Correlations Between Sets of Data for Investigating Bridge Conditions in Virginia

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B.S. in Civil and Environmental Engineering, May 2022, The George Washington University

A Thesis submitted to

The Faculty of
The School of Engineering & Applied Science
of The George Washington University
in partial fulfillment of the requirements
for the degree of Master of Science

May 19, 2024

Thesis directed by

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Dedication

This thesis is dedicated to my parents George and Arlene Commissiong, my brothers Philip, Brian, and Jason Commissiong, and my wife Theresa Buechler, for the endless love, support, and encouragement they give me.

Acknowledgments

The author wishes to acknowledge Professor Pedro Silva for the knowledge and experience I gained during my time spent as his student and his patience, guidance, and support as my thesis advisor.

Abstract of Thesis

Correlations Between Sets of Data for Investigating Bridge Conditions in Virginia

The main objective of this thesis is to investigate the predominant linear correlations between data sets in the National Bridge Inventory (NBI) Bridge Condition Rating. An overall bridge condition rating can be any of the following three: “Poor”, “Fair” and “Good”. According to the NBI criteria, a structure is rated as “Good” if all its structural components are rated as 7 or better, rated “Fair” when all structural components are rated in the range 5 to 6, and rated “Poor” when all structural components are rated 4 and below (FHWA, 2023). The NBI also states the bridge condition rating is determined by the lowest rating of substructure, superstructure, and deck condition ratings, respectively (FHWA, 2022).

Using the LTBP *InfoBridge*^{TM} web portal, a query of bridges in the commonwealth of Virginia was performed in achieving the main objective of this project. This query provided a total of 14,068 bridges. Because the topic of this thesis deals with overall bridge condition ratings, only bridges that cross over at least one lane of traffic were investigated in this research. The logic behind excluding bridges that have no traffic lanes under the structure is that these bridges are not susceptible to either overhead and/or pier collisions resulting from heavy truck collisions. A bridge’s component condition rating plays a significant role in determining the likelihood of collapse resulting from heavy truck collisions. As a result, only 2,719 bridges across the commonwealth of Virginia were investigated in this research.

Data mining of these bridges led to the development of a correlation between sets of data that are auxiliary predictors of overall bridge condition ratings. Linear correlations between these sets of data were established and are presented herein with the aid of maps, scatter plots, distribution plots and the Pearson Correlation Coefficients. In conclusion, data correlations play a crucial role in identifying key factors influencing bridge condition ratings. This insight is essential for evaluating if the current classification method adequately represents bridge health, thus supporting effective maintenance and safety measures.

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CHAPTER 1 - Introduction

1.1 BACKGROUND

Since the collapse of the Silver Bridge in 1967, the President of the United States and Congress made it law in creating uniform standards for performing routine bridge inspections (Dekelbab, Al-Wazeer, & Harris, 2008). As part of this federal law, states must also perform inspections on all public road bridges with a length exceeding 20 feet. Further, there is the requirement of the United States Secretary of Transportation, in cooperation with state governments, to create and maintain an inventory of bridges in the United States transportation infrastructure. This law led to the creation of the Federal Highway Administration's (FHWA) National Bridge Inventory (NBI).

Over the years the FHWA collected information on bridges and culverts across the United States. Creation of the NBI promoted many research projects in evaluating and studying bridges throughout the country such as the one presented in this thesis (Dekelbab, Al-Wazeer, & Harris, 2008). In addition, NBI promoted a better understanding of bridge performance during its lifetime and determining models for better prediction of bridge's condition ratings (Dekelbab, Al-Wazeer, & Harris, 2008). Since its inception, the NBI database has expanded, and most recently has been organized through a web portal for access, visualization, and analysis. This web portal is the National Bridge Inventory Long-Term Bridge Performance *InfoBridge*^{TM}. The LTBP *InfoBridge*^{TM} only includes structures that are longer than 20-ft (FHWA, 2004). Using the LTBP *InfoBridge*^{TM} (FHWA- LTBP, 2024), at the time of this research, 621,581 bridges are part of the NBI database. Among the 157 bridge items present in the NBI, this

research queried the data repository according to bridge type, number of spans, type of material, and bridge condition ratings.

Through the National Bridge Inspection Standards (NBIS), safety inspections are performed for bridges on public roads (FHWA, 2022). With these inspections, information on material compositions, structural geometry, functional characteristics, descriptions, ownership, and maintenance responsibility is documented (FHWA, 2022). It is through these inspections that a rating of bridge components is conducted. These primary components are the deck, superstructure, and substructure (FHWA, 2015). The overall purpose of these inspections is to ensure safe use.

Published January 1st, 2015, the FHWA published a Notice of proposed rulemaking (NPRM), where stakeholders' opinions on how conditions were classified was brought up. In the NPRM, it was stated stakeholders were divided about what data should be utilized when determining a bridges condition while also mentioning the FHWA should consider the cost of repair or replacement and the importance of the infrastructure with regards to how many vehicles it served (FHWA, 2015). Some stakeholders noted that only measuring the physical condition of a bridge does not provide the best insight into infrastructural issues (FHWA, 2015). The NPRM led to differing opinions among stakeholders and interested parties regarding the FHWA's approach to the country's highway system. The FHWA conducted a study titled "Improving FHWA's Ability to Assess Highway Infrastructure Health Pilot Study Report" where they evaluated several methods of assigning bridge conditions using the NBI database.

Four different weighted average methods, and one minimum condition rating method, were considered (FHWA, 2015). This study reached four main conclusions: 1) The minimum condition rating method resulted in the highest percentage of interstate system bridges being categorized as in Poor condition. 2) The classification of bridges as "Good", "Fair", or "Poor" remained consistent across all four weighted average methods and the minimum condition rating method. 3) The classification of bridges based on the four weighted average methods showed little sensitivity to changes in weights. 4) Bridge deck conditions alone are usually not the main factor for condition classifications (FHWA, 2015). The FHWA proposed the minimum condition measure that would reflect the lowest component condition rating for the bridge. Within the Pavement and Bridge Condition Performance Measures final rule, published in January 2017, the proposed changes went into effect as part of a shift to a performance-based program (FHWA, 2017).

The *Specifications for the National Bridge Inventory* (SNBI), implemented to replace the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (Coding Guide) (Hartmann, 2022), provides the classification criteria of bridge conditions with regards to bridge components. According to the SNBI, a bridge is deemed in "Good" condition if the lowest rating among the deck, superstructure, substructure, and culvert conditions is between 7 and 9. It is classified as "Fair" if the lowest rating among these components falls to 5 or 6. And finally a bridge is categorized as "Poor" if the lowest rating of those components is 4 or below (FHWA, 2022). Table 1.1 shows a definition of each rating code.

Table 1.1 - Condition Rating Codes outlined in the NBI

Condition	Code	Description
Excellent	9	Excellent condition
Very Good	8	No problems noted
Good	7	Some minor problems.
Satisfactory	6	Structural elements show some minor deterioration.
Fair	5	All primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
Poor	4	Advanced section loss, deterioration, spalling, or scour.
Serious	3	Loss of section, deterioration, spalling, or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
Critical	2	Advanced deterioration or primary structural elements. Fatigue cracks in steel or shear in concrete may be present or scour may have removed substructure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken.
Imminent Failure	1	Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic.
Failed	0	Out of service-beyond corrective action.

Historically, The Coding Guide utilized several factors for defining what was called a Sufficiency Rating (FHWA, 1995). The Sufficiency Rating, ranging from 0 to 100%, is determined by four main factors: Structural Adequacy and Safety, Serviceability

and Functional Obsolescence, Essentiality for Public Use, and Special Reductions. Each of these factors includes various sub-factors that contribute to the overall rating (FHWA, 1995).

The condition rating of a bridge serves as a key indicator of safety. In Virginia, with more than 14,000 bridges and some experiencing an Average Daily Traffic (ADT) exceeding 200,000 vehicles (BTS, 2021), there is significant public dependence on these structures. Maintenance and appropriate assessment of these bridges throughout their lifecycle are imperative for ensuring safety. It was noted previously that the sufficiency rating system determined whether a structure was deficient or not. The assessment parameters for a bridge's overall condition have expanded since before the introduction of the SNBI, leading to a more streamlined approach. Despite this, it's essential to evaluate whether the current method for rating bridge conditions is both adequate and comprehensive. The examination of how certain data sets correlate with overall bridge condition ratings in the LTBP *InfoBridge*^{TM} (FHWA- LTBP, 2024) is intended to clarify this issue.

As stated previously, there are over 14,000 bridges within the commonwealth of Virginia. Of those, there are 2,719 bridges that cross over at least one lane of traffic. This can be seen using LTBP *InfoBridge*^{TM} (FHWA- LTBP, 2024) and querying *Lanes Under the Structure (28B)* and excluding bridges without lanes under structure. This research will focus only on those 2,719 bridges to highlight potential safety concerns revolving bridges susceptible to heavy truck collisions in relation to what their condition ratings are. Figure 1.1 illustrates a geographical representation of the location of these bridges.

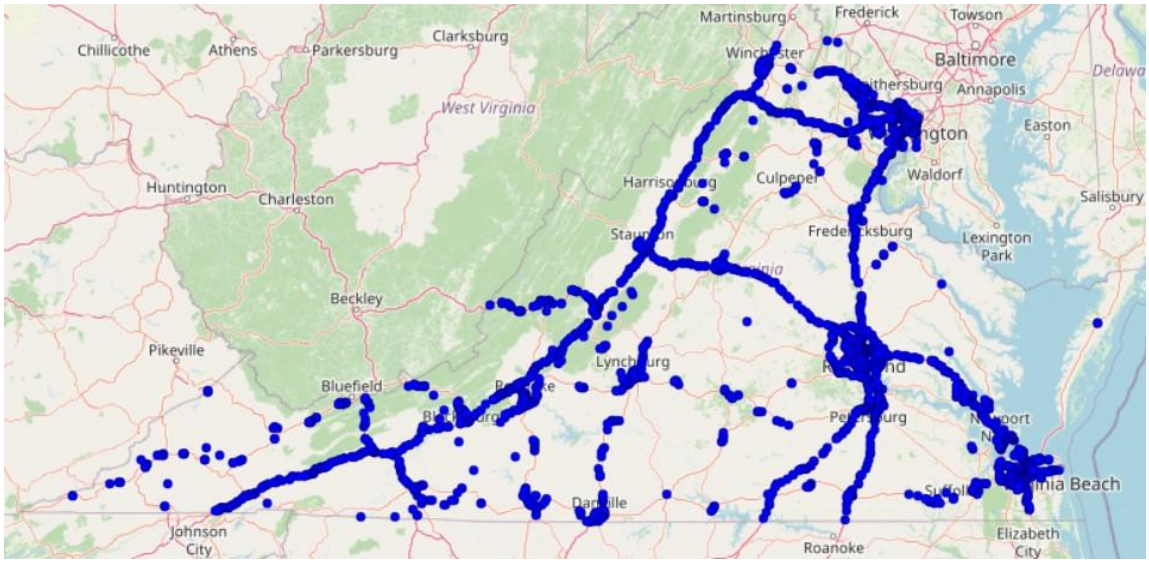


Figure 1.1 - Geographical Distribution of Bridges Investigated

This study examines the selected bridges, analyzing data and identifying linear correlations between various factors: condition ratings and construction materials, construction year and conditions, Annual Daily Traffic (ADT) and condition ratings, potential relationships between maintenance entities and condition ratings, structural evaluation appraisal ratings and overall condition ratings, and the impact of individual component ratings on the overall condition rating.

1.2 LITERATURE REVIEW

The safety and maintenance of bridges have received considerable attention in academic and practical research. Given the continuous use by the public, the emergence of larger vehicle designs, and the yearly escalation in vehicular traffic, ensuring the integrity of national infrastructure is critical. Various studies have been undertaken to assess the present condition of roads and bridges, and to determine whether bridges require reconstruction, replacement or should be considered no longer viable. This section aims to review these studies, emphasizing key findings relevant to this thesis.

A study that analyzed the database of the National Bridge Inventory (NBI), titled Operational Structural Performance of Bridge Types by Areas, sought to evaluate the operational structural performance of several bridge types across the country. The research investigates a relationship between structurally adequate and structurally deficient bridges by deck area (Farhey, 2013). This study revealed that specific types of bridges exhibit a reduced service life contrasted against life-cycle expectancy (Farhey, 2013). Further, through the structural performance evaluation conducted, bridge condition was given priority while durability was valued less (Farhey, 2013). In their conclusions it was found that the average service life before structural deficiency was 56% of the objective life-cycle expectancy and that the average equivalent structural performance of bridge types by deck area is low and lower still when bridge count is considered (Farhey, 2013).

A methodological approach to defining a more functional determination of a bridge's condition was the goal of the following research. Titled New Measure to Understand and Compare Bridge Conditions Based on Inspections Time-Series Data, the

study's goal was to introduce a Baseline Difference Score (BDS) to provide deeper insight to a bridge's health and complement the NBI condition ratings (Kale, Ricks, & Gandhi, 2021). According to the author, BDS follows a normal distribution, and categorizes bridges as poor, average, and good using standard deviation measures (Kale, Ricks, & Gandhi, 2021). Their research operated in six phases: data collection, data cleaning, data transformation, factor selection, BDS computation, and identifying significant factors (Kale, Ricks, & Gandhi, 2021). Through data cleaning, researchers found that only about 42% of the original data set was suitable for analysis (Kale, Ricks, & Gandhi, 2021). Through their work, they investigated 11 different factors, including environmental factors, that could influence bridge conditions. Of those 11, the top three factors that had the largest impact on bridge condition were material used, snowfall, and maintenance (Kale, Ricks, & Gandhi, 2021). They found material type had the highest association with bridge conditions while the factor that had the smallest effect was ADT. Finally, they found the individual factors alone cannot fully explain the condition of bridges and that BDS does not consider the variance of an individual bridge's condition (Kale, Ricks, & Gandhi, 2021).

In a different study, Integrated Condition-Based Rating Model for Sustainable Bridge Management, the topic of obtaining a conclusive and less subjective bridge condition rating system for bridge management systems was the focus. Published June 2020, this paper references the NBI's rating system of rating individual components and concludes to an overall rating of structurally deficient (SD), functionally obsolete (FO) or structurally adequate (SA) (Alsharqawi et al., 2020). It also relates a similar concept of the Bridge Health Index (BHI), which utilizes the Pontis system, in which a bridge is

rated between 0 and 100. Where at 0% the bridge is in its worst state and 100% its best state (Alsharqawi et al., 2020). The author states the NBI rating system did not provide detailed measurement and considered general measures for identifying maintenance strategies, while they found the BHI method did not consider defect interdependencies at an element level (Alsharqawi et al., 2020). Ultimately, their goal was to develop an integrated condition-based model for rating bridge condition using the *k*-means clustering technique to facilitate maintenance, repair, and replacement (MRR) (Alsharqawi et al., 2020). The author concludes that, with the method being implemented on four case studies, the results obtained showed effectiveness. With the use of ground penetrating radar (GPR) technology, they were able to provide ratings with defined threshold values between different condition ratings and provide advice on what should be done for the bridge (Alsharqawi et al., 2020).

The following research determined methods for modeling deck condition ratings on prestressed concrete bridges. Titled National Bridge Inventory Data-Based Stochastic Modeling for Deck Condition Rating of Prestressed Concrete Bridges, the authors stated their goal was to "investigate and model the impact of explanatory variables collected through NBI inspections to predict the deck condition rating for prestressed bridges" (Hasan & Elwaki, 2020). As noted within the previous studies, the author notes the subjective nature of rating conditions. Researchers used a deterministic approach using regression analysis methods to highlight the variables affecting deck conditions (Hasan & Elwaki, 2020). Then, through utilizing that information, a stochastic analysis approach through Monte Carlo simulations was used to develop probability distributions for the prediction of deck conditions relative to those variables (Hasan & Elwaki, 2020). The

results of the research done are as follows: the use of Monte Carlo simulations as a method of stochastic analysis provided a realistic probability distribution for predicted deck condition, degree skew, structure length and deck width have negative effects on deck condition of prestressed bridges, higher max values of span length, percent of ADTT, road width and frequency of inspection are associated with a higher rated deck condition, and the higher deck condition rating and max span length and percent of ADTT contradicts previous studies within the field. Further, it is noted that specific maintenance actions are not available within the NBI database (Hasan & Elwaki, 2020).

Research published Nov 12, 2022, within the *Journal of Infrastructure Systems* by ASCE, worked on another approach to predicting condition ratings. With Bridge Infrastructure Management System: Autoencoder Approach for Predicting Bridge Condition Ratings, the goal of the research was to create a bridge condition prediction model that was effective with or without the use of historic condition ratings and evaluations (Rajkumar et al., 2022). To achieve this, the authors had to also determine the components that influence bridge deterioration, investigate the best model method that considered bridge factors, and develop an autoencoder-random forest model and compare its performance to existing bridge rating prediction models (Rajkumar et al., 2022). The work done on this study yielded positive results. Researchers found their methodology outperformed existing models through achieving accuracy of around 90% for deck condition ratings when the model is considering other ratings and evaluations from NBI (Rajkumar et al., 2022). When the model is not considering outside factors, their model predicted deck condition, superstructure condition and substructure condition with about 79%, 78% and 77% accuracy respectively (Rajkumar et al., 2022). Further, they stated

that no other prediction model at the time was able to produce condition ratings without the use of historic ratings of operating rating, inventory rating and structural evaluations (Rajkumar et al., 2022).

The mentioned studies, among many that were not touched on, are important to the development of maintaining an accurate record of bridge information. Certain studies focused on predicting bridge conditions accurately to provide potential MRR services if required. Other studies focused on being able to appropriately rate conditions and remove the subjective nature when classifying. Each of these studies used NBI information to investigate data to find evidence of larger stories that aren't explicitly stated. This thesis seeks to add to those studies and further investigate correlations between condition classifications and other sets of data.

1.3 THESIS OUTLINE

This section outlines the structure of the thesis, which focuses on the Commonwealth of Virginia. Chapter 2 examines the distribution of bridges, specifically those in Virginia that span at least one lane of traffic, based on various factors. Section 2.1 presents an analysis of the condition of these bridges for the year 2023, including a comparative study of bridge conditions from 1993 to 2023 to understand historical trends and classification changes over time. Section 2.2 explores the relationship between the condition of bridges and their maintenance entities, assessing the performance of different entities in maintaining bridge conditions. Section 2.3 investigates the impact of a bridge's age on its condition, considering whether maintenance activities have a significant effect on mitigating age-related deterioration. Finally, section 2.4 examines the influence of the main span material and design on bridge condition ratings.

Chapter 3 conducts an analysis of the factors identified by the National Bridge Inventory (NBI) as contributing to the categorization of the bridges by condition rating. Section 3.1 focuses on the assessment of individual component conditions, deriving an overall bridge condition rating in accordance with NBI criteria. This rating is then compared with existing bridge condition ratings in the dataset. Section 3.2 examines the linear relationship between structural evaluation appraisal ratings and bridge condition ratings, noting that these appraisal ratings are from a rating system that is no longer employed.

Finally, in chapter 4, a discussion based on the findings of the study is stated as well as a conclusion and the recommendation based on those findings. All analysis, evaluations and correlations will be illustrated using histograms, scatter plots, geographical distributions and heatmaps.

CHAPTER 2 - Bridge Condition Distributions

2.1 HISTORICAL DISTRIBUTION OF BRIDGE CONDITION RATINGS

The National Bridge Inventory (NBI) reports that there are approximately 620,000 bridges across the United States, with more than 14,000 located in the Commonwealth of Virginia, according to the Federal Highway Administration's Long-Term Bridge Performance (FHWA- LTBP, 2024) program. This data is obtained from the NBI database by applying specific filters. The study focuses on bridges that span over lanes of traffic. Utilizing the LTBP *InfoBridge*^{TM} database (FHWA- LTBP, 2024) and excluding bridges without lanes underneath by using *'28B - Lanes Under the Structure'* query, a total of 2,719 bridges in Virginia as of 2023 are identified for further investigation. The analysis includes querying data on the overall conditions of these bridges. Figure 2.1 provides a visual representation of the geographical distribution of these bridges in Virginia, with colors indicating their condition.

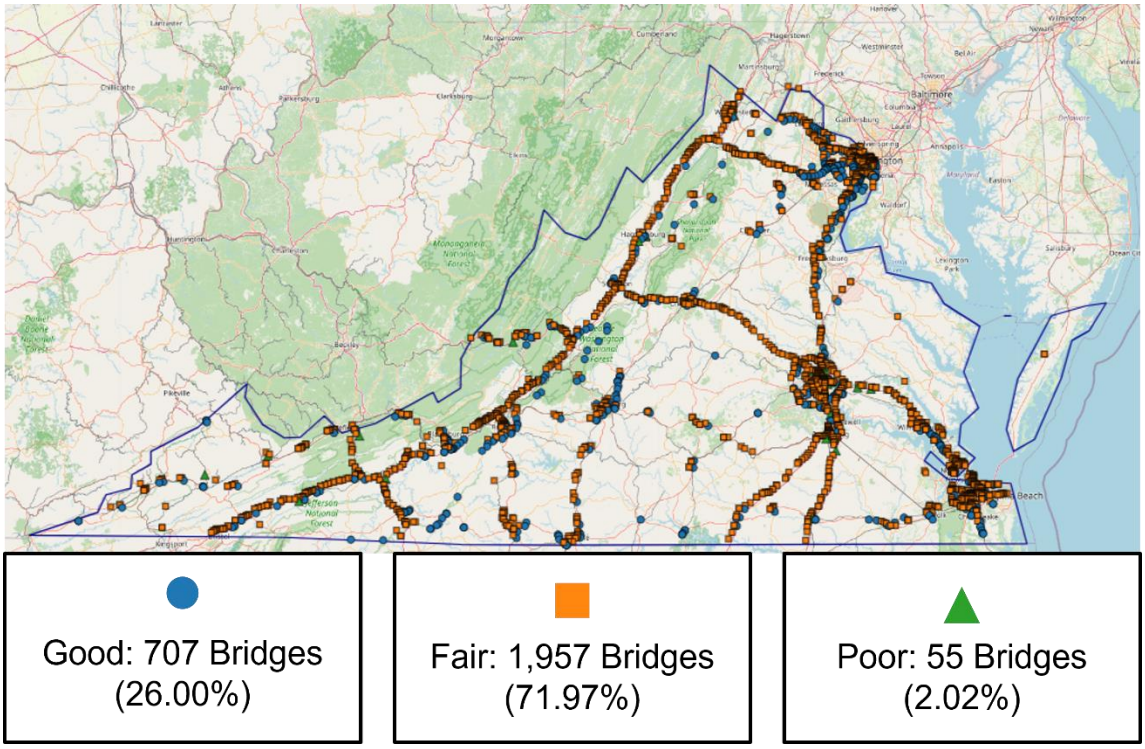


Figure 2.1 - Geographical Distribution of Bridges by Condition

In 2023, out of the 2,719 bridges analyzed, 707 were rated as “Good”, 1,957 as “Fair” and 55 as “Poor”. Most bridges fall into the “Fair” category, which according to the Federal Highway Administration (FHWA, 2022), indicates that while the primary structural elements of the bridge are sound, there may be minor issues such as section loss, cracking, spalling, or scour. This classification highlights the condition of bridges for the specific year of 2023. Additionally, Figure 2.2 provides a visual representation of the performance history of these bridges from 1993 to 2023, as recorded by the LTBP program (FHWA-LTBP, 2024). The plot illustrates annual changes in bridge condition ratings over this period.

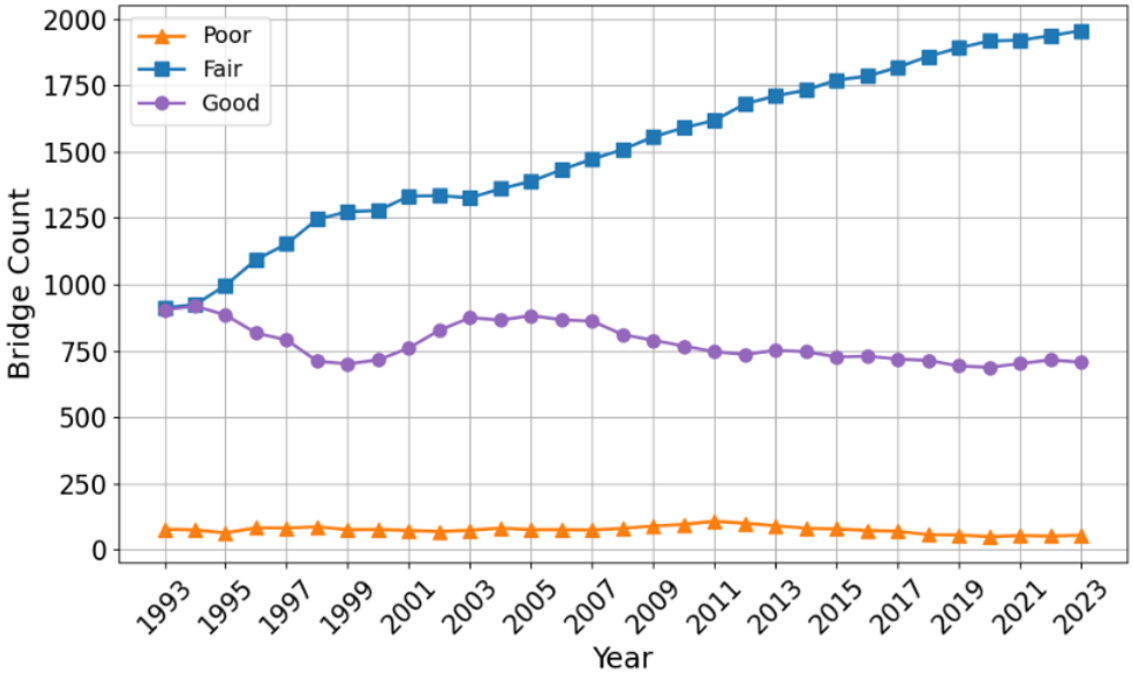


Figure 2.2 - Historical Condition Ratings by Bridge Count

The plot reveals a trend of increasing numbers of bridges rated as "Fair" alongside a decrease in those rated as "Good". This pattern aligns with the common assertion that bridges tend to deteriorate over time, which would be a straightforward observation if the total bridge count remained the same. However, records from 1993 to 2023 show an increase in the overall bridge inventory. Figure 2.3 highlights the annual addition of new bridges, with a peak in 2001 when 95 bridges were introduced. In contrast, 2008 saw a reduction with 8 bridges removed. The Highway Bridge Replacement and Rehabilitation Program (HBRRP) Closed Bridge Report filed November 16th, 2001, states that bridges consistently closed without any remedial actions are deemed non-essential and may be excluded from the National Bridge Inventory (NBI). Over the three-decade span, there has been an annual average addition of 27.5 bridges.

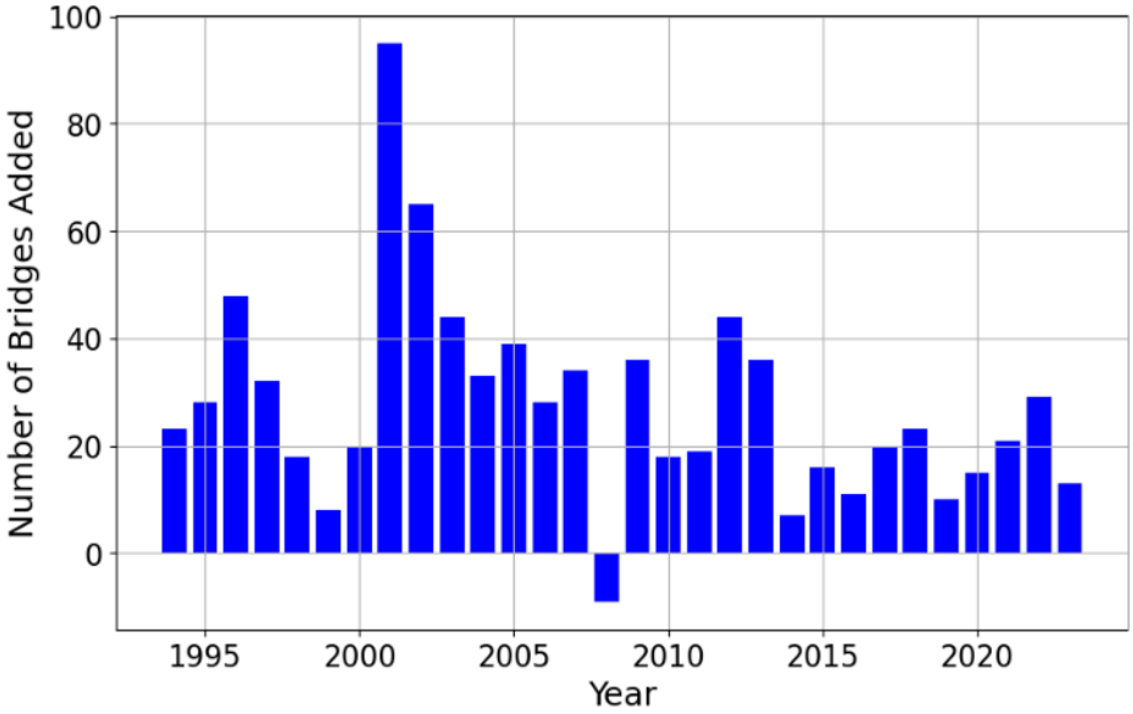


Figure 2.3 - Bridges Added Each Year

As noted in Operational structural performance of bridge types by areas, conducted by Daniel N. Farhey, D.Sc., deck area can be a more appropriate metric when evaluating bridge conditions across a large dataset of bridges (Farhey, 2013). Figure 2.4 illustrates a performance history of bridge condition based on deck area in square feet. From the plot, as time has passed, most of the deck area is in "Fair" condition and continues to trend upwards, while "Good" condition deck area appears to remain within a certain range. This tells a different story than that of total bridge counts by condition. This shows a weight given to deck area not considered to other structural components, such as superstructure and substructure. A decks condition does not determine the overall bridge condition, despite some studies prioritizing its classification categorization over other components (Hasan & Elwaki, 2020).

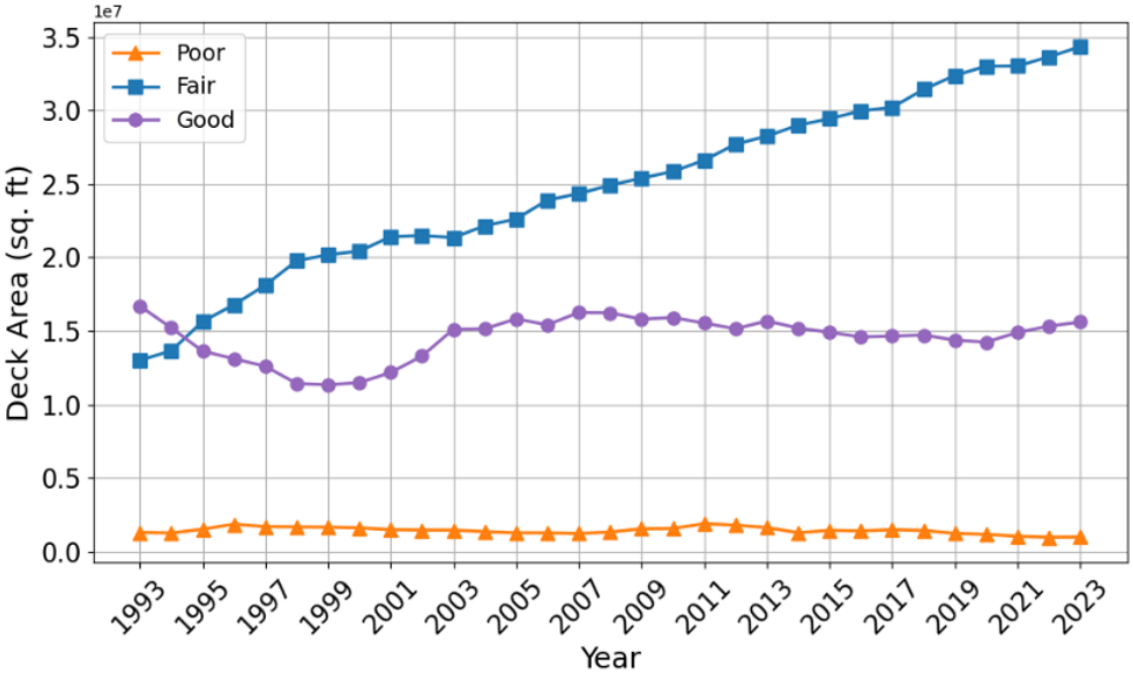


Figure 2.4 - Historical Condition Ratings by Deck Area

In conclusion, by 2023, a greater proportion of bridges were classified as “Fair”, constituting 71.97%, while the percentage of bridges deemed “Good” decreased to 26.00% compared to 1993. Simultaneously, the share of bridges rated as “Poor” diminished to 2.02% over the same period. Figure 2.5 illustrates the overall percentage change year after year. Section 2.2 will investigate distributions of bridges from 2023 by the entities responsible for their maintenance.

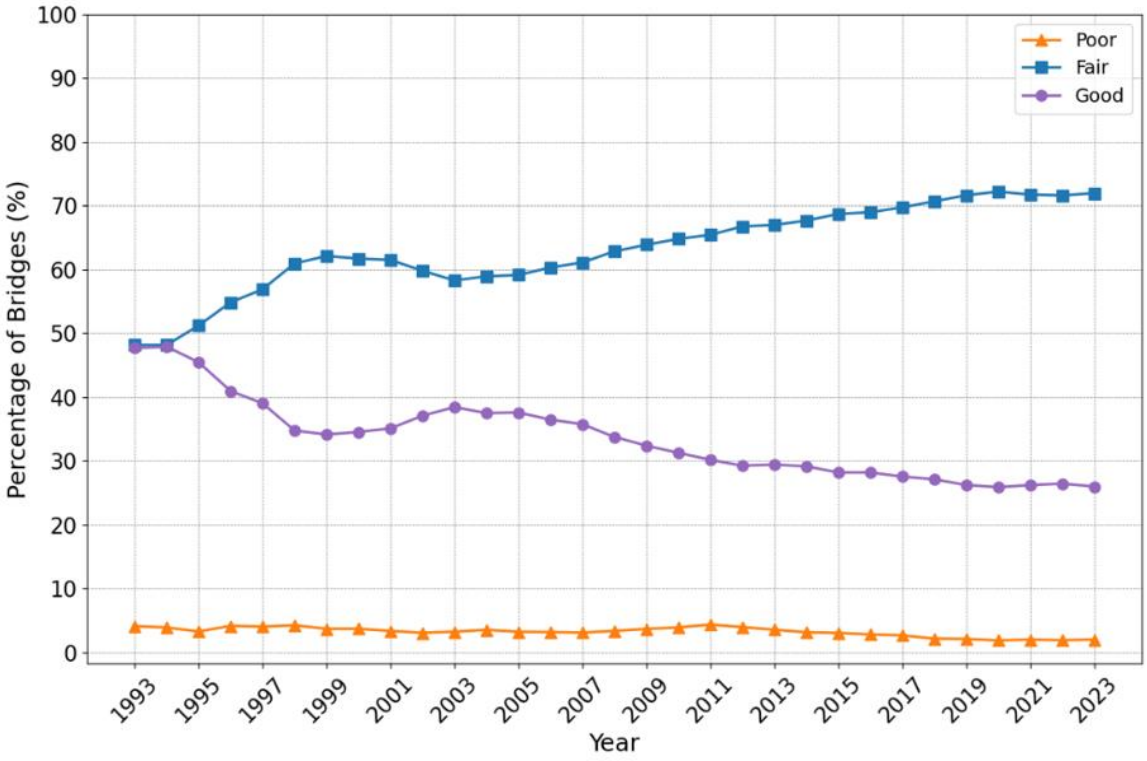


Figure 2.5 - Historical Condition Ratings by Percentage

2.2 DISTRIBUTION OF BRIDGE CONDITION RATINGS BY MAINTENANCE RESPONSIBILITY

There are many entities that are tasked with maintaining, repairing, or replacing bridges across the country. Most are maintained by the respective state authority; however, many bridges fall under the jurisdiction of other government agencies or even private companies. Here, the agencies responsible for the bridges being investigated were queried from NBI element '*21 - Maintenance* Responsibility'. In Figures 2.6, 2.7 and 2.8, a breakdown of each agency is illustrated based on a condition rating of "Poor", "Fair", and "Good" respectively.

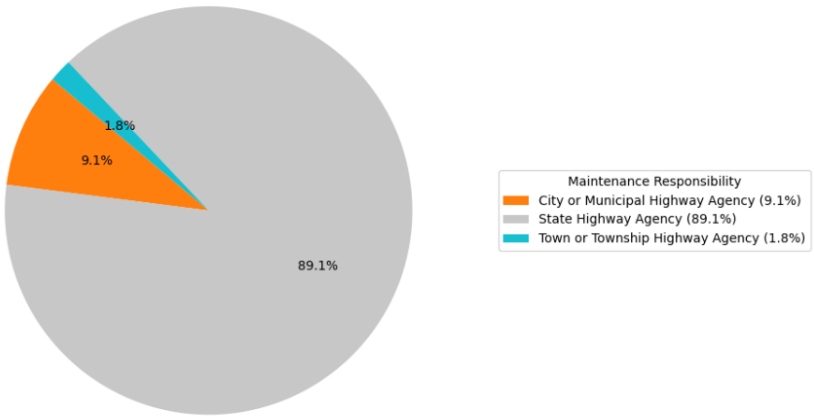


Figure 2.6 - Maintenance Responsibility: Poor Condition

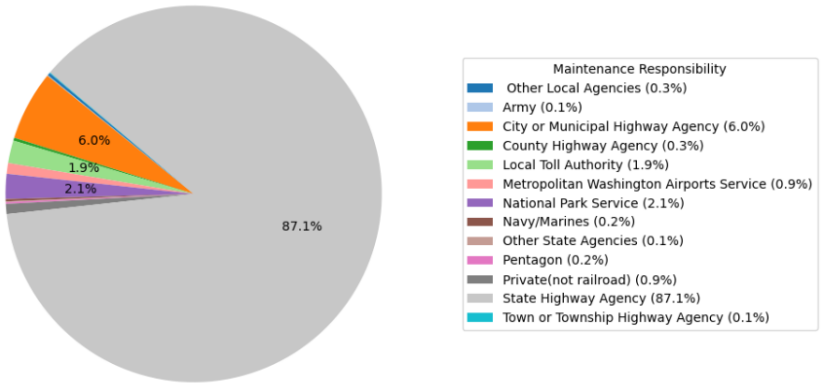


Figure 2.7 - Maintenance Responsibility: Fair Condition

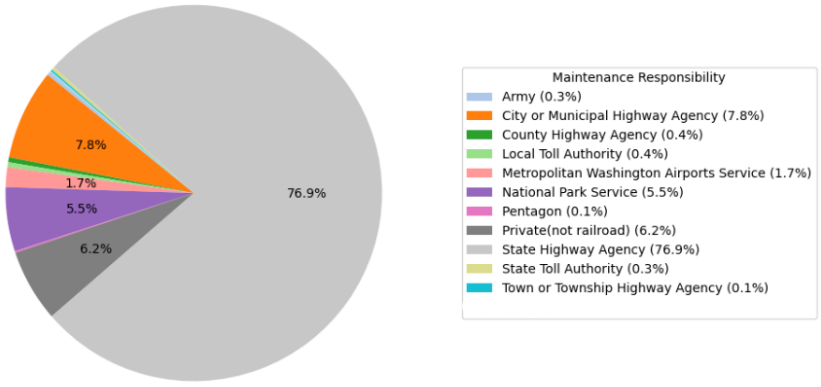


Figure 2.8 - Maintenance Responsibility: Good Condition

The data reveals the distribution of bridge maintenance responsibilities in Virginia. The *State Highway Agency* is responsible for 84.4% of the 2,719 bridges analyzed. It was noted that certain maintenance entities do not manage any bridges rated below "Fair" condition, despite significant usage. These bridges, on average, are older than those under the jurisdiction of *Town or Township Highway Agency*, *City or Municipal Highway Agency*, or the *State Highway Agency*. For example, the *National Park Service* oversees 81 bridges that cross above at least one traffic lane, among which 20 are over 75 years old. Notably, one of these, a 91-year-old bridge with a daily traffic volume exceeding 60,000, is rated as "Good" (FHWA- LTBP, 2024). In contrast, of the 2,298 bridges managed by the *State Highway Agency*, only 14 exceed 75 years of age (FHWA- LTBP, 2024).

2.3 DISTRIBUTION OF BRIDGE CONDITION RATINGS BY YEAR OF CONSTRUCTION

Age has long been suspected of being a major contributor to a bridge's condition rating. Deterioration of bridge components, if not maintained, over time can ultimately lead to unsafe conditions for travelers. Figure 2.9 shows a histogram depicting the percentage of initial construction and reconstruction of bridges by year. The cumulative percentage for initial construction can be seen through a blue line on the histogram. The cumulative percentage shows that 50% of the bridges being considered were constructed after around 1965. Further, between 1985 and 1995, there is the largest volume of bridge reconstruction.

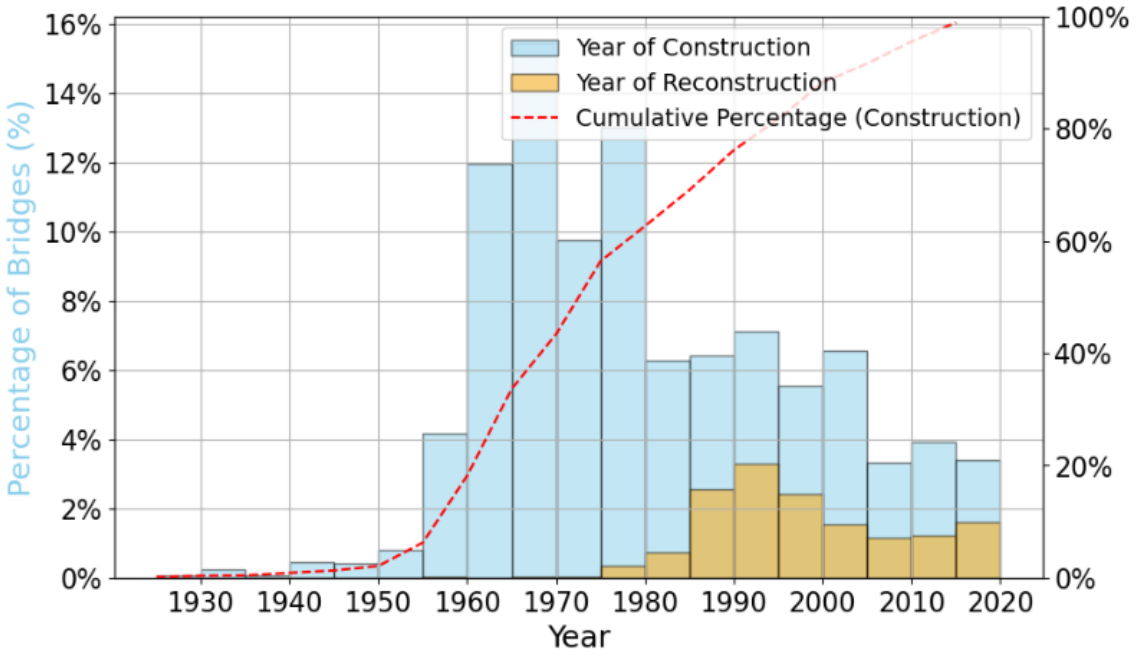


Figure 2.9 - Distribution of Construction and Reconstruction of Bridges

Analyzing the relationship between bridge age and condition, a Pearson correlation coefficient of -0.56 was calculated from historical data sourced from *LTBP InfoBridge*^{TM}, indicating a moderate negative linear relationship. This suggests that as bridges age, their condition tends to deteriorate moderately. The accompanying histogram in Figure 2.10 categorizes bridge ages into bins on the x-axis, with the count of bridges on the y-axis, and uses color coding to differentiate between conditions. The data reveals that bridges in “Fair” condition increase in frequency up to 61 years of age before declining, whereas bridges in “Good” condition decrease until approximately 50 years of age, then see a resurgence between 51 and 61 years. This pattern may hint at prevalent bridge management strategies, such as repairs or reconstruction, typically occurring when bridges reach 50 to 60 years old. Further, this indicates the average life cycle for brides is

between 51 and 61 years old. However, the absence of comprehensive reconstruction data within the NBI dataset limits the ability to conclusively verify this trend.

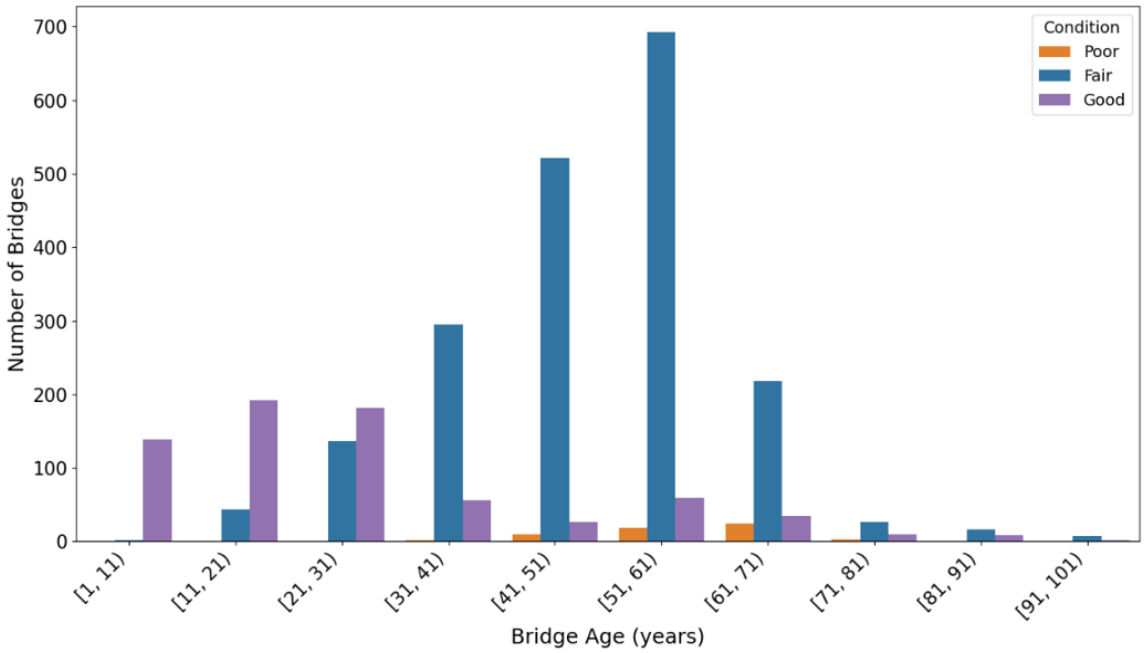


Figure 2.10 – Distribution of Bridge Age and Condition

2.4 DISTRIBUTION OF BRIDGE CONDITION RATINGS BY MAIN SPAN DESIGN AND MATERIAL

Through using the *LTBP InfoBridge*^{TM}, data regarding the material used for the bridge can be extracted. By querying NBI element '*Main Span Material (43A)*', a list of the different materials can be accessed. Figure 2.11 shows a geographical representation of all the bridges being considered based on their main span material. In the figure it is shown that over 70% of the bridges being considered are steel, with main span classifications being "Steel" and "Steel Continuous", while the rest are composed of concrete. There is one bridge that is considered "Other", however, the *LTBP InfoBridge*^{TM} does not specify what this means.

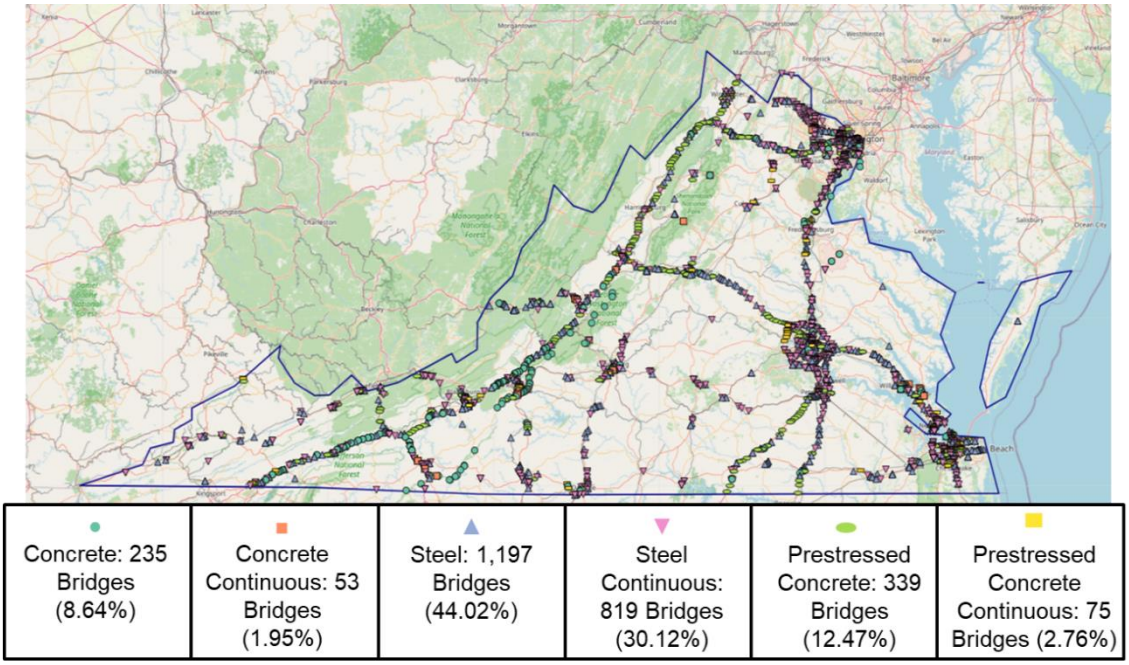


Figure 2.11 - Geographical Distribution of Bridges by Main Span Material

Of this distribution of bridges based on material, a further examination was completed. Figure 2.12 shows a plotted distribution of bridges by their main span materials and color coordinated with respect to their conditions. The y-axis represents the total number of bridges, and the x-axis provides the number based on the main span material. The numerical designation observed in the NBI database is also shown. The data revealed there was a larger percentage of "Good" condition bridges with concrete compared to those constructed with steel, despite steel being the more commonly used. This implies a trend of concrete spans performing better than steel.

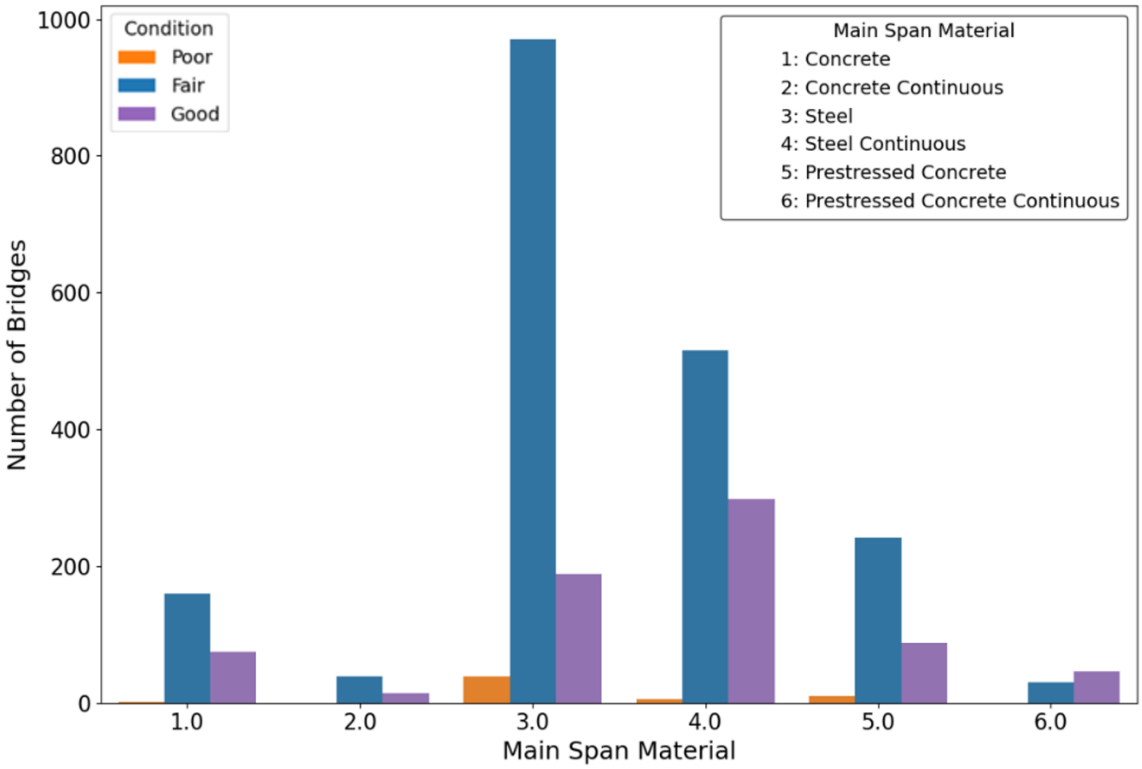


Figure 2.12 - Distribution of Main Span Material and Bridge Condition

Within the previous figures, steel main spans are the more popular material for the bridges being considered. Figure 2.13 illustrates a breakdown of main span materials by year built. Based on the data, from around the 1960s, steel was favored over concrete. This trend has continued into the 2020s, with prestressed concrete seemingly having a large rise in use between 1965 and 1970 then trailing off. Steel main spans have been the material of choice in Virginia.

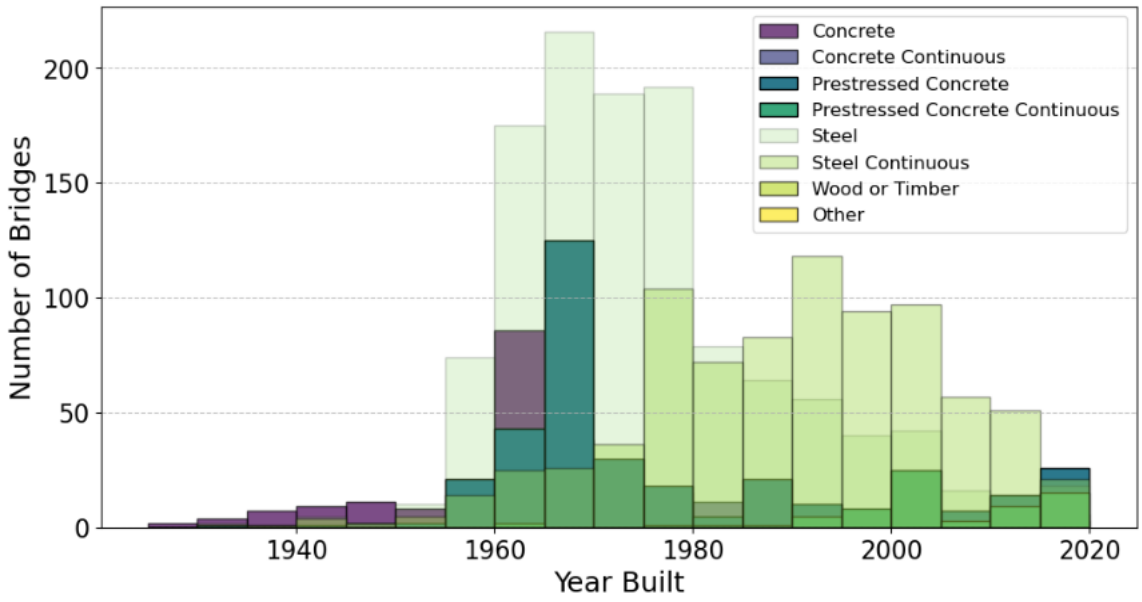


Figure 2.13 - Distribution of Main Span Material by Year Built

From the previous figures it is shown there are bridges that fall under being continuous and non-continuous. This part of the analysis categorizes bridges into continuous and non-continuous types, distinguishing between structures based on their design and support configuration. Non-continuous bridges may incorporate simply supported designs with supports only at the ends or may not maintain continuity throughout their length. For analytical clarity, bridges were grouped as either continuous or non-continuous.

Figure 2.14 presents a comparative distribution of condition ratings for both bridge types. Despite the predominance of non-continuous bridges in the dataset, continuous structures demonstrate superior performance in terms of condition ratings. Specifically, there are 357 continuous bridges, out of 947, rated as “Good”, surpassing the count of non-continuous bridges, 349 out of 1,771, in the same category. This

observation suggests that continuous bridges, by virtue of their design, offer enhanced resilience against live loads, contributing to their better condition ratings.

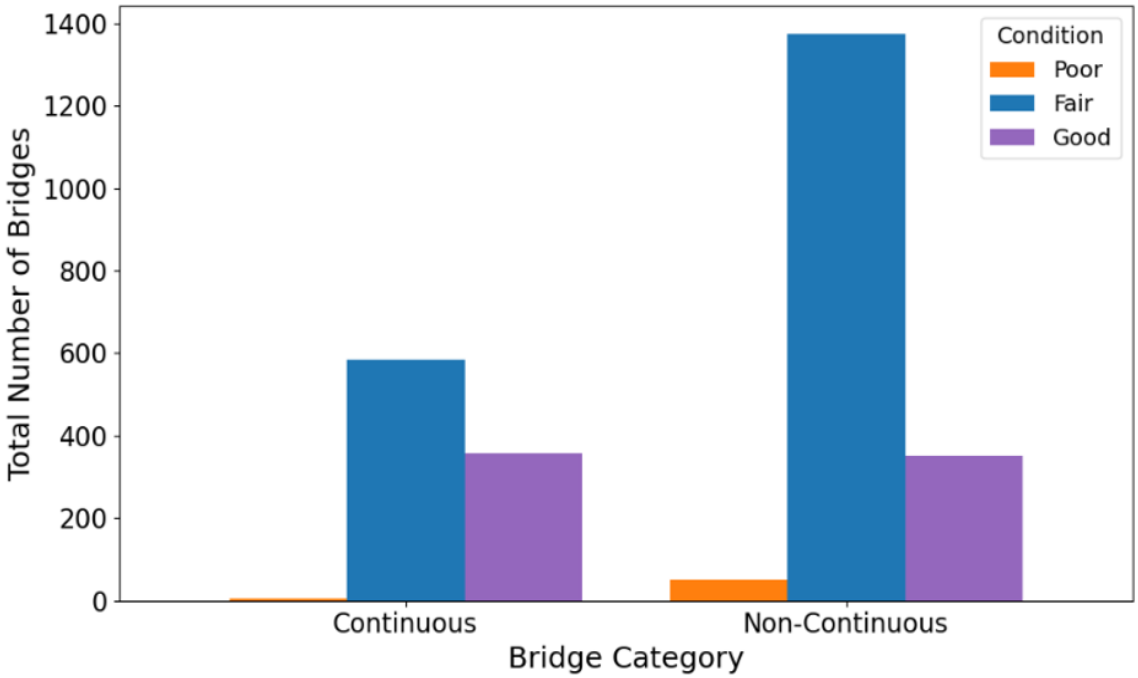


Figure 2.14 - Continuous vs. Non-Continuous Conditions

Figure 2.15 presents the distribution of bridge conditions alongside their main span designs. Citing the study "Operational structural performance of bridge types by areas" by Farhey (2013), it is noted that the "Stringer/Multi-beam or Girder" design is predominant, accounting for nearly 88% of the sample. This design is recognized in that study for its widespread use, offering an average level of durability and longevity. The dominance of this design significantly impacts the overall analysis. Within this category, 83% of the bridges utilize steel as the primary material, highlighting a substantial preference for steel in "Stringer/Multi-beam or Girder" constructions within the studied bridges.

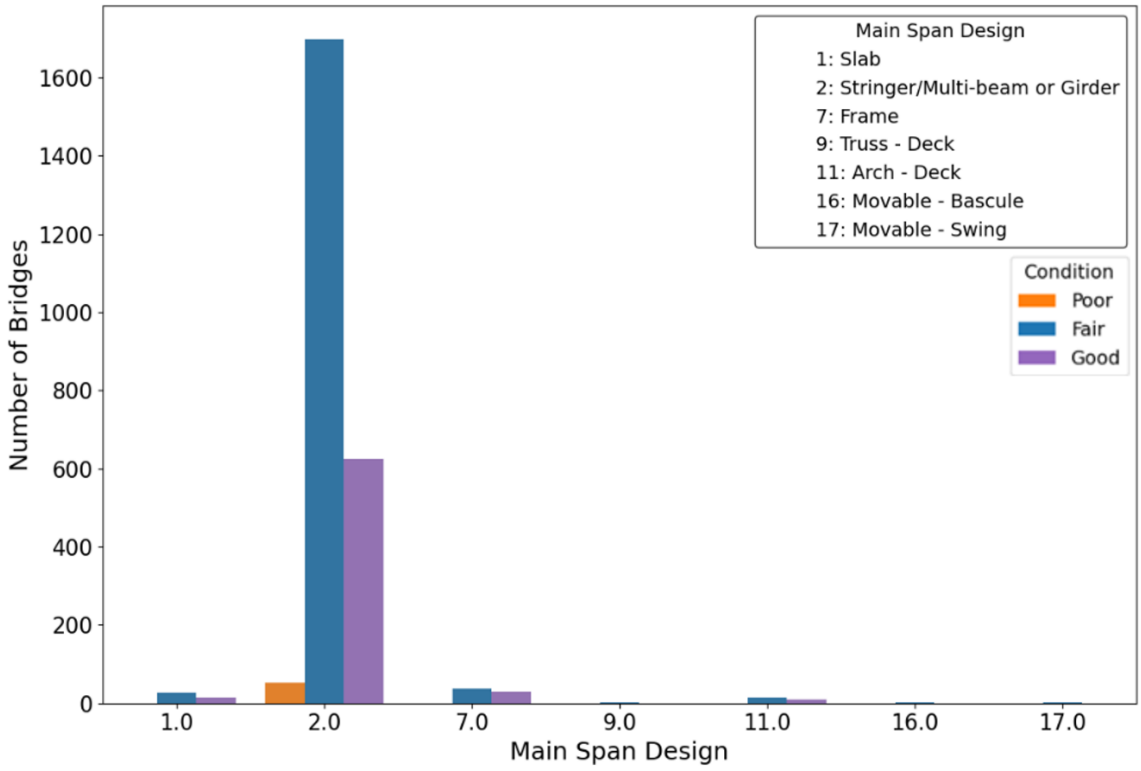


Figure 2.15 - Distribution of Main Span Design and Bridge Condition

The main span design, material and the bridge condition are now considered within a correlation heatmap in Figure 2.16. The heatmap is meant to determine and visualize relationships between those three parameters. A correlation coefficient of 1.0, or -1.0, indicates a perfect correlation. A perfect correlation can be seen on the heatmap when variables are correlated with itself. The only notable linear correlation illustrated is between the main span design and the main span material, which is -0.36. This value indicates there is a tendency for certain types of designs to be associated with specific materials, however the relationship is moderate.

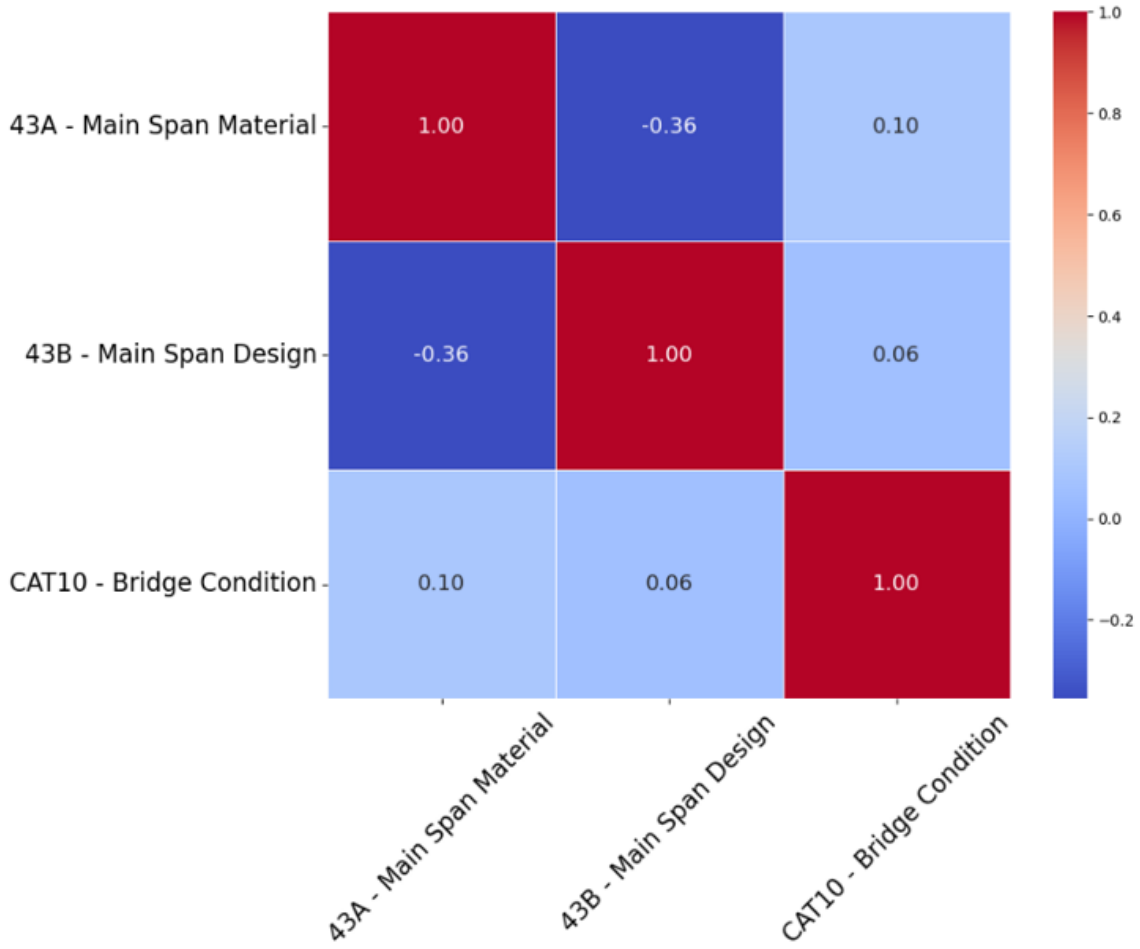


Figure 2.16 - Correlation Heatmap of Span Design, Material and Bridge Condition

Distribution of bridges based on the number of spans is shown in Figure 2.17. Bridges with 2 to 3 spans are the most common within the dataset being analyzed, with a count of 1,451. There are more “Fair” condition bridges for each set of bins along the x-axis. Based on the data, there did not exist a discernable trend between the number of spans of a bridge and its condition.

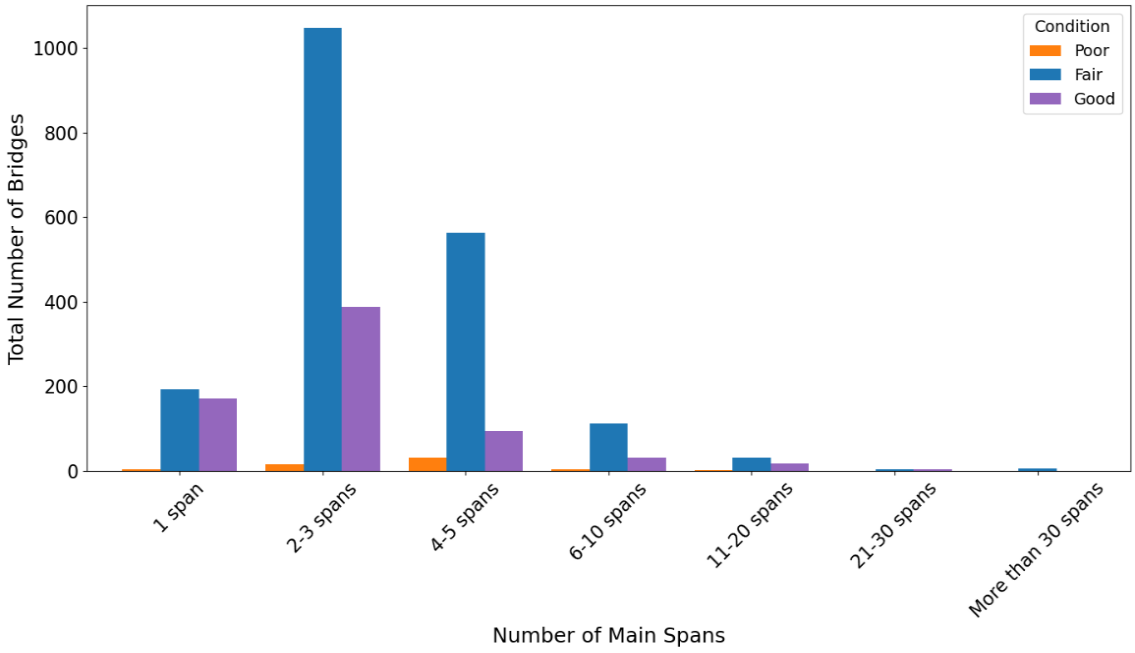


Figure 2.17 - Distribution of Number of Spans and Bridge Condition

CHAPTER 3 - Evaluation and Determination of Bridge Conditions

3.1 EVALUATION OF BRIDGE CONDITION BASED ON COMPONENTS

Based on the FHWA Pavement and Bridge Condition Performance Measures Final Rule, published in January of 2017, bridge condition ratings are to be determined based on the lowest component rating of the substructure, superstructure, and deck condition ratings (FHWA, 2022). It also considers culvert condition ratings as well, however, only if it applies. With this change to how bridge conditions are determined, there were also parameters with regards to what constitutes a given rating. The descriptions of each term and the associated code can be seen on Table 1.1.

The analysis of bridge conditions was conducted using a Pearson correlation coefficient and a scatter plot, utilizing data from *LTBP InfoBridge™*, which includes NBI elements '*58 – Deck Condition Rating*', '*59 - Superstructure Condition Rating*', '*60 - Substructure Condition Rating*', and '*CAT10 – Bridge Condition*'. The process involved selecting the lowest ratings for deck, superstructure, and substructure conditions for each bridge and correlating these with the overall bridge condition ratings. Additionally, an "Overall Bridge Condition (Calculated)" dataset was generated based on NBI parameters for a comparative analysis with conditions listed in '*CAT10 – Bridge Condition*'. The resulting scatter plot, depicted in Figure 3.1, aligns the calculated bridge conditions (x-axis) with the '*CAT10 – Bridge Condition*' ratings (y-axis).

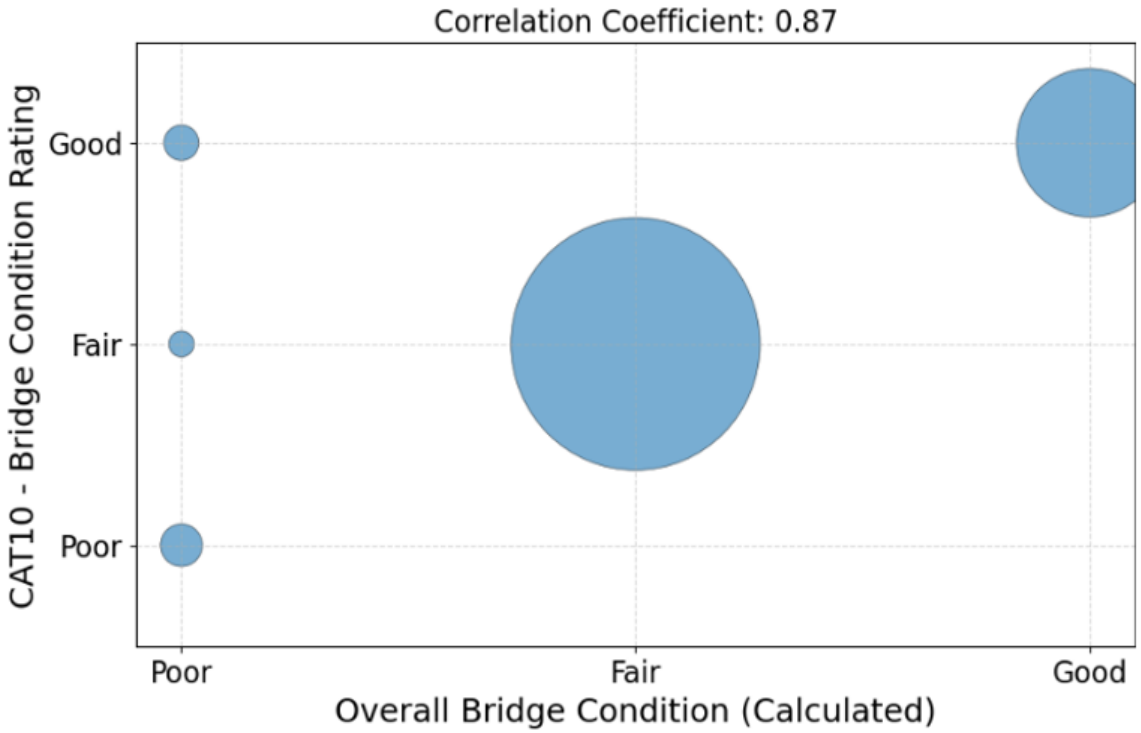


Figure 3.1 - Overall Bridge Condition Ratings vs. Calculated Condition Ratings

The Pearson correlation coefficient of 0.87 signifies a strong positive linear correlation, indicating that higher deck, substructure, and superstructure ratings correlate with increased overall bridge condition ratings. Additionally, 97.87% of the conditions calculated correspond with those observed in '*CAT10 – Bridge Condition*'. Table 3.1 presents a cross-tabulation detailing the alignment between the calculated bridge condition totals and the '*CAT10 – Bridge Condition*' totals, specifically highlighting the agreement on bridges classified as "Poor". However, discrepancies are noted in the classification of bridges deemed "Fair" and "Good" by NBI compared to those suggested to be "Poor" based on their parameters, affecting 20 and 38 bridges respectively.

Table 3.1 - Cross-Tabulation of Bridge Condition Ratings

		CAT10 - Bridge Condition			
		Poor	Fair	Good	Total
Bridge Condition (Calculated)	Poor	55	20	38	113
	Fair	0	1,937	0	1,937
	Good	0	0	669	669
	Total	55	1,957	707	**2,719**

A correlation coefficient of 1.0 denotes perfect correlation. The observed strong but imperfect linear relationship suggests potential noise within the data. The high match percentage for condition ratings indicates general reliability in condition assessments. However, discrepancies arise in the classification of bridges as "Fair" and "Good" when NBI's criteria would classify them as "Poor", pointing to overlooked complexities or data noise influencing categorization. Specifically, 113 bridges are identified as "Poor" through calculation, contrasting with the 55 bridges classified as "Poor" by '*CAT10 – Bridge Condition*'. Figure 3.2 depicts a heatmap that shows linear correlations between component ratings, the calculated condition rating, and ratings from '*CAT10 – Bridge Condition*'.

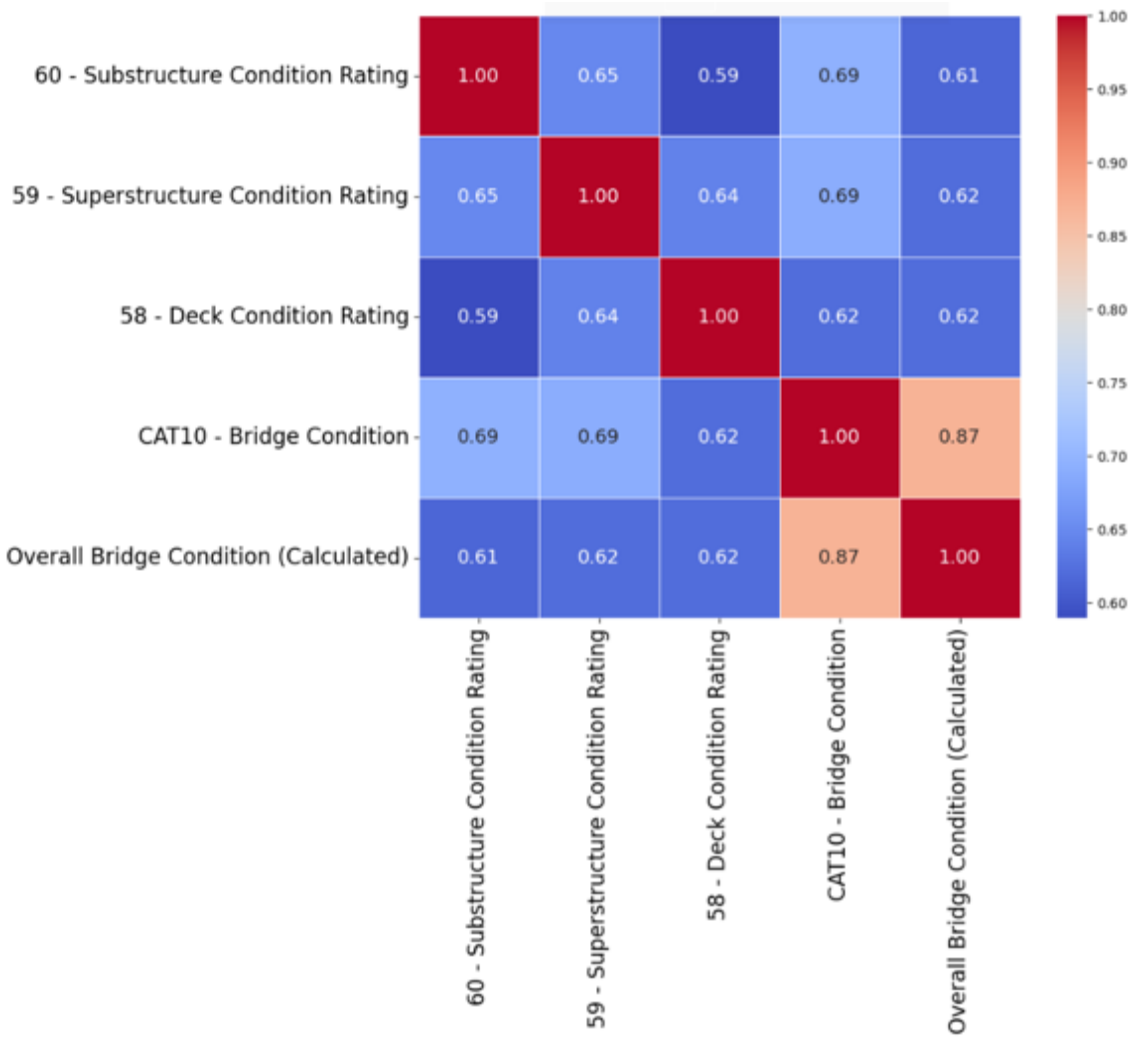


Figure 3.2 - Correlation Heatmap for Bridge Conditions

Data analysis reveals a moderate positive linear correlation among component condition ratings for bridges. This relationship is not strong but suggests that the condition of one component may have some influence on the condition of another. The rating process is subjective, relying on the inspector's judgement (Alsharqawi et al., 2020). Researchers aimed to create an integrated model for bridge condition assessment using k-means clustering to support maintenance, repair, and replacement decisions (Alsharqawi et al., 2020). Despite the inherent subjectivity, the observed moderate

correlation indicates a degree of consistency or standardization in the inspection process. This might imply that the conditions and performances of bridge components are somewhat interconnected. However, the moderate level of correlation alone does not suffice for predictive analysis.

3.2 EVALUATION OF BRIDGE CONDITION BASED ON STRUCTURAL EVALUATION APPRAISAL

From section 3.1, the data implied a strong positive correlation between the lowest component condition ratings and the overall bridge condition rating. In addition to this, there exists an apparent moderate positive correlation between the individual components where one component rating affects a separate component rating. Now, investigation into the structural evaluation appraisal ratings is considered. It is important to note, according to the NBIS, the FHWA discontinued certain appraisal ratings from the *Coding Guide* due to their findings that the items did not change from inspection to inspection (FHWA, 2022). The appraisals that were discontinued are: Deck Geometry (Item 68), Underclearances, Vertical and Horizontal (Item 69), and Structural Evaluation (Item 67).

According to the *Coding Guide*, structural evaluation appraisal ratings are based on Inventory Rating (Item 66) and Average Daily Traffic (ADT) (Item 29) (FHWA, 1995). With inventory rating being defined as the capacity rating that results in a load level which can safely utilize an existing structure for an indefinite period (FHWA, 1995). A description of the structural evaluation appraisal ratings can be seen in Table 3.2 while Table 3.3 provides criteria.

Table 3.2 - Structural Evaluation Appraisal Rating Codes and Description from NBI

Code	Description
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 being left in place as is
4	Meets minimum tolerable limits to be left in place as is
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 closed

Table 3.3 - Structural Evaluation Appraisal Code Criteria

Structural Evaluation Rating Code	Inventory Rating		
	Average Daily Traffic (ADT)		
	0-500	501-5000	>5000
9	>32.4 (MS18)	>32.4 (MS18)	>32.4 (MS18)
8	32.4 (MS18)	32.4 (MS18)	32.4 (MS18)
7	27.9 (MS15.5)	27.9 (MS15.5)	27.9 (MS15.5)
6	20.7 (MS11.5)	22.5 (MS12.5)	24.3 (MS13.5)
5	16.2 (MS9)	18.0 (MS10)	19.8 (MS11)
4	10.8 (MS6)	12.6 (MS7)	16.2 (MS9)
3	Inventory rating less than value in rating code of 4 and requiring corrective action		
2	Inventory rating less than value in rating code of 4 and requiring replacement		
0	Bridge closed due to structural condition		

Note: The Structural Evaluation Appraisal Code criteria table was obtained from the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (1995)*

Table 3.2 reflects the evaluation criteria for bridge structural appraisal as defined by the ADT and the carrying capacity in metric tons. Each structural evaluation rating corresponds to a specific code, with Code 9 indicating a capacity exceeding the necessary inventory ratings for all ADT levels, and Codes 8 through 4 representing fixed carrying capacity thresholds required for each rating. The carrying capacities are expressed as "MS" values, with "MS" designation corresponding to the AASHTO Standard

Specifications for Highway Bridges, 16th Edition's HS20 design truck load. The number following "MS" indicates the gross vehicle weight in tons that the bridge is designed to support, and the value above the MS designation represents the truck mass in metric tons. Bridges with a rating of Code 3 require corrective action, while Code 2 requires replacement. A bridge that fails to meet the minimum carrying capacity of 2.7 metric tons, as stipulated by the Coding Guide, will be closed (Code 0). In this context, the studied bridges are assessed to verify their capacity to sustain the designated loads, ensuring they meet the specified criteria.

Through the *LTBP InfoBridge™* (FHWA- LTBP, 2024), structural evaluation appraisal ratings can be extracted through querying NBI element '*67 – Structural Evaluation Appraisal*'. After extracting, the data was filtered and organized into a histogram that highlights the codes across all bridges. Figure 3.3 shows the average structural evaluation code of all bridges is 5.96, taken as 6, with a standard deviation of 0.9. The average evaluation code of 6 indicates that most bridges are equal to present minimum criteria, based on Table 3.2.

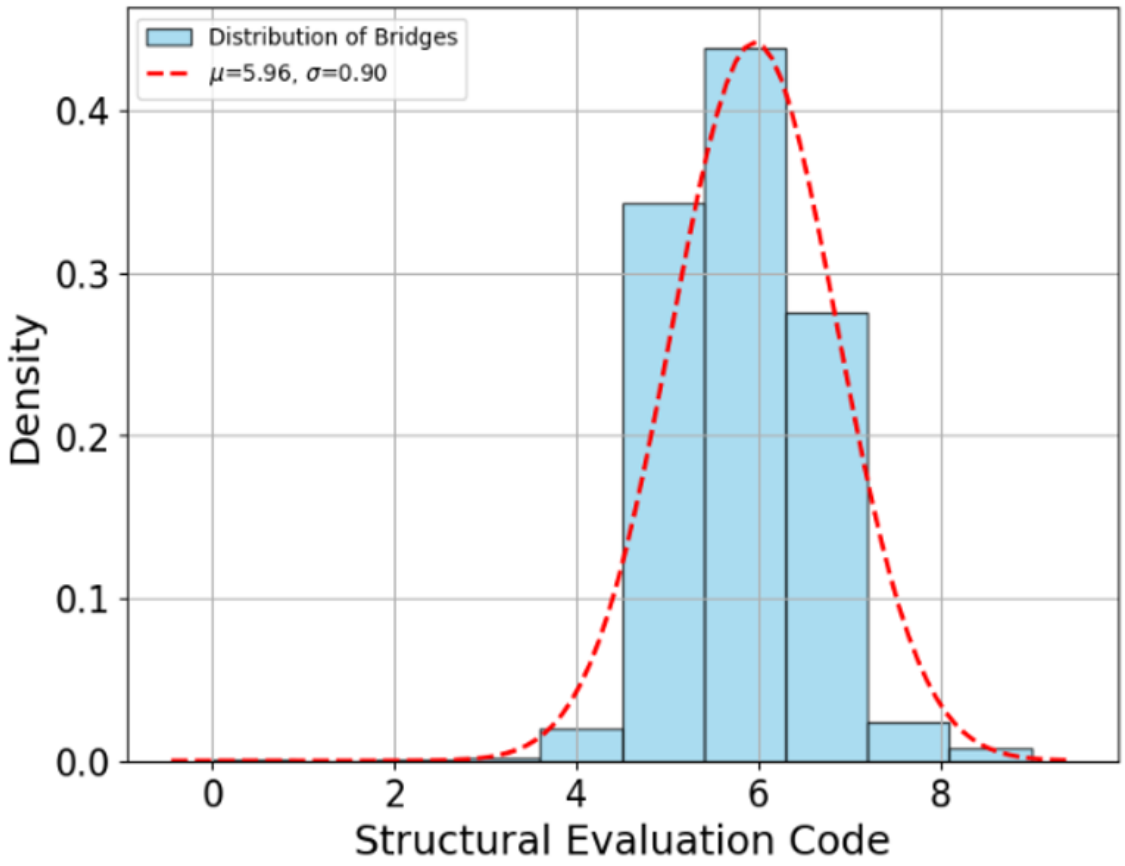


Figure 3.3 - Distribution of Structural Evaluation Appraisal Codes

An analysis is then conducted to explore the relationship between structural evaluation appraisals and the overall bridge condition rating. Given that evaluation codes factor in ADT and carrying capacity, it is posited that these aspects influence bridge condition. Figure 3.4 depicts this relationship through a scatter plot, with the structural evaluation appraisal codes from Table 3.1 on the x-axis and bridge condition ratings on the y-axis, investigating the potential linear correlation between these variables.

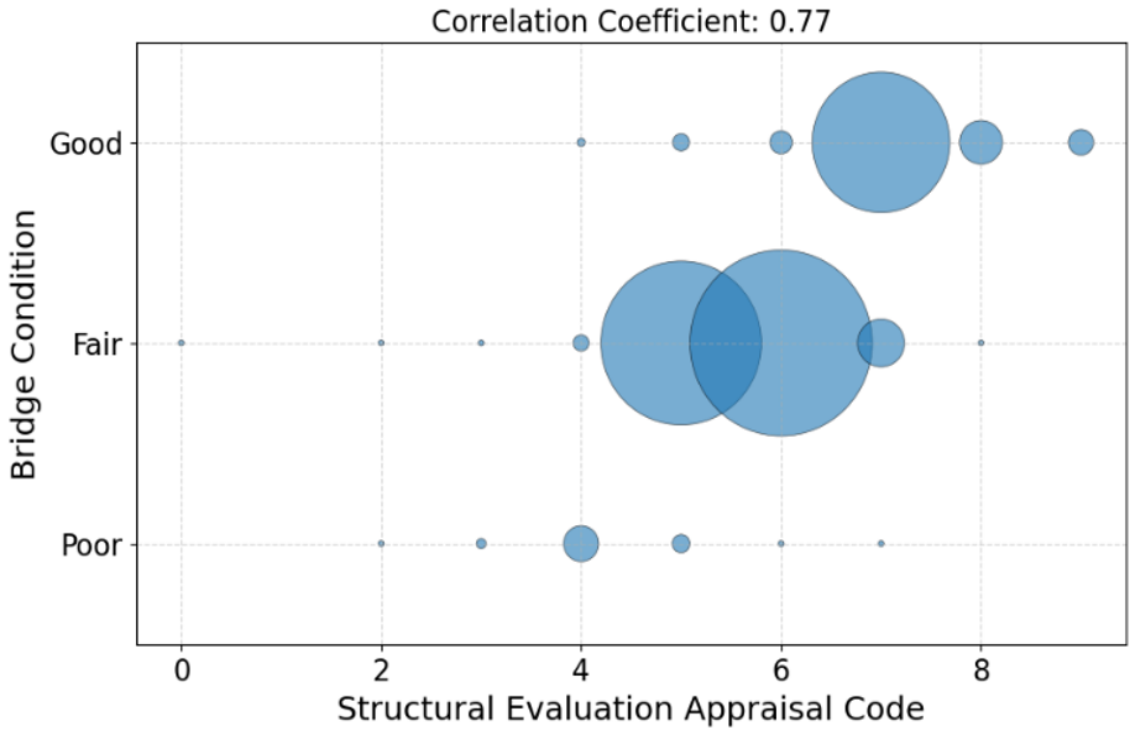


Figure 3.4 - Bridge Condition vs. Structural Evaluation Appraisal Scatter Plot

Figure 3.4 depicts a Pearson correlation coefficient of 0.77, denoting a strong positive linear correlation between bridge condition ratings and structural evaluation appraisal codes. This suggests a clear trend: as the appraisal codes, which reflect a bridge's capacity to handle ADT and its carrying capacity, increase, the condition ratings of the bridge tend to improve. The notable influence of traffic volume and load-bearing capacity on the condition rating is substantiated by this correlation. However, the strong positive linear correlation also implies the existence of additional factors that may be impacting the bridge's condition beyond these two parameters.

CHAPTER 4 - Discussion and Conclusion

4.1 DISCUSSION

Analysis of National Bridge Inventory (NBI) data, following specific data set filtration, yielded distinct observations that align with existing theories and studies on bridge condition ratings. This study, however, focused solely on a sample of 2,719 bridges in Virginia, each spanning across at least one lane of traffic, diverging from broader scopes reviewed in the literature review. Consequently, the observed trends and linear relationships are applicable only to this subset. To extend these findings nationally, a more comprehensive study encompassing a wider array of bridges would be necessary, providing further exploration of the aspects highlighted in this thesis.

The examination of bridge conditions from 1993 to 2023 revealed enduring patterns. The proportion of bridges rated “Poor” has been consistent, averaging 3.25% throughout the decades. Apart from the years 2011 and 2012, the number of bridges considered “Poor” was below 100. An inverse relationship was consistently noted between the numbers of “Fair” and “Good” rated bridges: as the former increased, the latter declined. However, this trend was less pronounced when analyzing deck areas alone; while “Fair” deck conditions increased over the years, “Good” deck conditions showed improvement in recent years. These patterns suggest targeted maintenance efforts, underscoring the intricacy of assessing bridge conditions.

The complexity of bridge condition assessment was further interpreted by calculating the Pearson correlation coefficient between bridge age and overall condition. The hypothesis that older bridges would generally have poorer condition ratings was not fully supported, with a coefficient of -0.56 indicating only a moderate negative

correlation. This suggests that while there is some tendency for older bridges to have lower ratings, the relationship is not definitive. Maintenance and repair interventions show a direct impact on bridge condition classifications. Yet, the data indicates that a simple absence of maintenance does not correspond linearly with lower condition ratings, pointing to other influencing factors in the determination of bridge health.

The investigation revealed that neither the material nor the design of the main span significantly affects bridge condition ratings on their own. However, a moderate negative correlation of -0.36 was observed between the material and design, indicating that design choices moderately influence the selection of materials. The prevalent design among the bridges studied is the steel stringer/multi-beam or girder. According to Farhey (2013), while this design is widely adopted, it is associated with below-average durability and longevity, yet it maintains an average rating in terms of condition. This correlation, alongside the findings from previous research, underscores the multifaceted nature of bridge design and material selection in relation to bridge longevity and condition.

Finally, according to the FHWA guidelines, the overall bridge condition rating is determined by the lowest rating of the deck, superstructure, or substructure components. Ratings are assigned as “Poor” if the lowest component rating is 4 or lower, “Fair” for ratings between 5 and 6, and “Good” for a 7 or higher. Analysis of the data yielded a strong positive correlation coefficient of 0.87, suggesting a robust association between the lowest component rating and the overall bridge condition. Additionally, there was a 97.87% concordance between the observed condition ratings and those calculated by NBI criteria, indicating the assessment’s high reliability. Nonetheless, the correlation fell short of the perfect score of 1.0, and instances of bridges rated as “Fair” or “Good” that should

be classified as “Poor” point to possible data inaccuracies or other variables affecting the ratings. Figure 4.1 depicts a heatmap of all factors considered correlated against the calculated bridge conditions and the ‘*CAT10 – Bridge Condition*’ dataset.

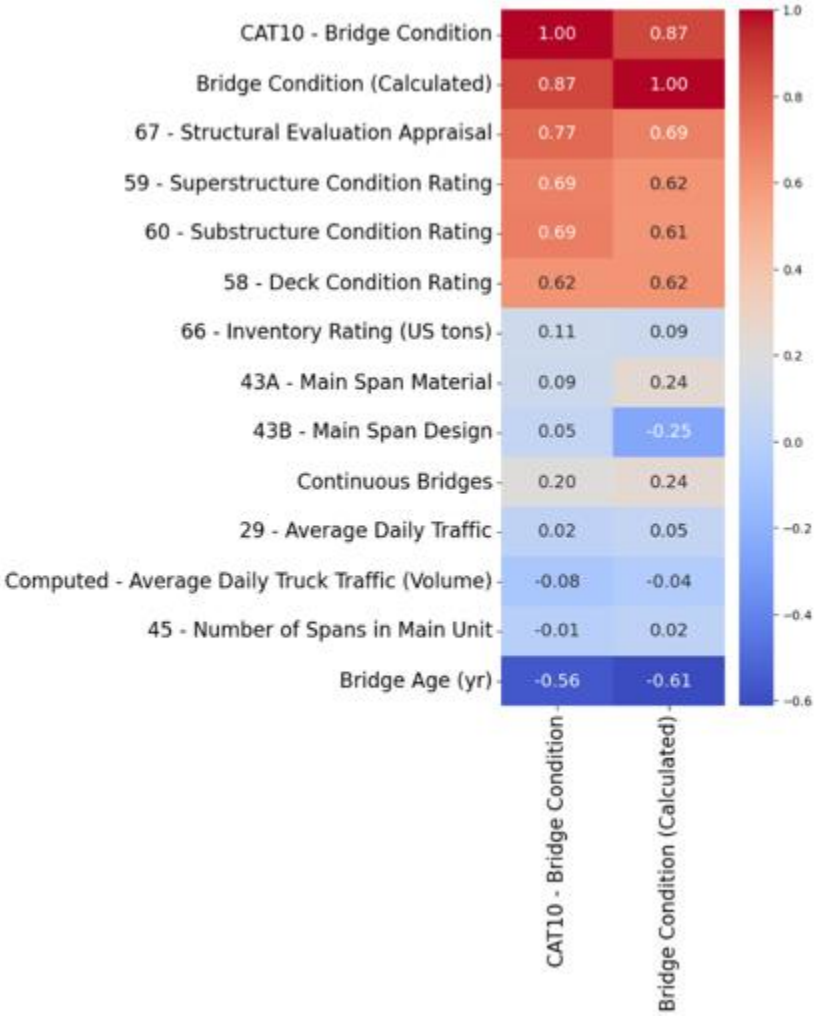
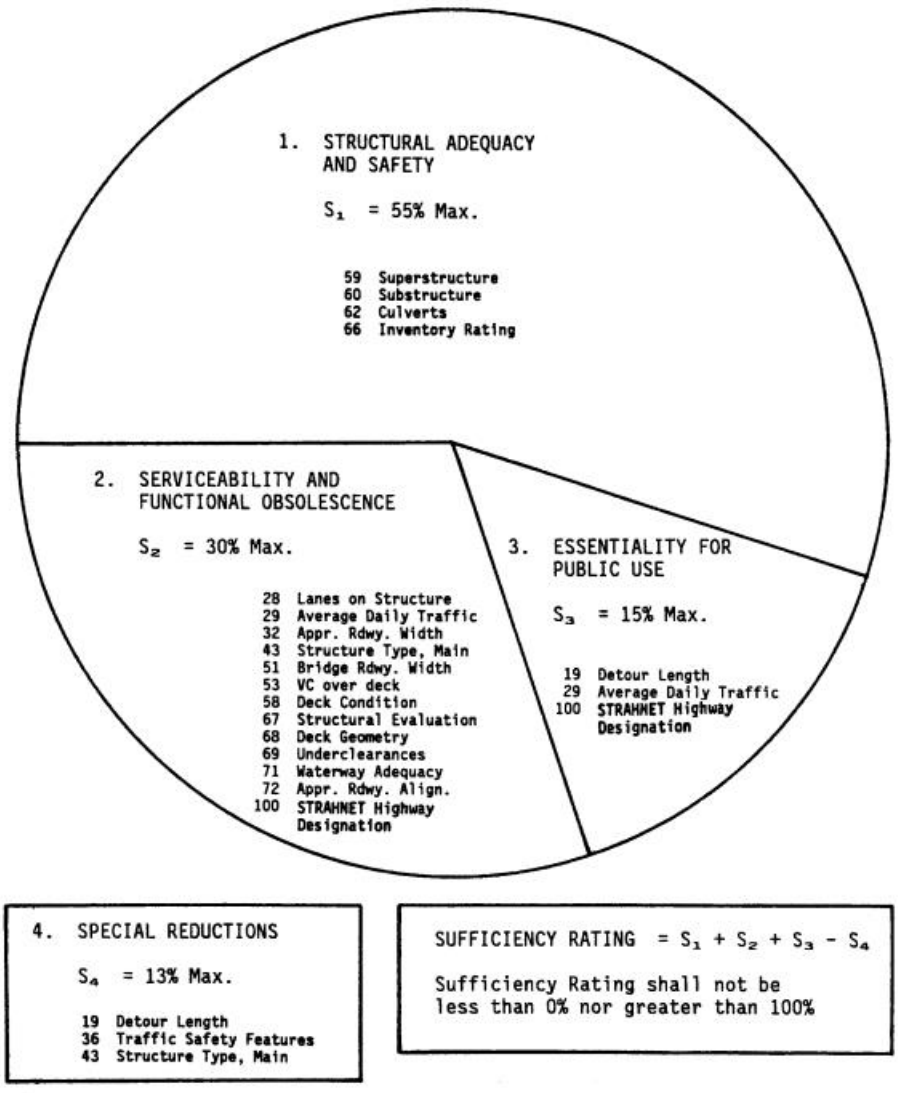


Figure 4.1 - Correlation Heatmap

4.2 CONCLUSION

This research identified multiple factors that impact but do not exclusively determine overall bridge condition ratings, with the most significant linear correlations observed in structural evaluation appraisal codes, minimum component ratings and bridge age. Notably, evaluation appraisal codes are influenced by the bridge's inventory rating and ADT, aligning with prior studies on factors affecting bridge condition ratings. The moderate negative correlation between bridge age and condition ratings is consistent with existing research. However, the presence of a strong but not perfect correlation with minimum component ratings suggests the influence of additional factors beyond the lowest component rating assessed during inspections. These findings underscore the complexity of factors affecting bridge condition ratings and support the recommendation to reintegrate the Sufficiency Rating system, as outlined in the Coding Guide, to complement the current rating system.

The Sufficiency Rating system incorporated numerous factors that were each weighted differently. Mentioned previously in this study, the Sufficiency Rating considered four factors: Structural Adequacy and Safety, Serviceability and Functional Obsolescence, Essentiality for Public Use, and Special Reductions. Figure 4.1 provides the breakdown of each factor and what makes them up.



Note: The Sufficiency Rating System pie chart was obtained from the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (1995)*

Figure 4.2 - Sufficiency Rating System

The Sufficiency Rating of bridges incorporates 23 categories of data across four key factors, enhancing the complexity of condition assessment. However, this multifaceted approach, when used alongside the existing categorization method, allows for a more nuanced analysis of bridges nationwide. The current system offers an immediate overview of a bridge's condition, while a deeper examination is possible by

evaluating the individual ratings of each factor. For instance, a bridge's Essentiality, measured by criteria such as average daily traffic, detour length, and Strategic Highway Network Designation (S_3), might indicate its importance to public use despite potential deficiencies in structural adequacy and safety (S_1), enabling a comprehensive assessment.

This research aimed to explore the linear correlations, trends, and factors impacting bridge conditions. It revealed that various factors could influence bridge conditions, extending beyond the traditionally identified lowest component ratings. The combined effect of ADT and inventory rating, as well as the apparent effect of reconstruction and maintenance on bridge conditions with regards to bridge age, suggests the need for future studies to address multivariate correlation analysis. The data's complexity and thoroughness underline the need for an enhanced rating system to augment the current methodology for evaluating bridge health.

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