Sealed
8 = Unknown
9 = Other
0 = None
N = Not Applicable

\[ N_f = \frac{N_i}{10} \quad \text{if } N_i = N, \quad N_f = -1 \]

All numeric values are divided by 10 and N is converted to -1

**Item #109 Average Daily Truck Traffic (Col 111)**
The code represents the percentage of ADT that are trucks

\[ N_f = \frac{N_i}{40} \]

All values are divided by 40

**Item #110 Designated National Network (Col 112)**
0 = Inventory route is not part of the National Network
1 = Inventory route is part of the National Network

\[ N_f = N_i \]

There is no change needed for normalization

**Item #111 Pier or Abutment Protection (Col 113)**
1 = Navigation protection not required
2 = In place and functioning
3 = In place, but in deteriorated condition
4 = In place, but reevaluate of design suggested
5 = None present, but reevaluation suggested

\[ N_f = \frac{N_i - 1}{5} \]

All values are subtracted by 1, then divided by 5

**Item #112 NBIS Bridge Length (Col 114)**
Y = 1 = Yes, is min. length for NBIS
N = 0 = No, does not meet min length for NBIS

\[ N_f = N_i \]

All values are converted as shown above

**Item #113 Scour Critical Bridges (Col 115)**
N = Bridge not over waterway
U = 11 = Bridge with unknown foundation that has not been evaluated for scour
T = 10 = Bridge over “Tidal” waters that has not been evaluated for scour, but considered low risk. Bridge will be monitored with regular inspection
9 = Bridge foundations (including piles) on dry land well above flood water elevations
8 = Bridge foundations determined to be stable; scour is above top of footing
7 = Countermeasures have been installed to correct previous scour problem; bridge is no
longer scour critical
6 = Scour calculation/elevation has not been made
5 = Bridge foundations determined to be stable for calculated scour conditions; scour
within limits of footing piles
4 = Bridge foundations determined to be stable for calculated scour conditions; field
review indicates action is required to protect exposed foundations from additional erosion/corrosion
effects
3 = Bridge is scour critical; bridge foundations determined to be unstable for calculated
scour conditions
2 = Bridge is scour critical; field review indicates extensive scour has occurred at
foundations; immediate action is required for countermeasures
1 = Bridge is scour critical; field review indicates failure of piers/abutments is imminent;
bridge closed to traffic
0 = Bridge is scour critical. Bridge has failed and is closed to traffic

\[ N_f = \frac{N_i}{11} \quad \text{if } N_i = N, \quad N_f = -1 \]

Non-numeric values are converted then divided by 11 and N is converted to -1

Item #114 Future Average Daily Traffic (Col 116)
The code represents the forecasted traffic volume per day
\[ N_f = \frac{N_i}{305000} \quad \text{* Max } = 304800 \]
All values are divided by 305,000

Item #115 Year of Future Average Daily Traffic (Col 117)
The code represents the year of the projected ADT
\[ N_f = \frac{N_i - YOF}{25} \]
All values are subtracted by the year of the file, then divided by 25

Sufficiency Rating (Col 133)
\[ N_f = \frac{N_i}{100} \]
APPENDIX 2

Categorization of Items

Items listed in the document *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges* will be used for deterioration analysis based on the specific information each item provides. The range of information types allows for categorization of this data into three groups:

1) Bridge Characteristics – Physical attributes of the bridge such as geometry and materials used which may affect how the bridge performs or reacts to loading.

2) Loading Assessment – Any loading information pertaining to how the bridge is loaded that may be a factor in deterioration rate.

3) Other Parameters – Miscellaneous features like humidity exposure from nearby waterways, location of the bridge (weather patterns), and other issues that do not relate with bridge characteristics or loading, but will have an effect on the deterioration of the bridge.

In addition to the above three categories, some of the items addressed in the document may be used for identification purposes to index specific bridges for the analysis process.

**Item #1 State Code (3)**
As each state is designated a numerical code, this item will be utilized in the identification process. This code will be a part of the index used to distinguish bridges.

**Item #2 Highway Agency District (2)**
This information will not be useful in the analysis as it simply states whether the structure is federal or state owned.

**Item #3 Country (Parish) Code (3)**
This information may be useful for index purposes. This item also includes a FIPS code under GIS, which may be useful in the Other Parameters Category for location designation to determine weather patterns.

**Item #4 Place Code (5)**
This information may be useful for index purposes. This item also includes a FIPS code under GIS, which may be useful in the Other Parameters Category for location designation to determine weather patterns.

**Item #5 Inventory Route (9)**
5A-Record Type (1): will not be useful as it simply specifies the NBI record "on" or "under" and the amount.
5B-Route Signing Prefix (1): Specifies type of road and will therefore be under the category of either Other Parameters, or Loading.
5C-Designated Level of Service (1): Specifies the type of traffic serviced by the structure and will therefore be under Other Parameters or Loading.
5D-Route Number (5): Will not be useful because it only serves as an index for the inventory route.
5E-Directional Suffix (1): Will not be useful because it only provides the direction of the inventory route.

**Item #6 Features Intersected (25)**
This item may be useful for features that are intersected such as rivers which will cause greater humidity. Also this item may be attribute to an importance factor for features that will be affected if the structure is under repair or out of service. This item is placed under Other Parameters.

**Item #7 Facility Carried by Structure (18)**
This item will be useful in specifying what type of loading the structure will be under as it gives the nature of facility that is carried by the structure if any. It is therefore categorized under loading.

Item #8 Structure Number (15)
This item may be useful for identification purposes as each bridge is given a unique number for every state.

Item #9 Location (25)
This item will not be useful because location will be more specifically described in other items for determining weather patterns.

Item #10 Inventory Route, Minimum Vertical Clearance (4)
This item will not be useful because vertical clearance will not be a factor in deterioration rate of bridges.

Item #11 Kilometer Point (7)
This item may be used for identification purposes as it uses LRS (Linear Referencing System) for specific location.

Item #12 Base Highway Network (1)
This item will not be useful because it simply states whether the structure is in the BHN for funding purposes.

Item #13 LRS Inventory Route, Sub-route Number
13A Inventory Route Number (10): May be useful for its correspondence to the LRS
13B Sub-route Number (2): Will not be useful because it is only an index for inventory route.

Item #14 & 15 Reserved

Item #16 Latitude (8)
This item will be useful along with Item #17 (Longitude) in determining specific location of bridges to compare to weather patterns in the vicinity. This item will be categorized under Other Parameters.

Item #17 Longitude (9)
This item will be useful along with Item #16 (Latitude) in determining specific location of bridges to compare to weather patterns in the vicinity. This item will be categorized under Other Parameters.

Item #18 Reserved

Item #19 Bypass, Detour Length (3)
This item will be useful in determining an importance factor of bridges by the need for a solution if the structure is out of service and will therefore be categorized under Other Parameters.

Item #20 Toll (1)
This item may be useful in determining an importance factor of bridges due to the revenue that it may create and will therefore be categorized under Other Parameters.

Item #21 Maintenance Responsibility (2)
This item will not be useful in determining and importance factor nor a deterioration rate of structures.

Item #22 Owner (2)
This item will not be useful in determining and importance factor nor a deterioration rate of structures.

Item #23-#25 Reserved
Item #26 Functional Classification of Inventory Route (2)
This item will be useful in determining the loading that a structure will undergo as it gives information about the function that a structure provides: rural or urban. This item will therefore be under Loading.

Item #27 Year Built (4)
This item will be placed under Bridge Characteristics because it may have relevance to the condition of a structure as a function of time.

Item #28 Lanes On and Under Structure (4)
28A Lanes On Structure (2): Will be useful under Bridge Characteristics as it is a physical attribute of the bridge and may have bearing on the rate of deterioration.
28B Lanes Under Structure (2): May be useful under Other Parameters as it may contribute to an importance factor of a structure.

Item #29 Average Daily Traffic (6)
This item will be categorized under Loading as it represents a major loading that the structure undergoes.

Item #30 Year of Average Daily Traffic (4)
This item will be categorized under Loading in conjunction with Item #29 (ADT).

Item #31 Design Load (1)
This item will be categorized under Bridge Characteristics because it dictates the physical attributes of how the bridge was designed.

Item #32 Approach Roadway Width (4)
This item will be categorized under Bridge Characteristics because it is a physical attribute of a structure.

Item #33 Bridge Median (1)
This item will be categorized under Bridge Characteristics because it is a physical attribute of a structure.

Item #34 Skew (2)
This item will be categorized under Bridge Characteristics because it is a physical attribute of a structure.

Item #35 Structure Flared (1)
This item will be categorized under Bridge Characteristics because it is a physical attribute of a structure.

*Item #36 Traffic Safety Features (4)
36A-Railings (1): Will be placed under Bridge Characteristics because it is a physical attribute of a structure that may have an effect on how the bridge takes loading.
36B-Transitions (1): Although is a physical attribute of the structure, it has no effect on how the bridge takes loading.
36C-Approach Guardrail (1): Although is a physical attribute of the structure, it has no effect on how the bridge takes loading.
36D-Approach Guardrail ends (1): Although is a physical attribute of the structure, it has no effect on how the bridge takes loading.

Item #37 Historical Significance (1)
This item will be categorized under Other Parameters because it may contribute to an importance factor of a structure.

*Item #38 Navigation Control (1)
This item will be placed under Other Parameters because it gives information on nearby waterways, which produce humidity.
Item #39 Navigation Vertical Clearance (4)

Item #40 Navigation Horizontal Clearance (5)

Item #41 Structure Open, Posted, or Closed to Traffic (1)
This item will be placed under Loading because “open” signifies that the bridge meets its intended loading standards, a posted bridge signifies that there are loading limits that are not met, and a closed bridge shows significant problems with the bridge in question.

Item #42 Type of Service (2)
42A Type of Service on Bridge (1): Will be placed under Loading for the information that this item provides about what type of loading the bridge will undergo.
42B Type of Service under Bridge (1): Will be placed under Other Parameters due to its contribution to a significance factor for the bridge.

Item #43 Structure Type, Main (3)
43A Kind of Material and/or Design (1): Will be placed under Bridge Characteristics because this item gives information about important physical properties of a bridge.
43B Type of Design and/or Construction (2): Will be placed under Bridge Characteristics because this item gives important information about physical attributes of a bridge such as slabs, girders, truss-deck, etc.

Item #44 Structure Type, Approach Spans (3)
44A Kind of Material and/or Design (1): Will be placed under Bridge Characteristics because this item gives information about important physical properties of a bridge.
44B Type of Design and/or Construction (2): Will be placed under Bridge Characteristics because this item gives important information about physical attributes of a bridge.

Item #45 Number of Spans in Main Unit (3)
This item will be placed under Bridge Characteristics because it represents a useful trait of a bridge that can be useful determining a deterioration rate and its contribution to deterioration.

Item #46 Number of Approach Spans (4)
This item will be placed under Bridge Characteristics because it may contribute to the deterioration rate of a bridge.

Item #47 Inventory Route, Total Horizontal Clearance (3)
This item will not be useful in determining how a bridge deteriorates, as it does not have significance physically to the health of a bridge.

Item #48 Length of Maximum Span (5)
This item will be placed under Bridge Characteristics because it may have an effect on how a bridge deteriorates.

Item #49 Structure Length (6)
This item will be placed under Bridge Characteristics as it provides information about the measurement of the entire roadway that is supported by a structure. This item can show how this measurement affects bridge deterioration.

Item #50 Curb or Sidewalk Width (6)
This item will be placed under Bridge Characteristics because it gives a physical attribute of a bridge that may affect how a bridge deteriorates.
Item #51 Bridge Roadway Width (4)
This item will be placed under Bridge Characteristics because it gives an important physical property of a bridge that may affect how a bridge deteriorates.

Item #52 Deck Width, Out to Out (4)
This item will be placed under Bridge Characteristics because it gives a physical attribute of a bridge that may affect how a bridge deteriorates.

Item #53 Minimum Vertical Clearance Over Bridge Roadway (4)
This item will not be useful in determining how a bridge deteriorates.

Item #54 Minimum Vertical Underclearance (5)
This item will not be useful in determining how a bridge deteriorates.

Item #55 Minimum Lateral Underclearance on Right (4)
This item will not be useful in determining how a bridge deteriorates.

Item #56 Minimum Underclearance on Left (3)
This item will not be useful in determining how a bridge deteriorates.

Item #57 Reserved

Item #58 Deck (Condition Rating) (1)
This item will be placed under Bridge Characteristics as it is coded based on an inspection rating using the AASHTO guide. This item indicates if cracking, scaling, spalling, leaching, chloride contamination, potholing, delamination, and if depth failures are present in the bridge at the time of inspection.

Item #59 Superstructure (1)
This item will be placed under Bridge Characteristics because it is coded based an inspection rating using the AASHTO guide. This item shows if distress, cracking, deterioration, section loss, malfunction, and misalignment of bearing are present in the bridge at the time of inspection.

Item #60 Substructure (1)
This item will be placed under Bridge Characteristics because it is coded based an inspection rating using the AASHTO guide. This item indicates if cracking, section loss, settlement misalignment, scour, collision damage, and corrosion are present in the bridge at the time of inspection.

Item # 61 Channel and Channel Protection (1)
This item will be placed under Bridge Characteristics as it deals with the physical properties of a channel below if one exists and how the channel flows. This item may also be useful under Other Parameters for indicating a nearby waterway, which is a source of humidity.

Item #62 Culverts (1)
This item will be placed under Bridge Characteristic as is indicates the physical property and condition of the structure for a culvert.

Item #63 Method Used to Determine Operating Rating (1)
This item will be placed under Loading in conjunction with Item #64 (Operating Rating) as it indicates the load rating method used in determining the operating rating of the structure.
Item #64 Operating Rating (3)
This item will be placed under Loading in conjunction with Item #63 (Method Used) as it indicates the absolute maximum capacity of a structure in metric tons and the structure’s sufficiency in carrying the present load.

Item #65 Method Used to Determine Inventory Rating (1)
This item will be placed under Loading in conjunction with Item #66 (Inventory Rating) because it indicates the loading method used.

Item #66 Inventory Rating (3)
This item will be placed under Loading in conjunction with Item #65 (Method Used) because it shows a capacity rating in metric tons using only MS loading and the structure’s sufficiency in carrying the present load.

Item #67 Structural Evaluation (1)
This item will be placed under Other Parameters to show the bridges sufficiency in relation to the level of service it provides. This item is calculated by the Edit/Update Program (or from tables).

Item #68 Deck Geometry (1)
This item will be placed under Other Parameters to show the deck’s adequacy in relation to the level of service it provides. This item is calculated by the Edit/Update Program (or from tables).

Item #69 Underclearance, Vertical and Horizontal (1)
This item will not be useful in determining how a bridge deteriorates, as its physical information does not affect loading capabilities.

Item #70 Bridge Posting (1)
This item will be placed under Loading as it shows if the structures load bearing capacity is below state and legal limits, which may affect the deterioration rate of a bridge.

Item #71 Water Adequacy (1)
This item will be placed under Bridge Characteristics as it states if overtopping is an issue for structural failure based on the opening and flow rate. This item will also be placed under Other Parameters as it also indicates if a waterway is present to contribute to a higher level or humidity.

Item #72 Approach Roadway Alignment (1)
This item will be placed under Bridge Characteristics for the information it provides on alignment of approach roadway. This item can indicate if re-alignment is needed, which can affect functionality of the structure.

Item #73 And #74 Reserved

Item #75 Type of Work (3)
75A Type of Work Proposed (2): Will be placed under Bridge Characteristics as it gives information on the physical conditions of the structure.
75B Work Done by (1): Will not be useful as this item simply indicates whether the work proposed is to be done by contract or force account.

Item #76 Length of Structure Improvement (6)
This item will be placed under Other Parameters for the measurement of change that is to occur, which will be a function of funding that relates with an importance factor.
Item #77 - #89 Reserved

Item #90 Inspection Date (4)
This item will be placed under Other Parameters in conjunction with Item #91 (Designated Inspection Frequency) for their dealing with how often the bridge is to be inspected, which may be an indication of either importance factor or near failure.

Item #91 Designated Inspection Frequency (2)
This item will be placed under Other Parameters in conjunction with Item #90 (Inspection Date) for their dealing with how often the bridge is to be inspected, which may be an indication of either importance factor or near failure.

Item #92 Critical Feature Inspection (9)
92A Fractural Critical Detail (3): Will be placed under Bridge Characteristics because it will indicate if critical details are present.
92B Underwater Inspection (3): Will be placed under Other Parameters because it will indicate if structure is near a waterway, which heightens humidity,
92C Other Special Inspection (3): Will be placed under Bridge Characteristics because it will indicate if reasons for special inspection are present.

Item #93 Critical Feature Inspection Date (12)
93A Fractural Critical Details (4): Will be placed under Bridge Characteristics in conjunction with 92A (Fractural Critical Detail).
93B Underwater Inspection (4): Will not be useful in determining a deterioration rate of the structure.
93C Other Special Inspection (4): Will be placed under Bridge Characteristics in conjunction with 92C (Other Special Inspection).

Item #94 Bridge Improvement Cost (6)
This item will be placed in Other Parameters for the information it gives on funding, which is a part of the importance factor.

Item #95 Roadway Improvement Cost (6)
This item will be placed in Other Parameters for the information it gives on funding, which is a part of the importance factor.

Item #96 Total Project Cost (6)
This item will be placed in Other Parameters for the information it gives on funding, which is a part of the importance factor.

Item #97 Year of Improvement Cost Estimate (4)
Will be placed in Other Parameters in conjunction with items #94, #95, and #96 (costs) for its information on funding, which is a part of the importance factor.

Item #98 Border Bridge (5)
This item will not be useful as it is only meant for bridge funding purposes.

Item #99 Border Bridge Structure Number (15)
This item will not be useful as it only is meant for bridge funding purposes in conjunction with Item #98 (Border Bridge).

Item #100 STRAHNET Highway Designation (1)
This item will be placed under Other Parameters as it may play a role in an importance factor.

**Item #101 Parallel Structure Designation (1)**
This item will not be useful in the analysis of bridge deterioration nor does it have a role in the importance factor.

**Item #102 Direction of Traffic (1)**
This item will not be useful, as direction of traffic will not affect how a bridge deteriorates.

**Item #103 Temporary Structure Designation (1)**
This item will be placed under Bridge Characteristics for indicating if a temporary structure is in use in place of the permanent structure.

**Item #104 Highway Systems of the Inventory Route (1)**
This item will not be useful in the analysis of deterioration rate of bridges.

**Item #105 Federal Land Highway (1)**
This item will not be useful in the analysis of deterioration rate of bridges.

**Item #106 Year Reconstructed (4)**
This item will be placed under Bridge Characteristics for indicating if the bridge was at any time reconstructed for any reason.

**Item #107 Deck Structure Type (1)**
This item will be placed under Bridge Characteristics for indicating the type of deck system the bridge has, which is a physical trait of the bridge that may affect the deterioration rate.

**Item # 108 Wearing Surface/Protective System (3)**
108A Type of Wearing Surface (1): Will be placed under Bridge Characteristics for giving a type of physical attribute on the structure.
108B Type of Membrane (1): Will be placed under Bridge Characteristics for giving a type of physical attribute on the structure.
108C Deck Protection (1): Will be placed under Bridge Characteristics for giving a protection type of physical attribute on the structure.

**Item #109 Average Daily Truck Traffic (2)**
This item will be placed under Loading for its information of truck usage.

**Item #110 Designated National Network (1)**
This item will be placed under Loading in conjunction with Item #109 (ADTT) to show a type of loading on the structure caused by amount of trucks.

**Item # 111 Pier or Abutment Protection (for Navigation) (1)**
This item will be placed under Bridge Characteristics for giving physical attributes of a structure.

**Item #112 NBIS Bridge Length (1)**
This item will be placed under Bridge Characteristics for giving physical attributes of a structure.

**Item #113 Scour Critical Bridges (1)**
This item will be placed under Bridge Characteristics for identifying vulnerability in terms of scour for a structure.
Item #114 Future Average Daily Traffic (6)
This item will be placed under Loading for representing a forecasted value for loading that the bridge will potentially face.

Item #115 year of Future Average Daily Traffic (4)
This item will be placed under Loading in conjunction with Item #114 (Future ADT) for representing a forecasted value for loading that the bridge will potentially face.

Item #116 Minimum Navigation Vertical Clearance (4)
This item will not be useful in determining a deterioration rate.
APPENDIX 3

Hierarchical Clustering Plots

Structural Adequacy: Boot 1:

Chart-0

Cluster 1

Cluster 2

Cluster 3
Chart-21

Chart-22

Chart-23
Structural Adequacy Boot 2:

Chart-0

Chart-1
Performance Index: Boot 1:

Chart-0

Cluster 1  Cluster 2  Cluster 3
Performance Index: Boot 2:
APPENDIX 4

Corresponding Pie Distributions of Hierarchical Clustering Plots

Structural Adequacy: Material Type: Boot 1:

P-1-0a

P-1a
P-321a

P-322a
Structural Adequacy: Structure Type: Boot 1:

![Pie chart](image)

P-1-0b

![Pie chart](image)

P-1b

Legend:
- Slab
- String/Multi-beam or Girdar
- Girder and Floorbeam Sys
- Tee Beam
- Box Beam or Girdar Mlt
- Box Beam or Girdar Sing/Spread
- Frame
- Truss-Deck
- Truss-Thru
- Arch-Thru
- Culvert
- Channel Beam
P-311b
Structural Adequacy: Material Type: Boot 2:

P-1a

P-2a
Structural Adequacy: Structure Type: Boot 2:
Performance Index: Material Type: Boot 2:
Performance Index: Structure Type: Boot 2

P-0-3pi

P-1b

Legend:
- Concrete
- Steel Continuous
- Wood or Timber
- Concrete Continuous
- Prestressed/Post-Ten Concrete
- Masonry
- Steel
- Prestressed/Post-Ten Concrete Continuous
- Aluminum or Iron
<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
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<td>Concrete</td>
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</tr>
<tr>
<td>Steel</td>
<td>25%</td>
</tr>
<tr>
<td>Wood or Timber</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Masonry</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Aluminum or Iron</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Prestressed/Post-Ten Concrete</td>
<td>3%</td>
</tr>
<tr>
<td>Prestressed/Post-Ten Concrete Continuous</td>
<td>3%</td>
</tr>
</tbody>
</table>