CHARACTERIZING BRIDGE AND CULVERT DETERIORATION IN ARIZONA USING NATIONAL BRIDGE INVENTORY DATA

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ABSTRACT

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The characteristics of more than 600,000 bridges in the United States are recorded in the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) database. The goal of this study was to quantitatively analyze the deterioration of concrete bridge decks and culverts between the years of 1992 and 2022 using this publicly available data. The results were determined using condition ratings on a scale from 0 to 9 that describe the existing, in-place bridge as compared to the as-built condition; a rating of 9 is excellent while a condition of 0 indicates failure. Two NBI coding items were used, Item 58 Deck and Item 62 Culverts that describe the overall condition rating of the deck and of a culvert, respectively. Furthermore, the effect of several key parameters on deck or culvert condition were evaluated, such as type of superstructure material, type of superstructure cross-sectional geometry, average daily traffic (ADT), type of wearing surface, and geographical location. Specifically, detailed results associated with the state of Arizona, as well as broad results associated with the entire United States are presented. The trends are based on NBI ratings over time, and bridge owners can use the results to properly assess deck condition, predict future deck condition, and plan for future bridge maintenance.

In Arizona, results indicated that bridge decks carried by concrete superstructures performed better than those carried by steel superstructures; within that subset, culvert ratings over time were higher compared to ratings of decks carried by traditional superstructures. Furthermore, bridge decks and culverts carrying an ADT greater than 10000 vehicles/day

exhibited more deterioration compared to those with low ADT. Overall, bridge decks and culverts in Arizona had a better rating than those in the U.S. considering comparable categories, but the rate of deterioration for bridge decks and culverts in Arizona was higher from 1992 to 2022 versus the U.S. considering many of the parameters investigated.

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Dedication

To my beloved parents- Om Prakash Kandgule and Latha Kandgule

To my brother- Sai Prakash Kandgule

For their endless encouragement, support, and sacrifice.

For believing in me and encouraging me to be the best version of myself.

To my graduate committee for believing in me, guiding me, and inspiring me to pursue my ambitions as an engineer in civil engineering.

Chapter 1. Introduction

1.1 Background

1.1.1 United States Bridges and Culverts

The United States has an extensive system of bridges and culverts that are critical components of the country’s transportation infrastructure. According to the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (2020), these structures are classified as spanning more than 20 ft. These bridges and culverts connect cities, towns, and rural areas, allowing people and products to move easily. Understanding the general condition of bridges and culverts in the United States is critical for ensuring the safety, efficiency, and sustainability of the country’s transportation infrastructure.

As technology evolved, reinforced concrete, steel and prestressed concrete became prevalent materials for bridge superstructures and decks, which allowed for the development of longer and more robust bridges. The condition of U.S. bridges varies widely. Some bridges and culverts are well-maintained and in excellent condition, while others are deteriorating and require immediate attention. The combined impacts of numerous complex phenomena, such as reinforcement corrosion, concrete degradation, creep, shrinkage, cracking, or fatigue results in the deterioration of bridge components.

There are 620,669 bridges, including culverts, across the United States. Currently, 42% of all bridges are at least 50 years old, and 7.5% of the Nation’s bridges are considered structurally deficient, meaning they are in “poor” condition. A structurally defective bridge is one that requires extensive repairs to vital components such as the bridge deck, superstructure, or substructure. Exacerbating this problem, 178 million trips are taken across these structurally deficient bridges every day. However, it is encouraging to note that, as of 2019, just one in 13 highway bridges were classified as structurally inadequate, or substandard, which is a major improvement from the 12.1% observed in 2009. It is also reassuring to see that the overall proportion of bridge deck area designated as structurally defective, or substandard, has dropped since 2018 totaling just 5.5% in 2019, compared to 6.3% in 2016 (ASCE 2021). These improvements to the Nation's infrastructure are likely due to regular maintenance and repair.

The backlog of bridge maintenance in the United States is a concern. Many bridges require rehabilitation or replacement, but budget limits and financial issues have resulted in postponed maintenance, which can lead to more complex and costly repairs in the future. Unfortunately, between 2020 and 2021, the rate of decline in the number of bridges with structural deficiencies has significantly reduced considerably to just 0.1% annually, while the number of bridges falling from good to fair condition has been increasing (ASCE 2021).

A methodical approach should be used while bridge improvements are undertaken to increase their durability. Bridge condition has a direct impact on safety. Bridge deterioration can be dangerous, and weight limitations can hamper the flow of goods and services. Addressing the deficiencies of U.S. bridges necessitates significant investment in infrastructure maintenance, repair, and replacement, federal and state governments, as well as municipal governments, are collaborating to find financial options to solve the backlog of bridge maintenance demands.

1.1.2 Classification of Bridges and Culverts Using the NBI Rating System

Despite their critical significance, the United States' bridges decks are facing an increasing challenge—deterioration. The unrelenting forces of time, weather, and heavy traffic have taken their toll on these vital structures. Many bridges decks are deteriorating, outliving their intended lifespan, and showing indications of wear and tear. Corrosion, cracks, and structural flaws have become all too widespread, raising concerns about the safety and reliability of the Nation's infrastructure. In the United States, condition ratings are used for standardized reporting of visual inspections of bridges in accordance with the National Bridge Inspection Standards (NBIS). Bridge owners report the details of each structure to the U.S. Department of Transportation (DOT) and Federal Highway Administration (FHWA), which use the National Bridge Inventory (NBI) *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* for coding of condition rating of bridge components (U.S. DOT 1995). This single source of data provides information about each bridge, such as structure number, location, year built, type of bridge superstructure, average daily traffic (ADT), deck condition rating, ownership, etc. NBI records are publicly available from the FHWA (2023) for the years 1992 through 2022. This research project specifically investigated the NBI items listed in Table 1.1.

Table 1.1: Summary of NBI items investigated in this study.

Item Number	Description
1	State Code
16	Latitude
17	Longitude
29	Average Daily Traffic (ADT)
43A	Superstructure Material
43B	Superstructure Cross-Sectional Geometry
58	Deck Condition Rating
62	Culvert Condition Rating
108A	Wearing Surface/Protective System

The current condition of bridge components in relation to their as-built condition is described using a condition rating code, which ranges on a scale from 0 to 9 as listed in Table 1.2. A rating of 0 represents a facility that is "failed condition - out of service" and 9 represents a structure that is "excellent condition." Structures are grouped into the following categories based on condition rating:

- "GOOD" condition structures have ratings of 7 or higher,
- "FAIR" condition structures have ratings of 5 or 6, and
- "POOR" condition structures have ratings of 4 or lower.

The condition rating of bridge decks is recorded as NBI Item 58. Culverts are given a single rating to indicate overall condition; individual culvert components are not rated. This rating considers the condition of the culvert barrel, joints, seams, voiding of backfill, deflection, distortion, misalignment, settling, or scour. The rating includes headwalls, wingwalls, or aprons (up to the first construction joint). Culvert condition is described by NBI Item 62.

Table 1.2: Summary of bridge deck and culvert condition rating.

Rating Code	Description
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 some minor deterioration.
5	Fair condition: all primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
4	Poor condition: advanced section loss, deterioration, spalling, or scour.
3	Serious condition: loss of section, deterioration, or spalling have seriously affected primary structural components. Local failures are possible.
2	Critical condition: advanced deterioration of primary structural elements. Closing the bridge may be necessary.
1	Imminent failure condition: major deterioration or section loss affecting structural stability. Bridge is closed.
0	Failed condition: out of service, beyond corrective action.

1.1.3 Bridge Distribution in Arizona

In Arizona, based on NBI data from 2022, there are 8497 bridges owned by the state and local public agencies that cover an area of 6,116,464 m^2 spread across 15 counties as shown in Figure

1.1. The Arizona Department of Transportation (ADOT) is responsible for maintenance of most of the bridges in Arizona that are listed in the NBI. Bridge distribution data in Figure 1.2 indicate that Maricopa County has the greatest number of structures Arizona, accounting for over 32.9% of total bridges; Pima and Pinal counties have over 13.7% and 8.3% of AZ bridges, respectively.

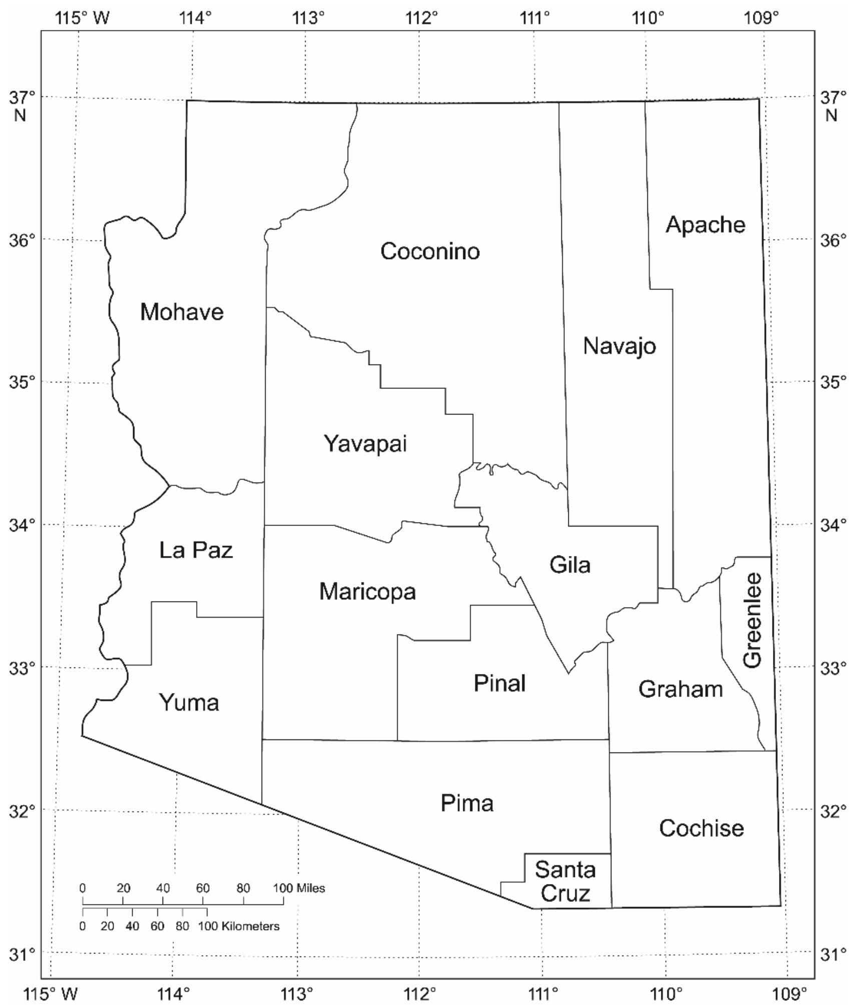

Figure 1.1: Map of counties in Arizona (Arizona Geographic Alliance no date).

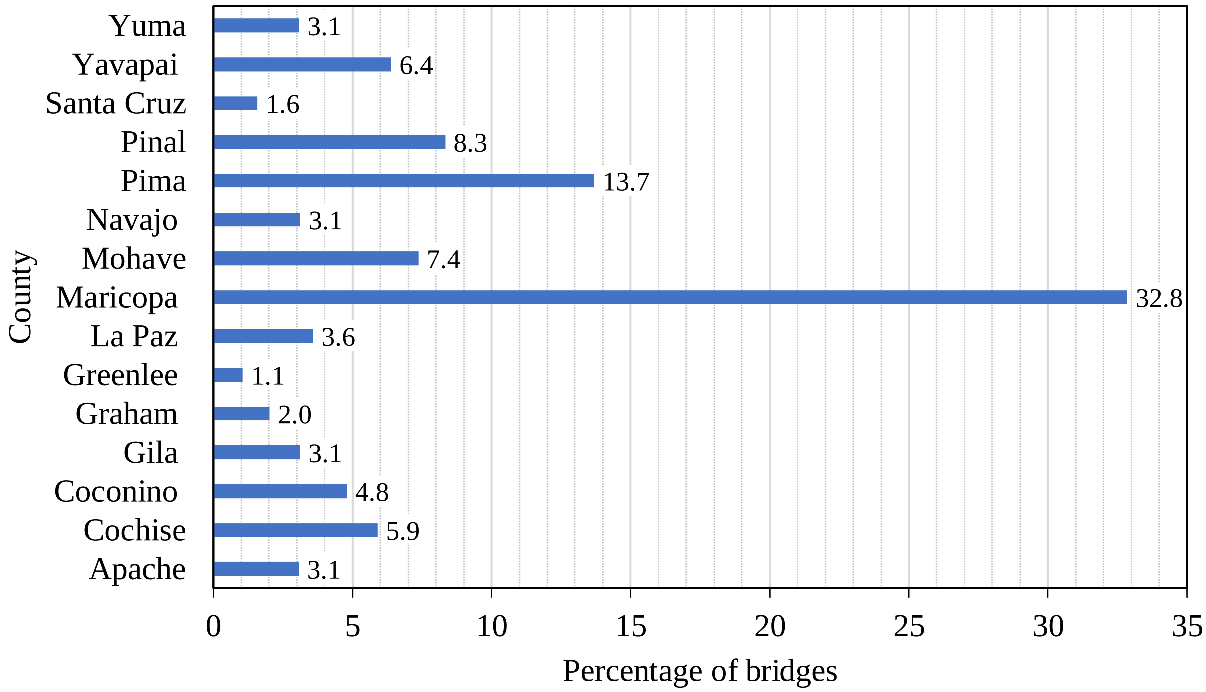

Figure 1.2: Percentage of bridges in each Arizona county.

1.1.4 Bridge Distribution in United States

The total number of bridges in the United States is 620,669 based on NBI data from 2022; these structures cover an area of 401,007,279 m^2. Bridge distribution data in Figure 1.3 indicate that Texas has the greatest bridge population, accounting for over 9% of bridges, followed by Ohio (4.4%) and Illinois (4.3%). Arizona includes about 1.4% of the Nation's bridges.

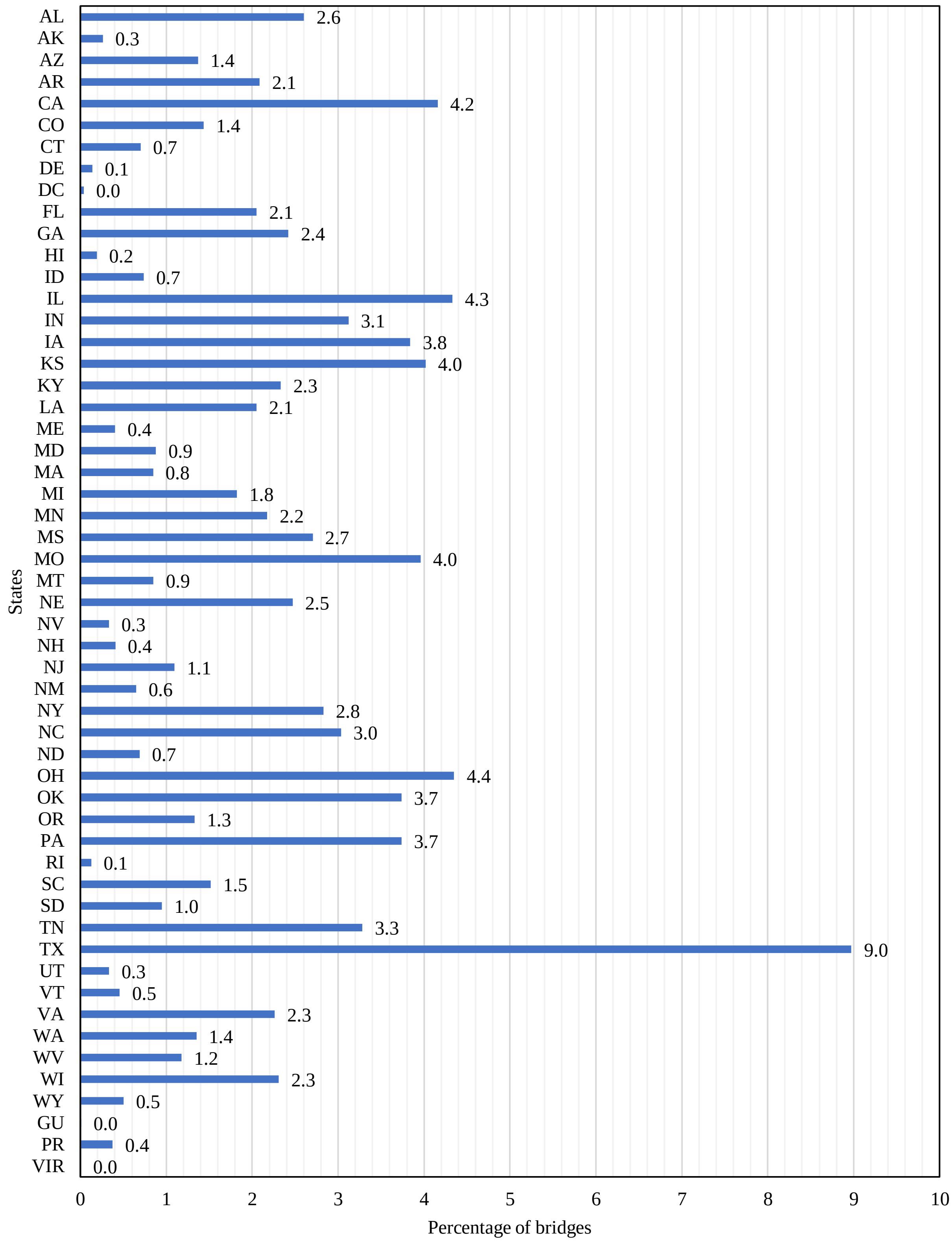

Figure 1.3: Percentage of bridges in each U.S. state.

1.2 Motivation

Bridges and culverts are critical components of the United States' transportation infrastructure, supporting the movement of products and people across the country. Keeping these structures secure and reliable is not just a question of public safety, but also a substantial financial concern for bridge owners, which include federal, state, and local governments. As a result, there is an essential need to characterize and quantify bridge deck and culvert deterioration rates to inform maintenance and repair, which can extend the service life of a bridge. This entails developing maintenance and repair techniques to avoid or slow down deterioration processes.

Understanding the different patterns of deterioration may allow bridge owners to better deploy resources. They can concentrate maintenance and repair activities by focusing on regions most vulnerable to deterioration, including deciding which bridges to repair first based on their condition rates, which maximizes their budgetary expenditures for maximum impact.

1.3 Objectives

The main objective of this research was to analyze the deterioration of bridge decks and culverts in Arizona and compare the State results with deterioration trends for bridges in the entire United States. To complete this objective, ratings from the years 1992 to 2022 were used to analyze how conditions changed with time and other bridge factors, including superstructure material (NBI Item 43A), superstructure cross-sectional geometry (NBI Item 43B), ADT (NBI Item 29), wearing surface material (NBI Item 108A), and location as defined by latitude and longitude (NBI Items 16 & 17).

1.4 Thesis Organization

This thesis is divided into five chapters. Chapter 1 outlines the background, motivation, and objectives. The findings of the literature review are documented in Chapter 2. The methodology used to analyze NBI data is discussed in Chapter 3. Chapter 4 provides results from the data analysis and discussions related to the deterioration trends. Chapter 5 summarizes the project, lists the main conclusions, and lists the recommendations.

Chapter 2. Literature Review

The purpose of the literature review was to identify key characteristics and strategies used by other transportation departments and scholars to quantify the rate at which bridges and culverts deteriorate. Various prior research projects concerning bridge deterioration modelling have been examined and are discussed in this chapter.

2.1 Deterioration Rates of Minnesota Concrete Bridge Decks

Previous research projects like (Zimmerman et al. 2007; Nelson 2014; Treat and Dymond 2019) have examined deck cracking and deterioration in MN, with the aim of identifying the main causes of water and salt infiltration through cracks, resulting in the corrosion of reinforcement. This process ultimately reduces the lifespan of the bridge deck. These studies focused on one or two specific components of the deck, and the investigators evaluated performance over a relatively brief period.

For instance, Treat and Dymond (2019) examined the effects of using different types of reinforcement on deck deterioration rate, such as a mixture of both black bars and epoxy coated bars in the same deck. The investigation studied 115 bridge decks to record obvious problems such corrosion staining, spalling with exposed rebar, leaching or efflorescence, and fissures. Treat and Dymond (2019) found that the mixed rebar decks spent an average of 8.5 years in condition state 2 prior to entering condition state 3; in this system of rating, condition state 2 is associated with a total “distressed area” on the underside of a concrete deck equal to 2% or less of the total deck area and a conditions state 3 is associated with a total “distressed area” on the underside of the concrete deck more than 2% but not more than 10% of the total deck area. Compared to mixed rebar decks with prestressed concrete superstructures, a larger percentage of mixed rebar decks with steel superstructures (about 30%) had already attained condition states 3 and/or 4. Additionally, compared to decks with prestressed concrete superstructures (1.15%), decks with steel superstructures showed a higher percentage of the total deck area in condition states 3 and/or 4. Treat and Dymond did not observe correlation between deck degradation and ADT.

Zimmerman et al. (2007) studied the performance of low slump concrete coverings on 492 MN bridges. This study focused on a specific type of overlay that was placed on concrete bridge decks in Minnesota between 1974 and 1981. The study discovered that thinner overlays had longer service lives than superstructures made of reinforced concrete, steel, and prestressed concrete. Furthermore, longer spans were found to have shorter overlay service lives than shorter spans, and higher levels of ADT correlated with shorter overlay service lives compared to lower ADT levels. The investigation also discovered that the deterioration rates of the decks and overlays were not linear; they were exponential.

2.2 Developing Deterioration Models for Nebraska Bridges

The Nebraska Bridge Management System (NBMS) was created in 1999 to aid in the optimization of the allocation of funds for highway bridge repair, rehabilitation, and replacement costs (Hatami and Morcous 2011). The method used in NBMS for maintenance, repair and rehabilitation decision making was primarily focused on engineering assessment, with insufficient consideration given to the life cycle cost evaluation of suggested actions.

The NBMS uses two general categories of methods to calculate deterioration rates for bridge elements, deterministic and stochastic methods. Deterministic models rely on a mathematical or statistical equation to establish a correlation among the factors influencing the deterioration of a bridge. Stochastic methods such as the Markov decision process are becoming more prevalent to assess infrastructures deterioration.

Hatami and Morcous aimed to create degradation models using condition rating records received from bridge inspections carried out between 1998 and 2010. Bridge deterioration data from Nebraska was employed to develop stochastic degradation models relative to each of the nine NBI condition rating levels. Each rating level was considered as a distinct state in a Markovian system. When building the models, they evaluated the impact of major elements such as structure type, deck type, wearing surface, deck height, average daily traffic, average daily truck traffic and the highway district. These models were rather simple, indicating a decrease of one condition rating level in the deck every eight years and a decrease of one condition rating level in both the superstructure and substructure every ten years.

2.3 Effects of Overloads on Deterioration of Concrete Bridges

Deck damage can occur in several ways; one of the causes is transverse or longitudinal cracking in the concrete deck. The severity of deck cracking caused by wheel loads is greater in structures with lower dead load to total load ratios (James et al. 1987). Decks composed of reinforced concrete on steel I-beams are more vulnerable to this type of damage than decks on prestressed girders, due to the inherent flexibility of steel girder bridges.

James et al. (1987) carried out field research to investigate the relationship between physical damage produced by wheel loads. Their study tracked the distribution of cracks across the width of bridge decks. They choose control structures with comparable design, age, support systems, and traffic patterns to compare the level of damage caused by high truck traffic. These investigated bridges functioned as outward haul routes for trucks leaving several aggregate quarries. Table 2.1 summarizes the study’s findings, which estimated that roughly 180 trucks per hour were coming from the quarries. This intense traffic was thought to have lasted approximately 26 years.

Table 2.1. Research findings from James et al. (1987).

Variable Investigated	Findings
Bridge type	Decks supported by prestressed concrete girders were less prone to damage caused by progressive overload than decks supported by steel girders.
Crack density	Under severe load, cracks in both the longitudinal and transverse directions were found to be more common in higher traffic levels (95-106/day).

2.4 Bridge Deterioration Model to Support Indiana's Bridge Management System

Moomen et al. (2016) used the NBI database to develop degradation curves for various components of bridges, resulting in the formation of curve families. Moomen et al. created models to represent the deterioration of bridge decks, superstructures, and substructures in Indiana's bridge management system. They examined the impact of parameters such as traffic volume, truck traffic, design type, and climatic conditions on the rates of bridge deterioration using both deterministic and probabilistic models. Conclusions from their investigation are shown in Table 2.2.

Table 2.2: Research observations from Moomen et al. (2016).

Variable Investigated	Findings
Location	General degradation differences were detected throughout Indiana maintenance districts, but the differences were not uniform.
Traffic loading	Faster concrete deck deterioration correlated with higher traffic ADT.
Climate factors	The freeze index, number of cycles of freezing and thawing, and typical precipitation had a greater influence on bridge deck and substructure deterioration than the superstructure.

In terms of climate factors, the effect of freeze index is related to the water within the concrete structure, which may expand and contract because of freeze-thaw cycles in areas with high freeze indices. The performance and structural integrity of the bridge deck may eventually be impacted by the concrete's progressive deterioration and cracking caused due to this recurrent expansion and contraction. The frequency of temperature variations on the bridge deck that cause the water in the concrete to freeze and thaw is what defines the number of freezing and thawing cycles. Every cycle has the capacity to start and widen concrete fissures. Over time, these fissures may erode the bridge's structural integrity and roughen its surface. The rate at which a bridge deck deteriorates can be influenced by precipitation, including rain and snow. Water can seep through the concrete and reach the steel reinforcing, which can cause corrosion and lower structural strength. Adequate drainage systems are essential in areas experiencing heavy precipitation. Water buildup on the bridge deck due to inadequate drainage can exacerbate the impacts of freeze-thaw cycles and hasten degradation.

2.5 Evolution of Bridge Deck Cracking in Montana

Transverse cracking is a common occurrence on concrete bridge decks across the U.S. and is a common issue for bridge decks maintained by the Montana Department of Transportation (MDT). Nelson et al. (2021) investigated the causes of the transverse cracking and made recommendations to the MDT on how to mitigate the impact from these cracks. The researchers conducted an inquiry that included reviewing papers, conducting on-site inspections, analyzing samples in the laboratory, and developing basic analytical models of the bridge decks in Montana. The goal was to discover and recommend solutions to the causes of transverse cracking in bridge decks. The findings were based on studies undertaken by nine other state transportation departments, including Montana. This study classified the potential causes of bridge deck cracking into five categories, each having its own impact on cracking, as shown in Table 2.3.

Table 2.3: Factors affecting bridge deck cracking, adapted from Nelson et al. (2021).

Factor	Effect on Bridge Deck Cracking
Concrete strength	High strength concrete has a greater tendency to crack due to its higher modulus of elasticity (i.e., larger stresses associated with thermal or shrinkage strains). The initial set of concrete is followed by a faster development of the modulus of elasticity compared to the tensile strength, lasting approximately 3 to 5 hours.
Concrete mixture design	Thermal and autogenous shrinkage can be affected by the type of cement employed. Thermal stresses can be reduced by employing Type II cements. Additionally, the use of fly ash and slag can reduce both thermal and shrinkage strains. However, finely ground cements, such as Type III cements, may contribute to higher heat of hydration and the resulting thermal strains. Using a large volume of coarse aggregates with a low coefficient of thermal expansion helps reduce both shrinkage and thermal stresses.
Construction practices	Early plastic shrinkage cracking can be prevented by procedures that restrict evaporation from freshly installed concrete surfaces. Plastic shrinkage cracks can be sealed by mechanical vibration, but roller due to regional increases in near surface paste consistency, screeding may increase the danger of cracking.
Restraint conditions	Restraint is highest in interior spans (due to intermediate supports) and at integral abutments (due to fixed-end conditions). Connections that are simply supported or have pins can help to reduce cracking. Curved girders and skew can increase constraint.
Element design	When the deck is less stiffness than the girders, cracks become more visible. Thin decks (less than 8.5 inches), composite steel plate girders, wide flanges, and cross framing are all affected. Cracks can be reduced by increasing the distance between girders and employing thicker decking. Furthermore, due to their lower coefficient of thermal expansion, concrete girders may provide less resistance than steel girders.

High-strength concrete usually has a larger modulus of elasticity than conventional concrete because it is less prone to deformation under stress. This property may cause higher strains related to shrinking or heat stressors. Because of its decreased deformability, concrete may be more prone to cracking, particularly when exposed to temperature fluctuations brought on by freeze-thaw cycles or other temperature changes that cause bridge deterioration.

2.6 Investigation of the Causes of Transverse Bridge Deck Cracking

The Iowa Department of Transportation has seen multiple cases of transverse deck cracks emerging shortly after bridge construction. This is a critical issue since these gaps can provide a direct path for water and chlorides to permeate. The goal of the research conducted by Phares et al. (2022) was to identify the characteristics that frequently result in the development of transverse cracks at an early stage, with the goal to identify solutions to prevent them in the future. Water, salts, and other potentially corrosive materials may enter the interior of the bridge structure through transverse cracks. These aggressive chemicals can initiate and accelerate the corrosion of the reinforcing steel within the bridge components after they have penetrated the concrete through transverse fractures. Over time, corrosion can weaken the bridge's structural integrity. Their research was motivated by accelerated reinforcement corrosion, concrete deterioration, and increasing maintenance expenses. Table 2.4 summarizes transverse deck cracking observations related to six bridge characteristics.

Table 2.4: Research findings from Phares et al. (2022).

Bridge Characteristic	Findings
Location	Deck cracking was more prevalent in the southern and eastern regions of Iowa compared to other regions. The difference was attributed to different material properties of the concrete aggregates used.
Cement type	In comparison to Type 2 cement, Type 1 and IP (Portland-pozzolan) cement had a higher likelihood of deck cracking.
Concrete type	Bridge decks built of high-performance concrete (HPC) were more likely to crack than bridge decks made of non-high performance concrete materials.
Bridge age	Bridges built between 1960 and 1980 had a higher incidence of deck cracking.
Girder type	Steel beam bridges were less prone to develop deck cracking than precast, pretensioned concrete beam (PPCB) bridges. There were 122 steel bridges and 1835 PPCB bridges that were investigated in this study.
Evaporation rates	Enhanced evaporation rates from the six observed concrete bridge deck installations enhanced the likelihood of deck cracking.

2.7 Stochastic Regression Deterioration Models for Prestressed Concrete Bridges in CA

The primary goal of Hasan and Elwakil (2019) was to investigate the key parameters that influence the state of prestressed concrete bridges to develop a predictive model for the superstructure condition. To achieve the goal, an approach which combines both deterministic and stochastic approaches was developed. A regression approach and Monte Carlo simulations were used to make predictions. NBI data for California was utilized in this investigation. Initially, observations relevant to bridge reconstruction or rehabilitation were not taken into consideration to avoid any competing reconstruction impacts. Data were divided into two categories to ensure consistency: functional categorization (for urban roads) and maximum span length (varying from 20 to 30 m), as well as age (ranging from 30 to 39 years). This classification resulted in the inclusion of four structure types: slab, stringer/multi beam or girder, T-beam, and box beam or girder.

Hasan and Elwakil investigated the influence of non-periodic maintenance on NBI condition ratings. They observed that increasing age and increasing ADT were the most important variables in accelerated bridge deterioration with poorer conditions. Span length, structure length, deck width, high degree of skew, average daily truck traffic, and roadway width were also identified as characteristics associated with greater rates of superstructure deterioration. More deterioration was associated with the maximum span length, structure length, and deck width; this suggests that bridges with high related values should undergo more frequent inspections.

Hasan and Elwakil used the National Bridge Inventory for California to develop regression models and Monte Carlo simulations to estimate the superstructure condition of four different structure types: slab, stringer/multi beam or girder, T-beam, and box beam. This study demonstrated that the following important variables had a high coefficient of determination (R^2 = 86%) on the degradation of the superstructure: superstructure, age, ADT, degree of skew, maximum span length, roadway width, deck width, structure type. The models that were constructed have undergone validation using the average validity percentage approach, yielding a satisfactory result of 93%. The created models can assist infrastructure organizations and departments of transportation in estimating the condition rating and setting priorities for bridge maintenance.

2.8 Developing Bridge Deterioration Models Using an Artificial Neural Network

Bridge management systems (BMS) make it easier to make decisions about how to cope with bridge deterioration by employing an accurate model that can properly anticipate bridge condition ratings. Althaqafi et al. (2022) intended to improve the Ohio BMS by building an artificial neural network (ANN) model that enhanced the accuracy of predicting bridge deck, superstructure, and substructure deterioration. The goal of this study was to develop artificial neural network (ANN) models that could forecast the condition ratings of three unique bridge components: bridge deck, superstructure, and substructure. These models were built using previous studies of bridge conditions in Ohio from 1992 to 2019.

Althaqafi et al. (2022) developed bridge deterioration models using data from the NBI database. The data used in this study included information about the geometric parameters of the bridge, such as its length, width, degree of skew, operational category, road network, building materials, and design. Several ANN models with various configurations were created and used to forecast the degradation of the bridge deck, superstructure, and substructure components. To increase forecast accuracy, the proposed model considered a wide variety of geometric and operational aspects of the bridge structure. Finally, the proposed model was trained and tested on various portions of the dataset, including the bridge deck, superstructure, and substructure components, using the most effective ANN setup.

The results were evaluated in terms of accuracy, precision, recall, and F1-score (which measures a model accuracy using the harmonic mean of precision and recall). The final model created for the deck, substructure, and superstructure components achieved an accuracy rate of more than 89%. Ultimately, a bridge deterioration model was created using the suggested ANN models to forecast deterioration in all bridge systems. As such, this model can help provide the best possible schedule for bridge upkeep. It was concluded that the proposed ANN models produced a strong link between projected and observed values in the NBI dataset.

2.9 Analysis of National Bridge Inventory (NBI) Data for California Bridges

Using information taken from the National Bridge Inventory (NBI) database, the study presents a thorough analysis and visualization of bridge data for California by Yu (2019). Large volumes of bridge data are available from the NBI, although little state-specific research has previously been done using the database. A review of the literature indicates that most of the earlier research utilizing NBI data concentrated on study at the federal level or on certain states outside of California. Wu and Chase (2010), for instance, used MATLAB and GIS to perform an exploratory analysis of NBI data for each of the 50 states. Bridge characteristics such as location, traffic, type of structure, and environmental conditions were examined in the study. It was shown that the design requirements and temporal insufficiency patterns of bridges in eastern states are often lower. Similarly, Chase et al. (2000) created regression models for forecasting bridge deterioration from weathering factors using national NBI data. Deck, superstructure, and substructure deterioration were accurately forecast by their models. This study addressed the research gap by doing a thorough visualization and analysis of NBI data specific to California.

Yu investigated the more than 25,000 bridges in the state by gathering information about bridge material composition, age, structural defect status, and daily traffic. California has the greatest percentage (3.5%) and area (6.7%) of concrete bridges in the country, after Texas. In addition, only 14% of California's bridges are made of steel, compared to 85% of concrete bridges. With 15% of the nation's average daily traffic (ADT), California leads the nation in this regard, followed by Texas with 11%. In California, metropolitan traffic accounts for a larger portion of the ADT than does local traffic. In addition to providing a measure of the state's daily traffic volume, these figures may be used as a foundation for choices about transportation planning, vehicle-related air pollution, and federal financing for highway upkeep and improvement. Yu highlighted the densely populated counties that surround Los Angeles, which have 39% of all California bridges. The data indicated that key arterial highways comprise more than 40% of California's bridges.

According to calculations made in the research, almost 40% of the concrete bridges in the state were constructed between 1959 and 1973. This shows that a significant percentage are getting close to or beyond typical design lifespan. The research revealed disturbing data regarding the condition of California's bridges. More than 42% of the state's total bridge deck area is deemed either structurally or functionally antiquated. Los Angeles County has the greatest percentage of bridges that are inadequate in Southern California. This emphasizes the difficulties California's vast bridge network faces in financing its infrastructure.

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

Chase et al. (2000) studies intended to improve the way that the extensive National Bridge Inventory (NBI) information is used for sophisticated analysis in support of bridge management choices. With over 600,000 highway bridge inspections conducted in the U.S. since 1972, the NBI has over 6 billion bytes of detailed inspection data at its disposal. Nevertheless, there are obstacles in effectively deriving insights from this large dataset. The authors investigate data mining, data warehousing, and geographic information system (GIS) integration to make the most of NBI data. The goal of Chase et al. was to make bridge data from the NBI easier to retrieve, create effective relational database storage and data mining techniques. Integrating the NBI with environmental and natural hazard data layers in a GIS will increase its usefulness. Latitude and longitude of the nature is considered in this study. Chase et al, involved four main stages comprised the technological approach: About 30% of NBI coordinates were shown to be inaccurate while geolocating bridges. County polygons (accuracy of 150 feet) were utilized to find bridges instead. Local and rural roads were not well served by linear referencing techniques.

Environmental data compilation has different datasets were represented as point or polygon models in the GIS and classified as climatological, hydraulic, soil, or seismic datasets. With an estimated positional precision of greater than 150 feet on the earth's surface, the county GIS layer used for this study was derived from USGS 1:100,000 scale data. This offered more than sufficient accuracy for the conducted research. Applying modeling methods such as generalized linear and additive models, statistical analysis is the process of investigating the improved NBI data. This paper presented results from analyzing the improved database that shows aspects such as age distribution, construction material, and geographic patterns in inadequacy levels can all be understood by descriptive statistics. For estimating condition ratings of decks, superstructures, and substructures based on variables including traffic, temperature, and frequency of deicing, generalized linear models fared better than non-linear algorithms.

In support of needs-based planning, the viability of quantitative, data-driven modeling bridge deterioration is shown.

2.11 A Comparison of Bridge Deterioration Models

Naderimoghaddam (2018) investigated condition assessment procedures and funds for bridge maintenance in Georgia. The element-level condition rating methodology and the overall sufficiency assessment method are two alternative approaches for quantifying bridge deterioration that are compared. To help with maintenance planning and budgeting, the goal was to look at models that can predict levels of deterioration. Georgia spends about $162 million a year on bridge maintenance. Every bridge has comprehensive data provided by routine inspections. Presently, 18% of municipal bridges have structural flaws, while 98% of state bridges are in fair or superior condition. Every bridge component, such as the deck and beams, has an element-level rating ranging from 1 (good) to 4 (severe). Weibull models and Markov chains were used to forecast declines in these ratings. Overall, the bridge sufficiency grade, ranging from 0 to 100, was used because it is linked to Federal rehabilitation and replacement funding, which are awarded based on ratings of less than 80% and 50%, respectively. However, there are no recognized predictive models for this statistic. To forecast changes in sufficiency ratings, the paper suggests examining a Poisson regression model and a mixed Bernoulli-Gamma model.

Naderimoghaddam (2018) used 25 years of Georgia bridge inspection records from the NBI database (1992–2016). The variables that were selected in this research included structure number, sufficiency rating, year built, traffic lanes on, traffic lanes under, route prefix, service level, median code, vertical clearance, structure kind, max span, structure length, and structure type. This paper used a Gamma distribution to model the amount of degradation and logistic regression to describe the probability of deterioration. Also, the models degrade when rating integers decrease. An exponential link function was used in the count-based Poisson distribution. The Poisson model outperformed the logistic-Gamma method in terms of projected rating variance, yielding tighter prediction intervals. Both models predicted that a bridge median rating will decrease gradually over a 25-year period.

2.12 Advancing Bridge Technology, Task 10: Statistical Analysis and Modeling of U.S. Concrete Highway Bridge Deck Performance

Ghonima (2018) conducted research on statistical modeling of the U.S. highway system's concrete bridge deck deterioration to aid maintenance scheduling. The NBI database was used. The goal of this study was to find reliable quantitative tools to gauge deck lifespan and determine the most effective plan for preservation expenditures. According to the report, states differ greatly in their current condition rating (CR) thresholds for rehabilitation, even if variables like corrosion and traffic loads are what cause degradation. Twenty-one structural and environmental characteristics, such as proximity to the sea and climate zone, were included in the compilation of the Nationwide Concrete Highway Bridge Deck Performance Inventory (NCBDPI) database, which improved the NBI with computed metrics such as time-in-condition rating (TICR) and deterioration rate (DR). Due to the expanded dataset, research on deterioration patterns was investigated using models of binary logistic regression that link factors like traffic volume and layout to the probability of high DR. Furthermore, TICR data were subjected to a Bayesian survival analysis to measure the effects of maintenance responsibility and location on CR longevity. These methods took into consideration various censoring effects in the multi-year inspection data. The variables of traffic numbers, climate, proximity to the sea, and maintenance responsibilities were found to be significant determinants of deterioration in both approaches. The direction and intensity of impacts were measured by coefficients. The fitted models performed well in terms of predicting test data. In summary, the sophisticated modeling offers useful information about bridge deck degradation across the country. Results can help inform maintenance and project prioritization choices for better lifetime management.

2.13 Summary

In summary, this literature review considered how prior studies investigated concrete bridge deck and culvert deterioration and which factors affected the deterioration. Thinner concrete overlays had longer service lives, according to several studies that looked at the rates of cracking and degradation of bridge decks; greater traffic volume was associated with accelerated overlay degradation. Using NBI information, Nebraska and Indiana created Markovian degradation models for bridge components. Precipitation, freeze-thaw cycles, and traffic volume were important factors. Every eight years, the condition of Nebraska's bridge deck dropped one rating level.

Increased age and traffic were shown to be the main factors that contributed to deterioration of bridge decks in a California study. Bridge superstructure condition ratings were predicted by models, and the span length, deck width, and skew were critical variables. Deck, substructure, and superstructure deterioration were successfully predicted by an Ohio study utilizing artificial neural network models with NBI data, considering bridge geometry, materials, and traffic volumes.

High temperatures and freeze-thaw cycles, particularly in higher elevations like Flagstaff, as well as increasing traffic levels, are likely important factors to consider while modeling Arizona bridge deterioration. Bridge-specific data such as type of superstructure material, superstructure cross section, wearing surface type, and location could be used to create degradation models through machine learning methods such as artificial neural networks, survival analysis, logistic regression, or Markov chains. The models could likely estimate future component condition ratings by quantifying the effects of materials, traffic volumes, weather, and maintenance. Prioritizing maintenance projects and allocating funds would be made easier for ADOT based on the potential findings. To model Arizona bridge deck and culvert deterioration, the literature review offered an excellent basis for choosing model variables and analytical techniques.

Chapter 3. Research Methodology

3.1 NBI Data Extraction

NBI ratings for Item 58 (bridge decks) and Item 62 (culverts) for each of the years between 1992 to 2022 served as the primary source of data for analysis during this investigation. The factors were selected based on the previous studies in other states. The following additional factors and how they affect bridge deck and culvert condition ratings were considered:

- NBI Item 43A — superstructure material,
- NBI Item 43B — superstructure cross-sectional geometry,
- NBI Item 29 — average daily traffic,
- NBI Item 108A — wearing surface material,
- NBI Item 16 — latitude (location), and
- NBI Item 17 — longitude (location).

Since the majority of the NBI database material is published in .txt format available via html, the first step of this research involved completely understanding the database. An enormous amount of data is stored by the NBI; the record for each bridge, in each state, for each year has over 115 attributes or variables associated with that bridge. NBI data from 2022 were used to capture overall bridge counts, current condition ratings, etc. since the 2022 dataset was more complete than the 2023 records, which were being reported by states at the time of this research project and thus were not complete datasets.

3.2 Summary of Arizona Data

3.2.1 Superstructure Material (NBI Item 43A)

The superstructure material of bridges is critical, as they have a large impact on the structure's performance; the material type can also have a considerable impact on maintenance requirements and life cycle costs. Materials that necessitate frequent maintenance or replacement can lead to higher long-term expenses and disruptions. To identify differences in deterioration of bridge decks associated with superstructure material, three NBI categories were investigated: reinforced concrete, steel, and prestressed. Superstructures outside of those three categories were grouped as "others" and not investigated due to each type being a low percentage of structures in Arizona. Superstructure materials in the "other" category included masonry, aluminum, wrought iron or cast iron. The percentage of bridges containing each superstructure material type are depicted in Figure 3.1.

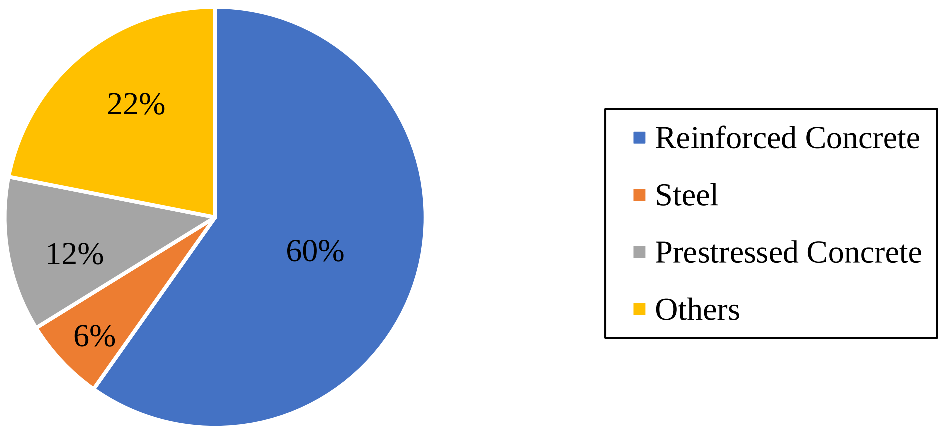

Figure 3.1. Percentage of bridges containing each superstructure material type.

According to Figure 3.1, 78% of bridges in Arizona have superstructures made of reinforced concrete, steel, and prestressed. Out of these three, most bridge superstructures contain reinforced concrete (60%), followed prestressed concrete (12%) and steel (6%). A total of 22% of bridges in Arizona have a superstructure that fell into the "other" category.

3.2.2 Superstructure Cross-Sectional Geometry (NBI Item 43B)

The NBI data for cross-sectional geometry was categorized into different types. In this study, slab, stringer, box beam (single and multiple), and culverts were investigated. The remaining bridges with a different superstructure cross-sectional geometry were grouped as “others,” which were ignored due to its small proportion. Superstructure cross-sectional geometries in the “other” category included floor beam systems, tee beams, orthotropic structures, truss decks, truss thru, arch deck, arch thru, frame (except from culverts), and channel beam. The percentage of bridges in each superstructure cross-sectional geometry category are depicted in Figure 3.2.

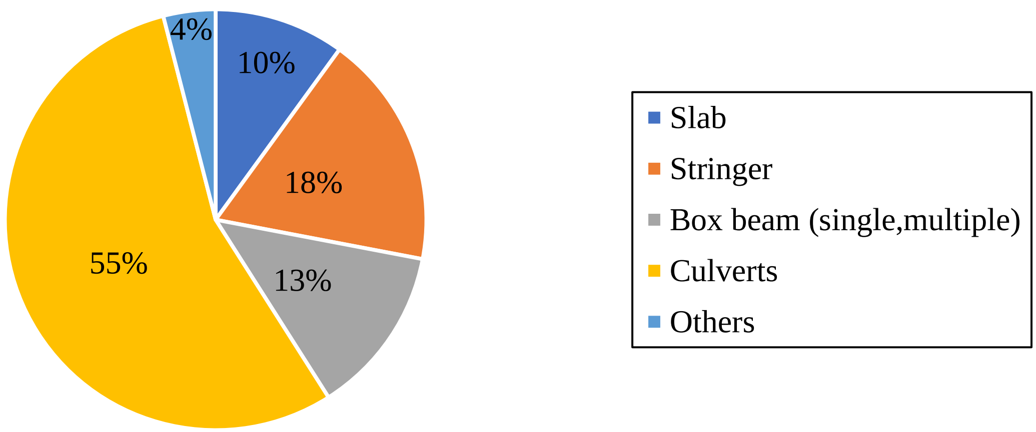

Figure 3.2: Percentage of bridges in each superstructure cross-sectional geometry category.

Data in Figure 3.2 illustrate that culverts account for the highest portion of structures in AZ, approximately 55%. Stringer structures account for 18% of the total, a significant but lesser share compared to culverts. The remaining superstructure cross-sectional geometry types included box beam (13%) and slab (10%); the count of structures in the “other” category was the smallest, accounting for 4% of the inventory.

3.2.3 Average Daily Traffic (NBI Item 29)

ADT data is essential for the construction and maintenance of bridges and culverts because it determines the load-bearing capacity required to handle the predicted traffic volume. It is required for prioritizing infrastructure projects, predicting maintenance requirements, and effectively allocating resources. Due to increased commuter traffic, bridges and culverts near cities often have greater ADT; higher ADT can also frequently be associated with bridges on the interstate system compared to those on rural roads. In this study, ADT (vehicles per day) was categorized into three bins, as shown in Figure 3.3: ADT < 5000, 5000 ≤ ADT ≤ 10000, and ADT > 10000.

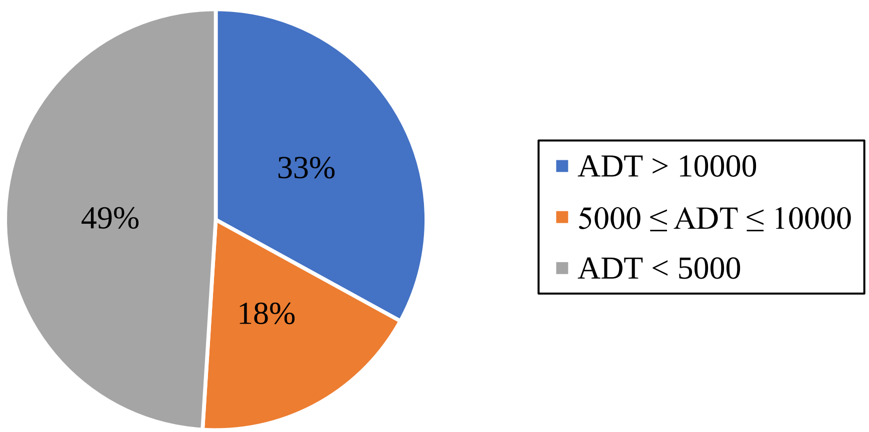

Figure 3.3: Percentage of bridges in each ADT category.

Data in Figure 3.3 indicate that structures with an ADT < 5000 make up the largest population of bridges in Arizona (49%). Bridges that carry more than 10000 vehicles per day makeup 33% of the inventory while bridges that carry between 5000 to 10000 vehicles each day makeup 18% of the inventory. The maximum ADT on a bridge deck in AZ is 333,069 vehicles per day; data in Figure 3.4 show the distribution of bridge decks in terms of ADT in AZ. A high percentage of bridges have an ADT < 5,000 and a low percentage of bridges have a very high ADT, greater than 100,000.

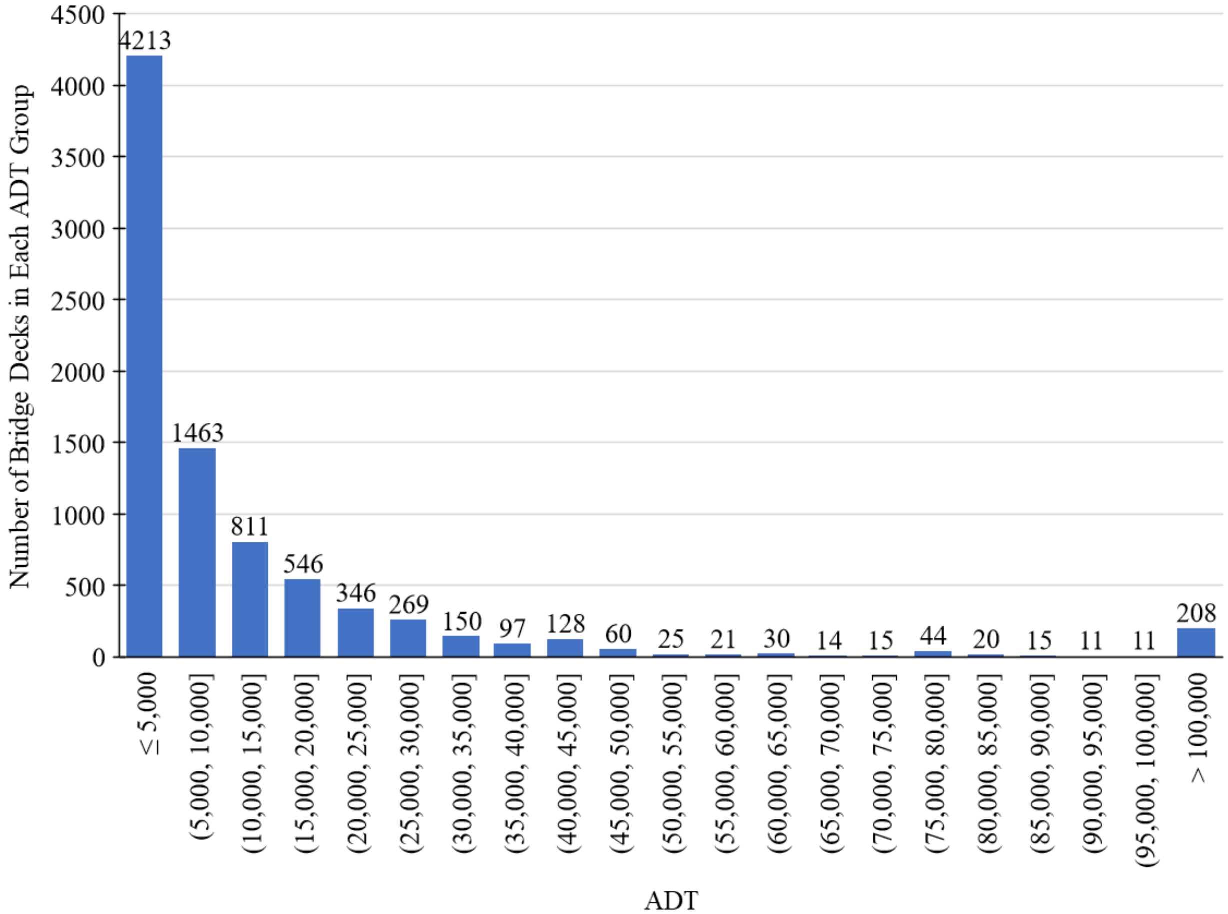

Figure 3.4: Histogram indicating the number of bridge decks in each ADT bin, grouped by 5000 vehicles per day increments.

3.2.4 Wearing Surface Material (NBI Item 108A)

The topmost layer or material applied to the bridge or culvert deck is referred to as the wearing surface. The wearing surface is intended to deteriorate over time more rapidly than the supers- or substructure and be replaced as a first line of protection. The wearing surface protects the underlying structure from factors such as water, chemicals, freeze-thaw cycles, and vehicular loads, which can cause deterioration and corrosion.

Wearing surfaces can be made of a variety of materials, depending on traffic volume, environment, and budget. In this study, only monolithic concrete and bituminous wearing surface materials were investigated because more than half of the bridges and culverts in Arizona have that type of wearing surface, as shown in Figure 3.5. The remaining wearing surface materials that were not considered in this study were categorized as "other" and included materials like epoxy overlays, gravel, wood or timber, and integral concrete.

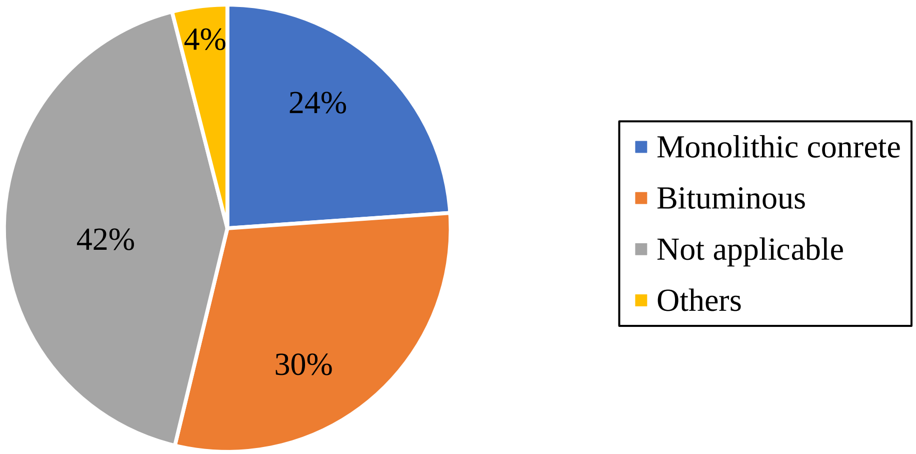

Figure 3.5: Percentage of bridges in each wearing surface materials category.

Data in Figure 3.5 indicate that 42% of structures in Arizona do not have any type of wearing surface material. In the NBI database, these structures are coded as 'N,' which means not applicable. Bituminous and monolithic concrete wearing surfaces are widely used in Arizona, and comprise of 30% and 24% of structures, respectively.

3.2.5 Latitude (NBI Item 16) and Longitude (NBI Item 17)

The Colorado Plateau, Grand Canyon, and Mogollon Rim are just a few of the mountainous regions in Northern Arizona. To connect towns and provide access to isolated locations, bridges in this region are essential because they frequently cross deep gorges, rivers, rough terrain, and running water due to snowmelt. Cities like Tucson and Phoenix are in southern Arizona, which is well-known for its dry and desert terrain. In the southern portion of the state, rivers, arroyos, and dry washes are essential for controlling flooding and frequently crossed by bridges and culverts to maintain traffic connectivity.

A combination of high desert, woodlands, and mountain ranges, including the White Mountains and the Apache-Sitgreaves National Forest, are found in eastern Arizona. In the eastern portion of the state, bridges are crucial for maintaining economic sectors like forestry and recreation while also serving as a link between population centers. Western Arizona contains the Lower Colorado River Valley and population centers like Lake Havasu City and Yuma. In this area, bridges are essential for traversing the Colorado River and establishing connections between Arizona and its neighboring states, California, and Nevada.

In this study, North, South, East, and West locations were categorized based on latitude and longitude. Figure 3.6 shows cities in the state of Arizona with latitude and longitude. Latitude coordinates greater than or equal to 34°N were taken as North, and latitude coordinates below 34°N were taken as South. Longitude coordinates greater than or equal to 112°W were taken as West, and longitude coordinates less than 112°W were taken as East. Figure 3.7 and Figure 3.8 shows the percentage of bridges in each geographic region of AZ. Phoenix is considered central to the state, with a latitude of 33.44844° and longitude of 112.0740°.

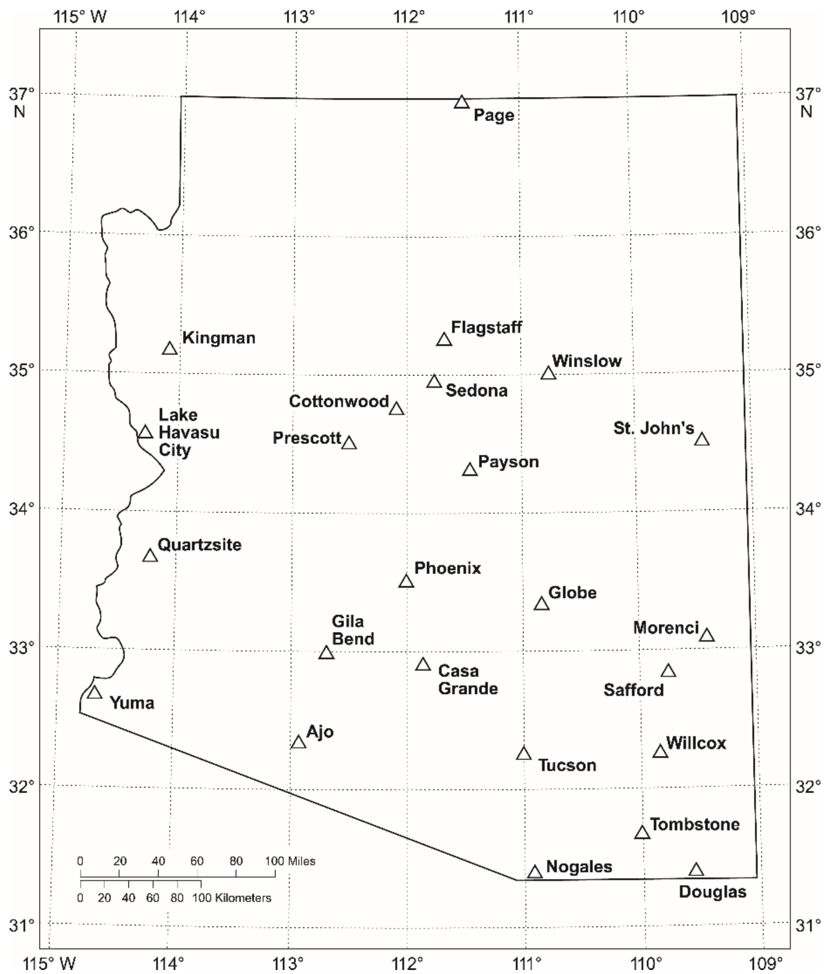

Figure 3.6: Map of Arizona cities with latitude and longitude (Arizona Geographic Alliance no date).

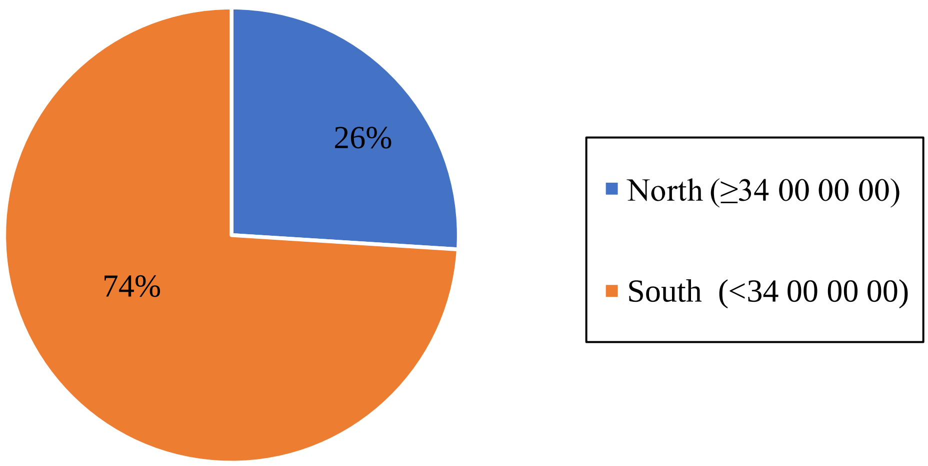

Figure 3.7: Percentage of bridges in North and South geographic regions of AZ.

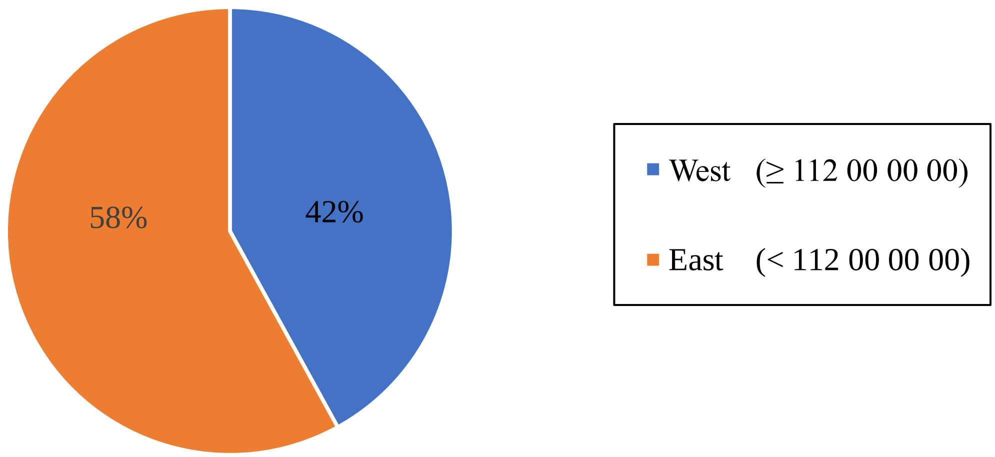

Figure 3.8: Percentage of bridges in East and West geographic regions of AZ.

Data in Figure 3.7 indicate that the highest percentage of bridges in Arizona are in the South (74%) versus the North, and data in Figure 3.8 indicate that more bridges are in the East (58%) versus the West. The higher percentages in the eastern and southern regions show that a significant portion of the state's population is in those areas. In contrast, the smaller percentages in the northern and western segments reflect the smaller population centers in those regions.

3.3 Summary of Data for Each State in the U.S.

Deterioration curves for all the structures in the United States were compared with those from Arizona. FHWA (2023) NBI data related to superstructure material, superstructure cross-sectional geometry, average daily traffic, and wearing surface material were exported for every state. Deck ratings based on each category defined in Section 3.1 were averaged for each state, and these categories were compared to the equivalent category containing only data from the state of Arizona, regardless of the number of those structures in each state. Furthermore, regions of the U.S. were considered for comparison; the regions were defined as West, Midwest, South, and Northeast as defined by the U.S. Census Bureau (2013) and shown in Figure 3.9.

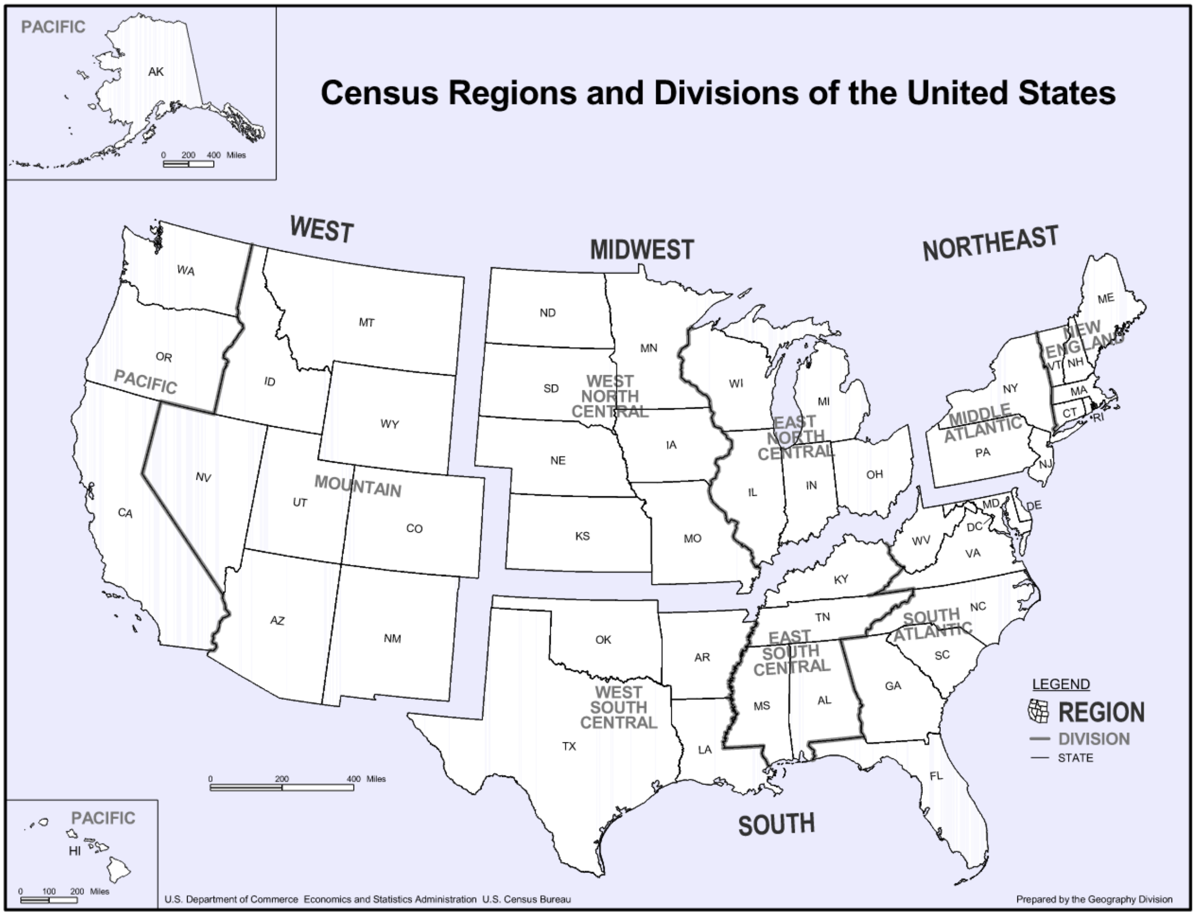

Figure 3.9: Map indicating geographical regions of the U.S. (U.S. Census Bureau 2013)

3.4 Data Processing

Once acquainted with the NBI database, relevant information was extracted into Microsoft Excel spreadsheets. The collected data were examined and interpreted using data visualization techniques and graphical representations. Since the primary focus of this research was on the deterioration of bridge decks and culverts in Arizona, the data were processed, and decisions were made based on the AZ inventory of bridges; the same variables and decisions were then used to select data for the rest of U.S. inventory since the final aim of the project was to compare Arizona bridge and culvert deterioration curves with those of the entire U.S. The following items were considered during data analysis:

- The total number of bridges was calculated from the structure number, NBI Item 8.
- Only bridges with data reported in NBI Items 43A, 43B, 29, 108A and 16/17 were included in this analysis. Bridges that did not have data in these categories were excluded.
- For NBI Item 43A, the following superstructure material item codes were investigated. Superstructure materials outside of those listed below were placed in a category labeled "other" and ignored.
    - Code 1 and 2 — reinforced concrete and reinforced concrete continuous,
    - Code 3 and 4 — steel and steel continuous,
    - Code 5 and 6 — prestressed concrete and prestressed concrete continuous.
- For NBI Item 43B, categories with the highest count of structures were only considered. In this research, the following superstructure cross-sectional geometry item codes were investigated:
    - Code 1 — reinforced concrete slab,
    - Code 2 — stringer /multi-beam or girder,
    - Code 5 — box beams or girders (multiple),
    - Code 6 — box beams or girders (single), and
    - Code 19 — culvert.
- For NBI Item 29, the ADT count (vehicles per day) was divided into three categories:
    - ADT < 5000,

    - 5000 ≤ ADT ≤ 10000, and
    - ADT > 10000.
- For NBI Item 108A, wearing surface material was divided into two categories based on item code:
    - Code 1 — monolithic concrete and
    - Code 6 — bituminous.
- For NBI Item 16 (latitude) and 17 (longitude), bridges and culverts in Arizona (not the entire U.S.) were categorized based on:
    - South < 34°N ≤ North,
    - East < 112°W ≤ West, and
    - additional analyses were completed using the southeast, northeast, southwest, and northwest quadrants.

Additional assumptions had to be made and used to process the NBI data. Publicly available NBI data only went as far back as 1992 at the time of this study; the age of some bridges was not continuously reported in NBI records, and some older bridge data was removed between 1992 and 2022. The bridges with continuous data for the full 30 years did not encompass the entire dataset in Arizona, so bridge age was not specifically considered. In this study, bridges of all ages were considered, regardless of when they were built.

3.4.1 Assumptions Related to Arizona Data

The following assumptions were used when processing Arizona data:

- The 2011 deck rating for NBI Item 43A superstructure material was not consistent. Data for several steel structures was missing. The information for 2011 was taken as the mean of the 2010 and 2012 data.

- Culvert condition ratings (NBI Item 62) for the year 2018 were missing entirely from the NBI database. As a result, the mean of 2017 and 2019 data were used to determine the culvert rating for 2018.
- The ADT values associated with the condition ratings for 2009, 2010, and 2011 were slightly lower than years prior and after. The condition ratings returned to the expected values in 2012 and have since continued that trend. Thus, data from these years were excluded; data for 2009 was the same as 2008, data for 2011 was the same as 2012, and the average of 2009 and 2011 values were used to generate 2010 data.
- Data associated with monolithic concrete wearing surface material had an abrupt drop in deck condition rating in 2013 and 2014 (5.95 rating) compared to the values in 2012 (6.32 rating) and 2015 (6.27 rating). Thus, the rating values for 2013 and 2014 were generated as the average from 2012 and 2015 ratings.

3.4.2 Assumptions Related to U.S. State Data

The following assumptions were used when processing data from the additional U.S. states, where trends had a glaring disparity. In general, individual datasets within all the U.S. state data were not processed in depth.

- For certain bridge NBI records, the bridge deck condition rating would occasionally rise or fall abruptly (by a small magnitude of approximately 0.5 to 1) for a year or two before returning to the prior rating. These abrupt, small, and short-term changes in rating were attributed to slight differences in the rating assigned by different inspectors, and the condition rating was manually changed to reflect the pre- and post-change reading. For example, if a concrete bridge deck had a condition rating of 7 for five years, then dropped to a condition rating of 6 for two years, and then returned to a condition rating of 7 for the next four years, this abrupt small magnitude change was an error and the condition rating was adjusted so that the condition rating of the concrete bridge deck was a 7 for all 11 years. This assumption applied to several U.S. states where data errors existed.

- In Idaho, the NBI deck rating for 2010 associated with ADT (at all levels), wearing surface material, and superstructure cross-sectional geometry was 1.0, which did not follow the typical trend. Thus, the average of data from 2011 was also used as the value for 2010.
- In New Mexico, the NBI deck rating for 1999 was completely unavailable for all the categories. In this case, the mean of 1998 and 2000 values were considered as 1999 deck rating values for each category of structure.

3.5 Deterioration Curve Generation Methods

After extracting the data for Arizona and the remaining states in the U.S., deterioration curves were generated using Microsoft Excel to determine the deterioration trends of deck and culvert ratings considering each of the categories mentioned herein. For any given variable and set of data, all rating data from any single year were averaged into a single data point for NBI Items 58 (decks) and NBI Item 62 (culverts); these data were used to determine the rating for specific bridges in a given category for a given year.

Deterioration curves were generated with the Deck or Culvert rating on the *y*-axis and the years over which the data were averaged (1992–2022) on the *x*-axis. Since the ratings for culverts and bridge decks differ, culvert ratings in Arizona were shown on the secondary *y*-axis of a plot. For example, every dot on the example deterioration curve shown in Figure 3.10 represents the average deck rating for a specific category for all bridges in Arizona in that specific year. Consider 1993, superstructure material (NBI Item 43A) was filtered for codes 5 and 6, which represents prestressed concrete and prestressed concrete continuous. The deck rating (NBI Item 58) for these variables averaged to generate a single deck rating for the year 1993 (7.38 in this case). The deck ratings for each year were calculated by repeating this approach for every variable across all evaluation years considered in this study. Thus, the deterioration curves shown in Figure 3.10 were generated using scatter plots in Microsoft Excel and linear regression trendlines were generated based the averaged data, as shown in Figure 3.10 as dashed lines. The rate of deterioration, rather than the current rating, for bridge decks of culverts can be interpreted as the slope of these linear regression trendlines.

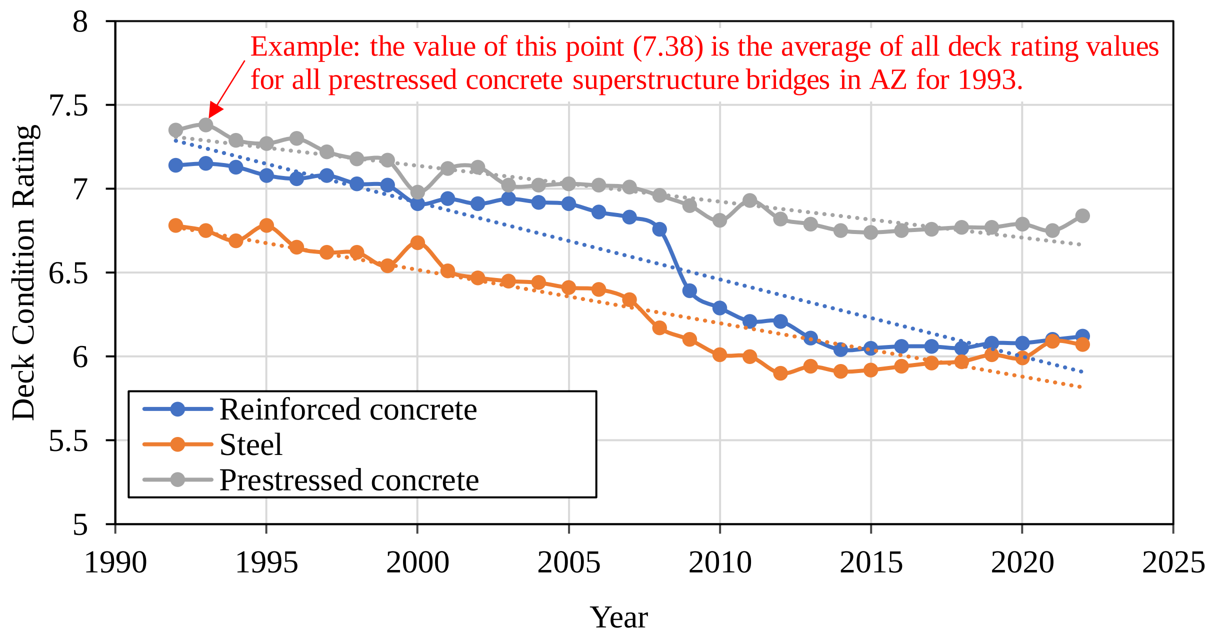

Figure 3.10: Example deterioration curve generated for bridge decks in Arizona considering superstructure material.

Considering data for each state in the U.S., the comparison of deterioration rates for Arizona and the U.S. states are presented for each variable. For example, data in Figure 3.11 indicate deterioration curves generated for bridge decks supported by reinforced concrete and reinforced concrete continuous superstructures in Arizona and other states in the U.S. Consider 1996, superstructure material (NBI Item 43A) was filtered for codes 1 and 2, which represents reinforced concrete and reinforced concrete continuous. The deck rating (NBI Item 58) for these variables averaged to generate a single deck rating for the year 1996 (6.68 in this case). Each dot in Figure 3.11 represents the average deck rating for reinforced concrete superstructures for AZ and the entire country in each specific year. Thus, the deterioration curves shown in Figure 3.11 were generated using scatter plots in Microsoft Excel and linear regression trendlines were generated based the averaged data, as shown in Figure 3.11 as dashed lines. The rate of deterioration, rather than the current rating, for bridge decks of culverts can be interpreted as the slope of these linear regression trendlines.

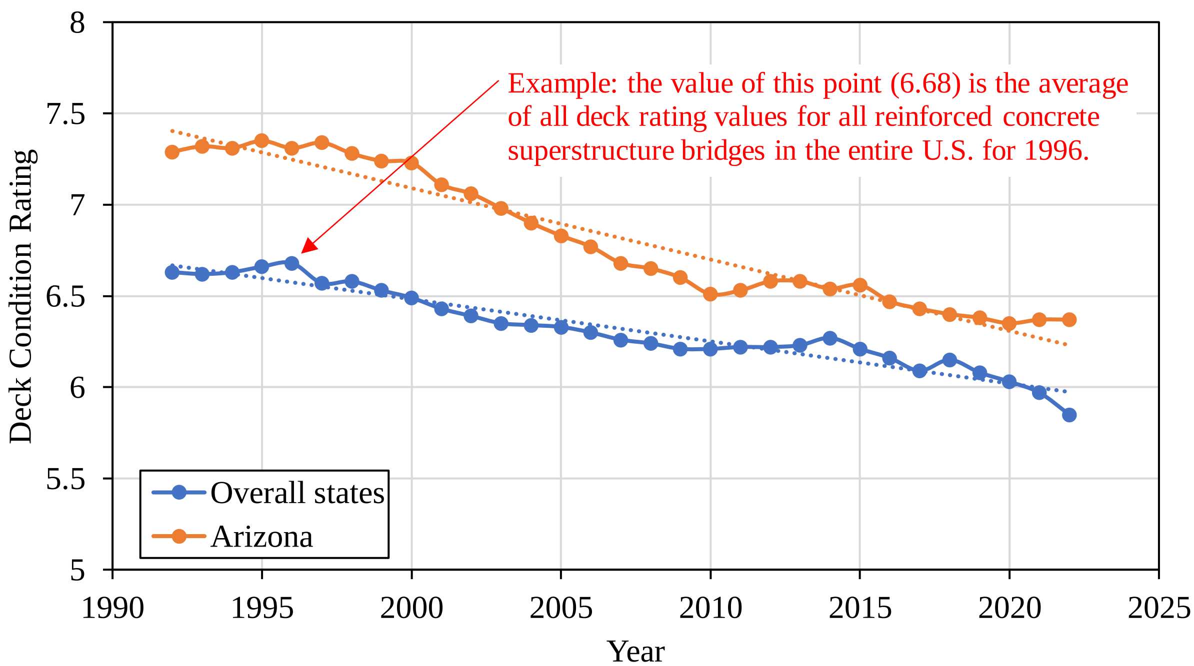

Figure 3.11: Example deterioration curve generated for bridge decks with a reinforced concrete superstructure material in Arizona and the other states in the U.S.

Chapter 4. Results and Discussions

4.1 Arizona Results

4.1.1 Superstructure Material (NBI Item 43A)

Most bridges in the United States, particularly those in Arizona, are built with reinforced concrete, steel, or prestressed concrete superstructure materials. As a result, understanding bridge behavior under the influence of each type of structure may be useful in selecting how to allocate resources for bridge deck maintenance, rehabilitation, and replacement measures.

Figure 4.1 depicts the deterioration curves of Arizona reinforced concrete, steel, and prestressed concrete bridge deck ratings from 1992 to 2022. It was determined that all three deterioration curves exhibit roughly the same behavior in 1992. In contrast, a difference in the degradation curves was observed in the selected 30-year timeline; ratings in 2022 were typically about a value of 1 less than in 1992 (e.g., deteriorating from a 7 to a 6). Bridge decks carried by reinforced concrete superstructures had the highest deterioration rate, dropping most rapidly from a rating of 7.2 in 1992 to a rating of 6 in 2022. The rating of bridge decks carried by steel superstructures were the lowest overall, but the rate of change was less than that of bridge decks carried by reinforced concrete superstructures. Bridge decks carried by prestressed concrete superstructures performed the best over time, only losing approximately 0.5 in the rating scale over 30 years. The faster deterioration rate for reinforced concrete and steel structures compared to prestressed concrete structures agreed with findings from Treat and Dymond (2019) in MN.

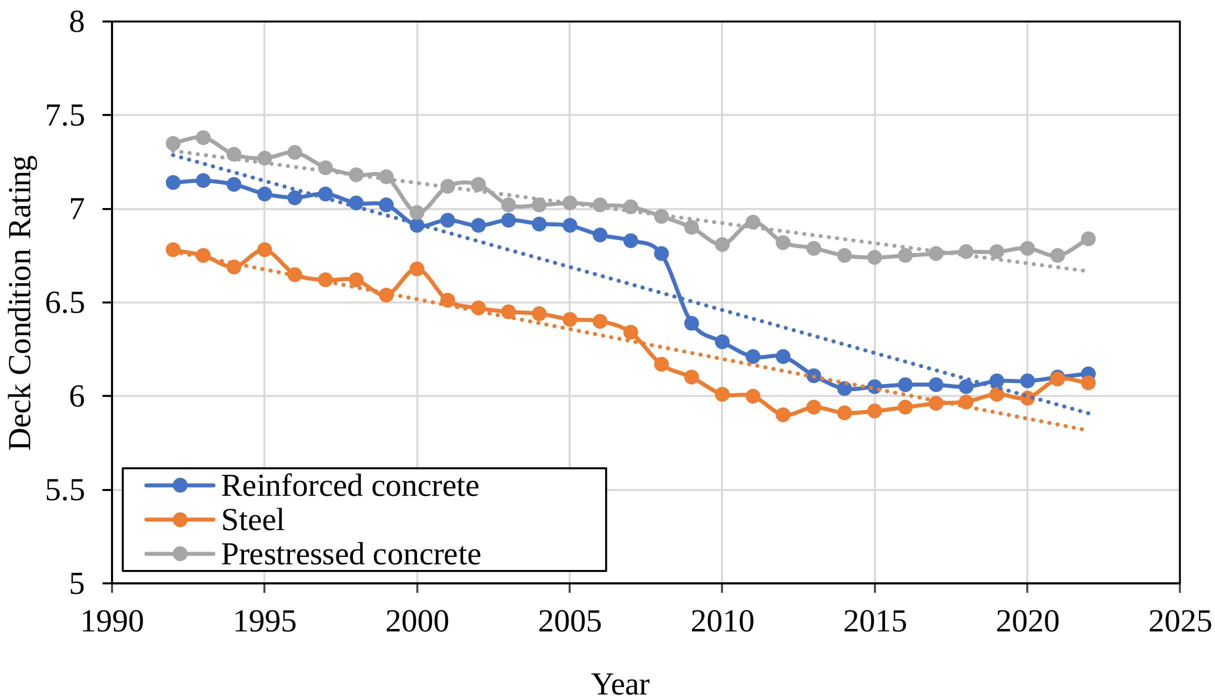

Figure 4.1: Deterioration curves of bridge decks in Arizona from 1992 to 2022 supported by reinforced concrete, steel, and prestressed concrete superstructures.

These trends may be affected by the location of bridge decks in Arizona, based on latitude. Structures made of reinforced concrete and steel may be more vulnerable to damage because of corrosion. Exposure to moisture and de-icing salts in severe settings can hasten the corrosion process, which eventually results in concrete cracking or steel section loss. In 2022, there were more reinforced concrete and steel structures in Northern Arizona compared to prestressed concrete structures, and the deterioration rate is higher for these structures. In the southern region, when compared to reinforced concrete, prestressed concrete structures usually perform better in terms of bridge deck rating.

4.1.2 Superstructure Cross-Sectional Geometry (NBI Item 43B)

Culverts are a significant percentage of the bridge inventory in Arizona and were thus a specific focus of this study. Data in Figure 4.2 indicate that culvert and box beam performance is similar, while the performance of slab and stringer cross sections is similar. Culverts and box beams performed well historically, before 1992, with rating values in 1992 of approximately 7.4 compared to rating values of approximately 7 for slab and stringer bridges. Over the 30 years investigated in this study, the rate of deterioration for bridge decks carried by box beams and slabs was faster compared to culverts and stringer cross sections, respectively. Overall, bridge decks carried by culverts performed the best, followed by those carried by box beams.

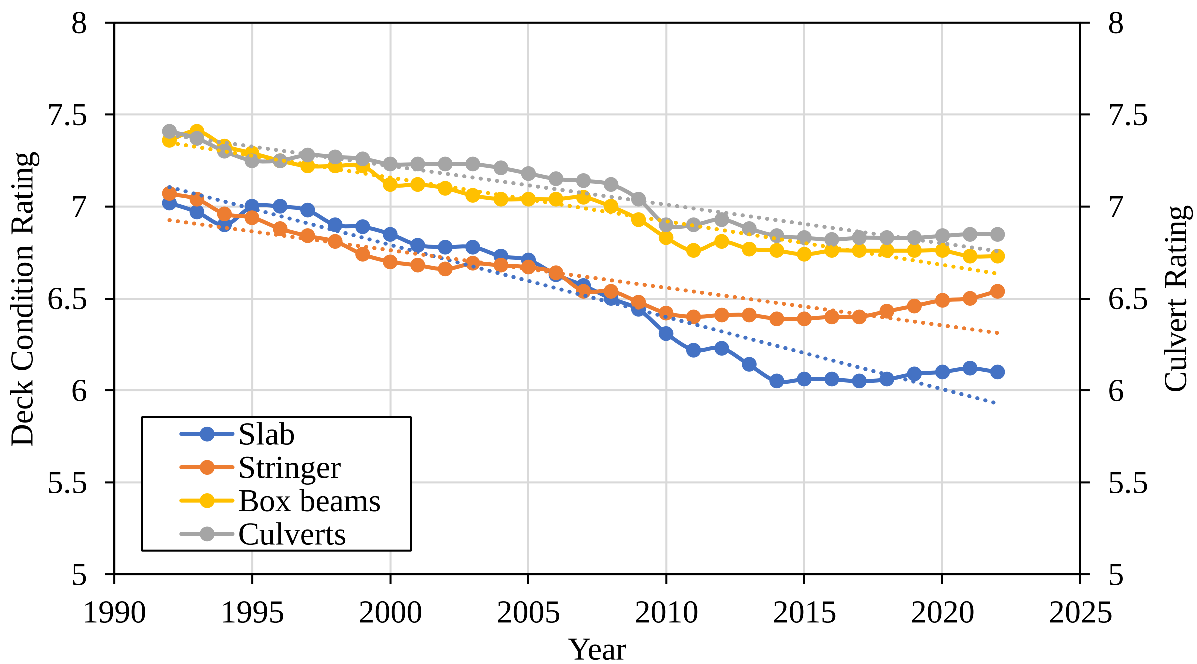

Figure 4.2: Deterioration curves of bridge decks and culverts in Arizona from 1992 to 2022 supported by various superstructure cross-sectional geometries.

The deterioration curves of slabs and stringers revealed interesting patterns. For the first few years after 1992, slabs and stringers seemed to function in the same way. But as the decades went by, something changed. In terms of maintenance costs and structural integrity, stringers gradually outperformed slabs and the bridge deck rating for stringer cross-sectional geometries improved starting in 2011(which is also when bridge decks carried by slabs deteriorated at a faster pace than those carried by stringers). As shown in Figure 4.2, bridge decks carried by stringer superstructures deteriorated at a slower rate, which may be due to more regular maintenance and repair.

4.1.3 Average Daily Traffic (NBI Item 29)

Due to increased commuter traffic, bridges and culverts near cities often have greater ADT; higher ADT can also frequently be associated with bridges on the interstate system compared to those on rural roads. Data in Figure 4.3 indicate that the condition of bridge decks was not significantly impacted by the level of ADT. On average, the condition rating for bridge decks in all three ranges of ADT started at a rating of approximately 7.1 in 1992 and were rated at a value of 6.8 in 2022. The ratings for all three levels of ADT improved between 2014 and 2022.

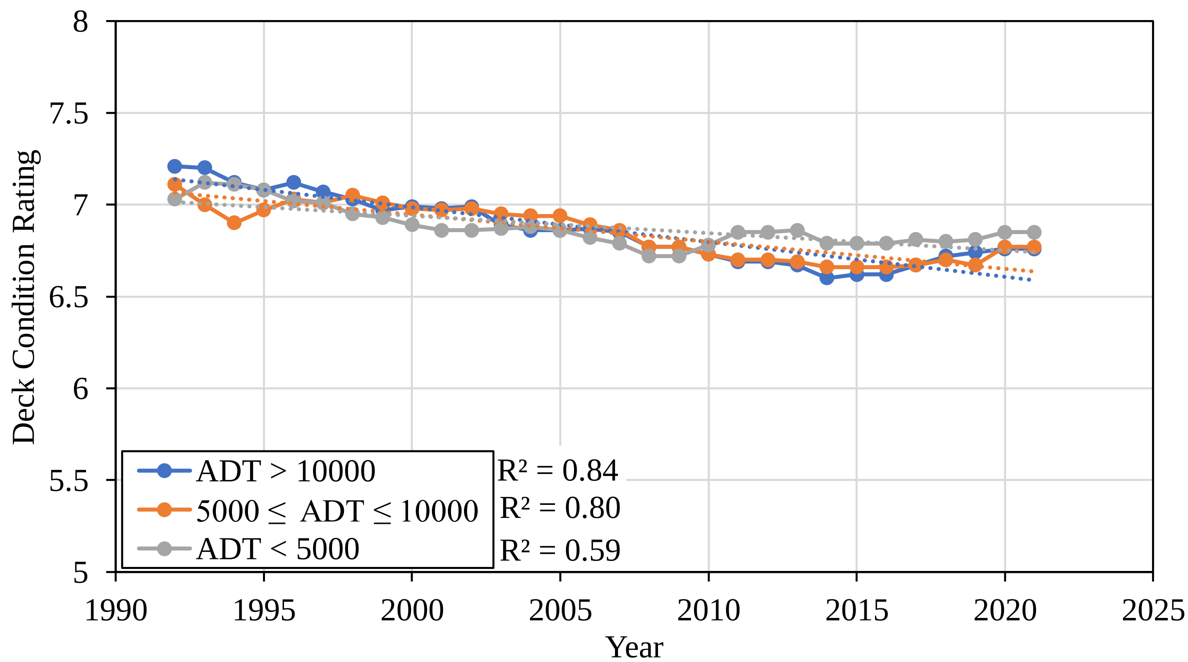

Figure 4.3: Deterioration curves of bridge decks in Arizona from 1992 to 2022 considering different levels of ADT.

However, the curves in Figure 4.3 demonstrate that the deck deteriorates at a faster rate as ADT increases. The traffic loads on bridges with an ADT of more than 10,000 are higher, which could be causing the bridge deck to deteriorate more quickly. A connection between higher ADT and degradation is indicated by the fir of the trendline; the R^2 value is highest for the ADT > 10,000 data (0.84 versus 0.80 or 0.59), which indicates the best association between greater degradation and higher ADT values. This finding was consistent with those from Moomen et al. (2016), who found that the deterioration of concrete decks was significantly more in higher traffic loading considering NBI data from Indiana.

4.1.4 Wearing Surface Material (NBI Item 108A)

In Arizona, bituminous and monolithic concrete wearing surfaces are on over 50% of structures with a wearing surface (Figure 3.5). Data in Figure 4.4 indicate that bridge decks with both types of wearing surfaces performed similarly. Bridge decks with a bituminous wearing surface had a modest deterioration curve over time, which means that frequent maintenance keeps them performing better than bridge decks with a monolithic concrete wearing surface, typically by a rating factor value of approximately 0.3. The deck ratings for structures with the two types of wearing surfaces vary throughout the years, but bridge deck ratings for both trended upward from approximately 2014 – 2022. The average rate of deterioration over time for bridge decks with both types of wearing surface is indicated by the slope of the trendlines in Figure 4.4. The slope of the deterioration line is steeper for bridge decks with bituminous wearing surfaces, which implies that bituminous bridge decks deteriorate more rapidly.

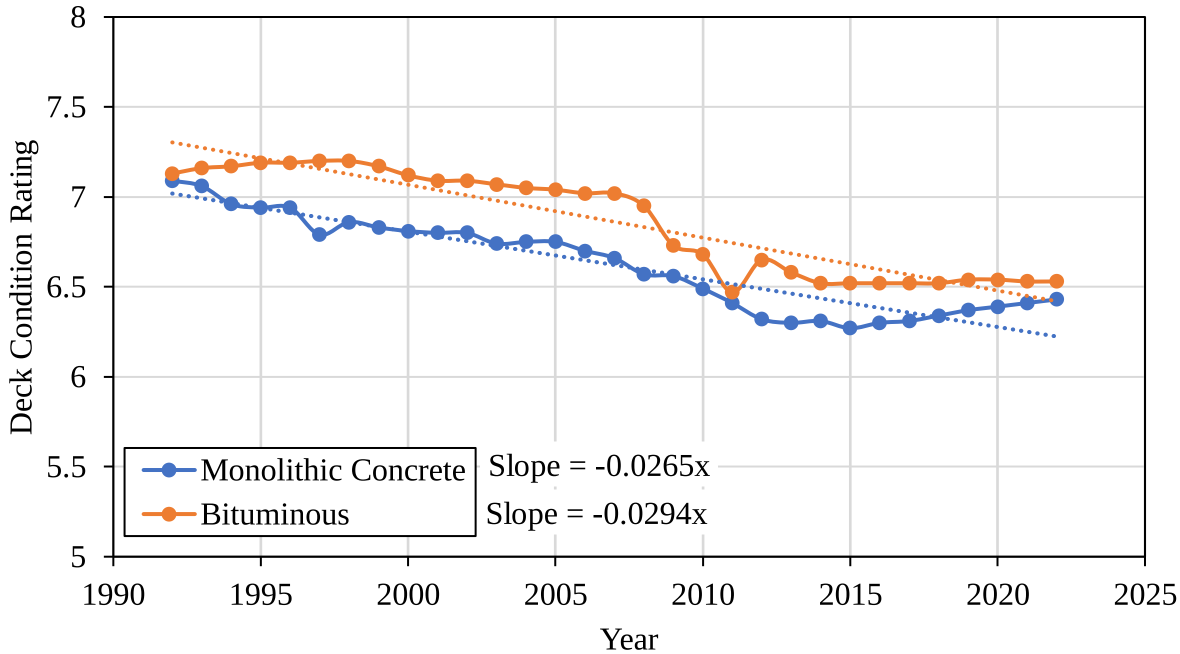

Figure 4.4: Deterioration curves of bridge decks in Arizona from 1992 to 2022 considering monolithic concrete and bituminous wearing surface materials.

The transition of bridge decks with these wearing surfaces from a Good to a Fair state took approximately two decades. This may be because of the flexibility of bituminous pavements, which can withstand thermal expansion and contraction in AZ due to the severe temperature swings. This elasticity offers a smooth driving surface and helps prevent cracking. Spalling and cracks in the concrete wearing surface can result from thermal expansion and contraction brought on by abrupt temperature changes, such as hot summers and freezing nights.

4.1.5 Location Considering Latitude (NBI Item 16) and Longitude (NBI Item 17)

Data in Figure 4.5 show that, in general, bridge decks in the Northern region of AZ typically have a lower rating than those in the Southern region; the difference in rating is approximately a value of 0.3. In both regions, the deck rating for structures gradually increased from 2001 to 2009 and then decreased once more starting in 2010 in north region; bridge decks in both regions have condition rating increases between approximately 2014 and 2022. Considering the deterioration rate, bridge decks in the Southern region deteriorated at a more severe rate than those in the Northern region.

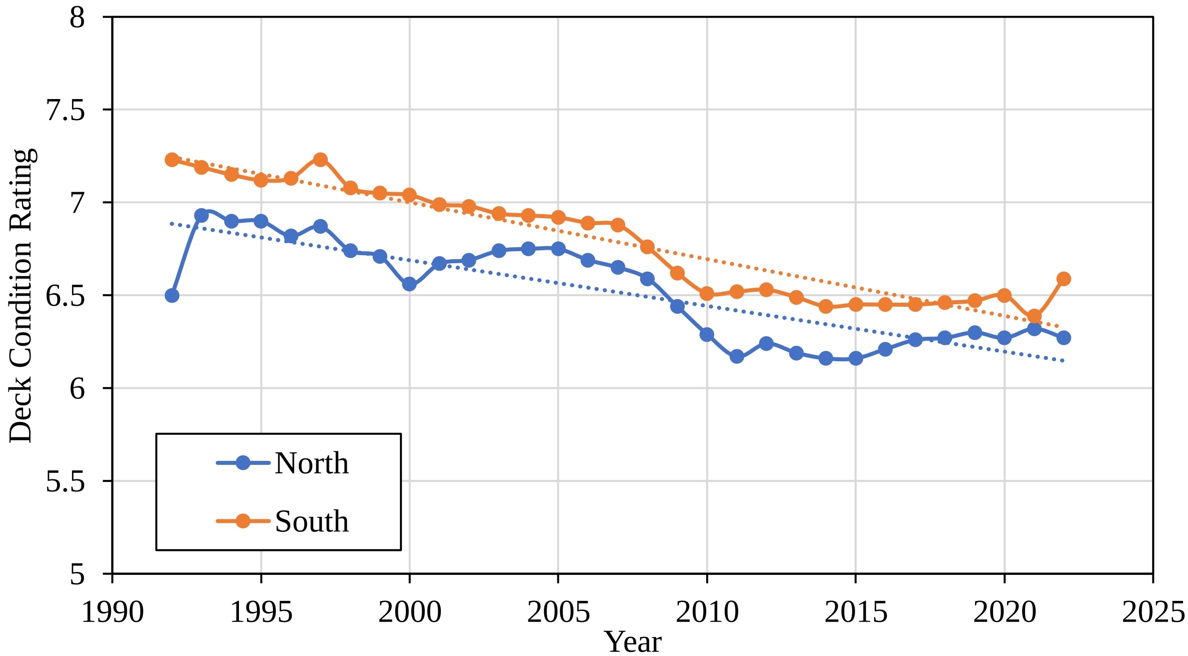

Figure 4.5: Deterioration curves of bridge decks in Arizona from 1992 to 2022 considering the Northern and Southern regions of the state.

Data in Figure 4.6 indicate that bridges on Arizona's East side, which are subject to harsh weather conditions performed well in the early years of this study (1992 – 2009) compared to those in the West region of the state. With the passage of time, an intriguing change happened. Due to several factors, bridge decks on Arizona's Western side eventually began to rate better than those on the Eastern side. This may be because, based on the longitude cutoff in this study (Figure 3.6), much of the suburban area surrounding Phoenix is on the Western side and may have received more maintenance to meet the demands of a growing population.

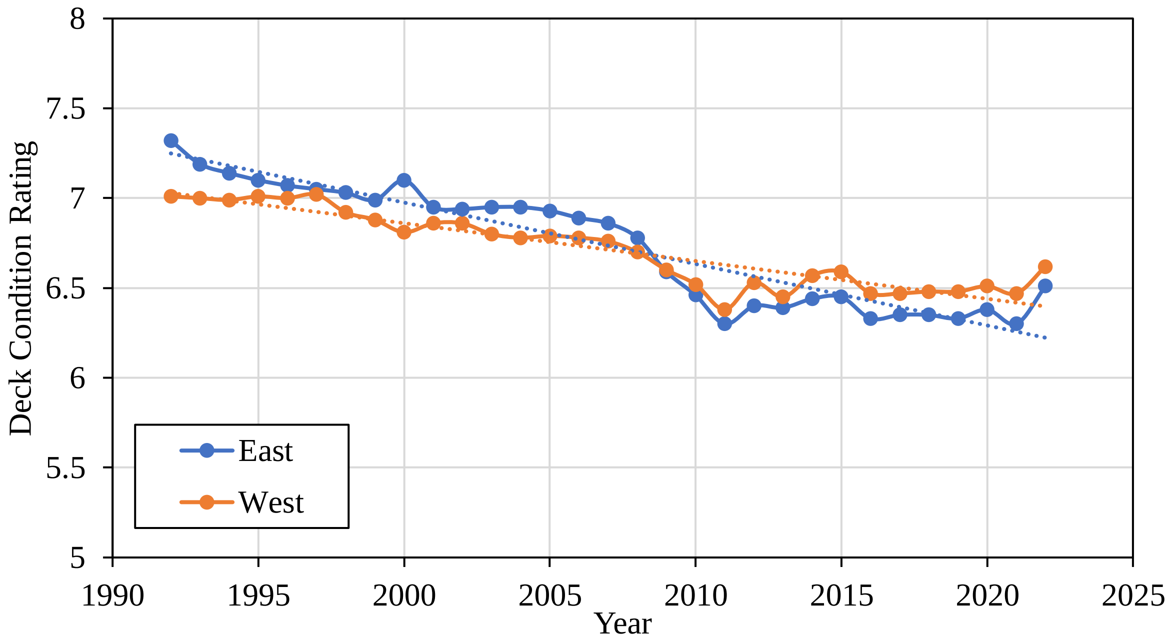

Figure 4.6: Deterioration curves of bridge decks in Arizona from 1992 to 2022 considering the Eastern and Western regions of the state.

Data in Figure 4.7 indicate that the Southeast and Southwest regions often have better-rated bridge decks when compared to those in the Northeast and Northwest regions of Arizona. In general, the climate in Arizona's Southeast and Southwest is milder than that of the state's Northern regions. Less temperature extremes and less snowy precipitation likely mean less stress from thermal expansion and contraction on the bridge decks, which may be linked with less deterioration and cracking.

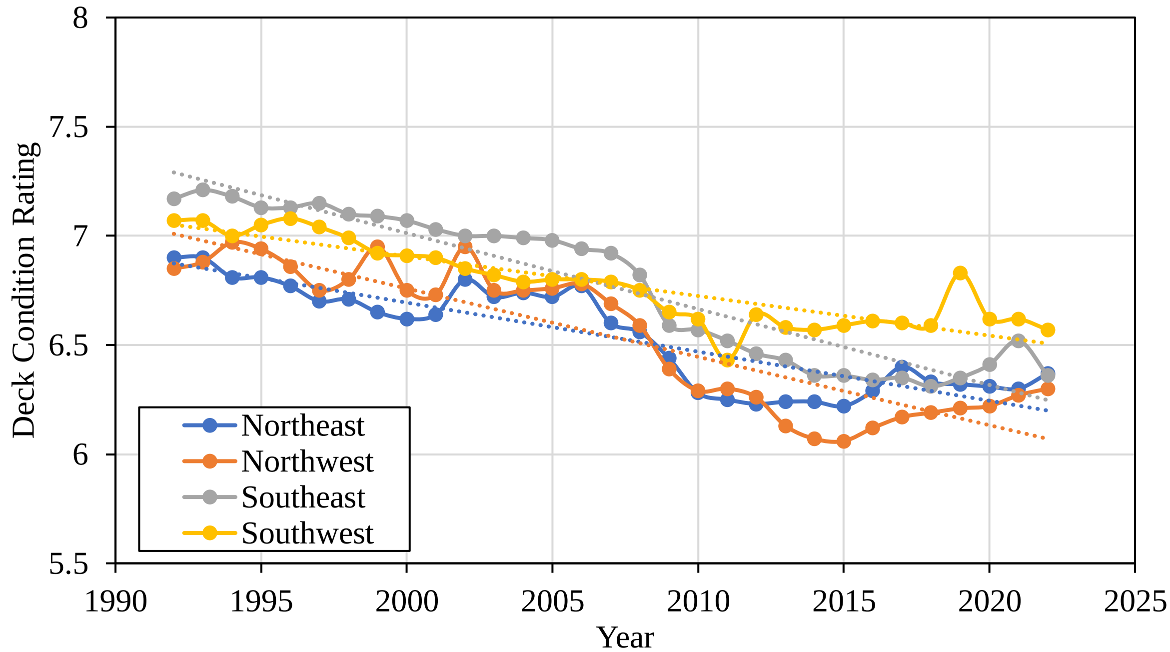

Figure 4.7: Deterioration curves of bridge decks in Arizona from 1992 to 2022 considering the Northeast, Northwest, Southeast, and Southwest regions of AZ.

4.1.6 Overall Comparison of Decks Carried by Bridges and Culverts in Arizona

Overall rating data in Figure 4.8 were used to compare the deterioration of decks carried by bridges versus culverts in Arizona. Decks carried by culverts outperformed those carried by bridges. Furthermore, the rate of deterioration was faster for decks carried by bridges compared to those carried by culverts. The linear deterioration regression lines in Figure 4.8 were also extrapolated to 2050. The deterioration trends indicate that, over the approximately 60 years shown, decks carried by bridges will deteriorate more (and at a faster rate) than those carried by culverts. Based on the trendlines, it is anticipated that the deck ratings of all decks carried by bridges or culverts will be 5.5 and 6, respectively, which correlate with Fair to Moderately Poor condition.

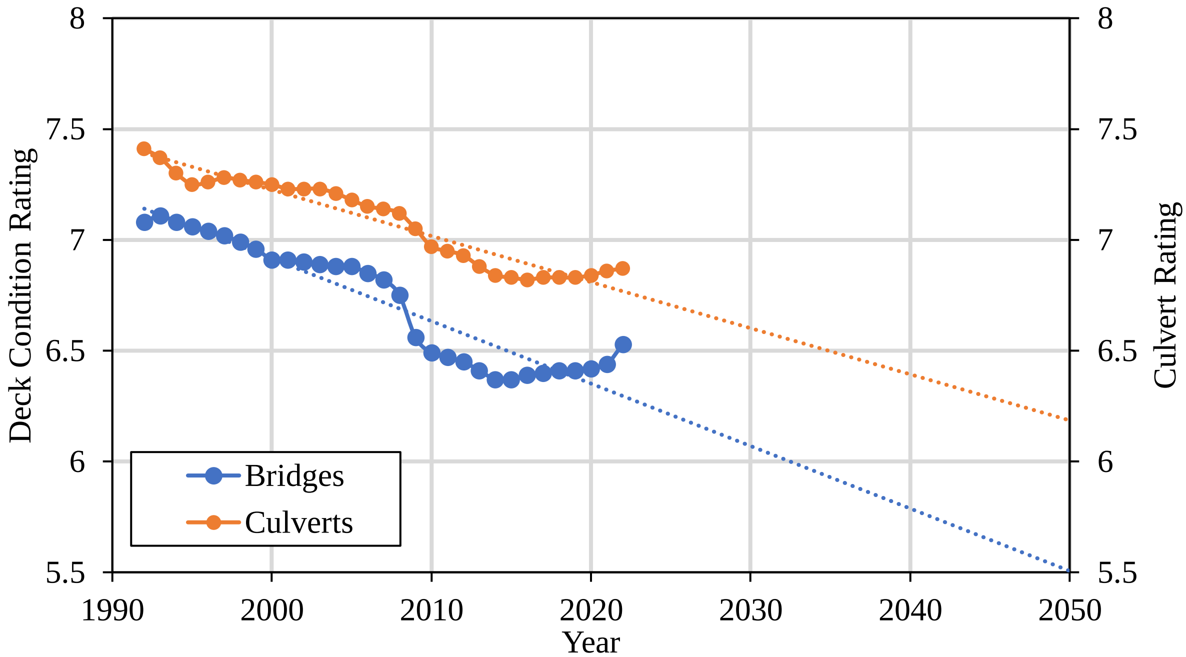

Figure 4.8: Deterioration curves of decks in Arizona from 1992 to 2022 based on whether the deck is carried by a bridge or a culvert.

4.2 Comparison of Deterioration Curves for Arizona and United States

4.2.1 Superstructure Material (NBI Item 43A)

Figure 4.9 through Figure 4.11 compare the deterioration of bridge decks in AZ and the entire U.S. based on superstructure material. In general, the magnitude of the deck condition rating is higher in AZ compared to the U.S. for each type of superstructure material. However, the deterioration rate for decks carried by each type of superstructure material is faster for bridges in AZ versus those in the U.S.

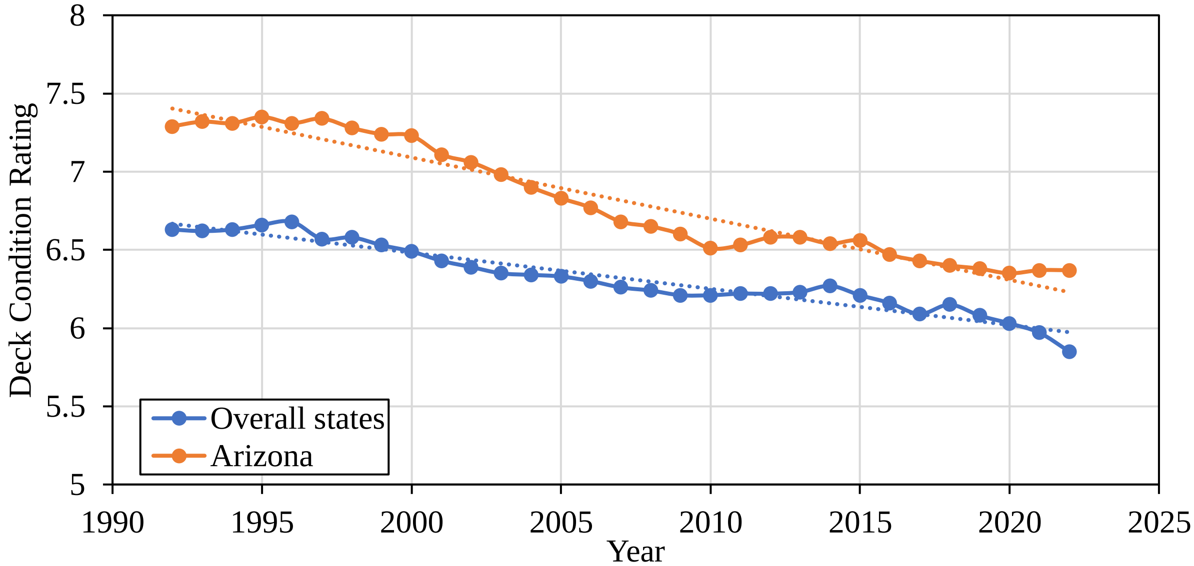

Figure 4.9: Deterioration trends for bridges in AZ and the U.S. with a reinforced concrete superstructure material.

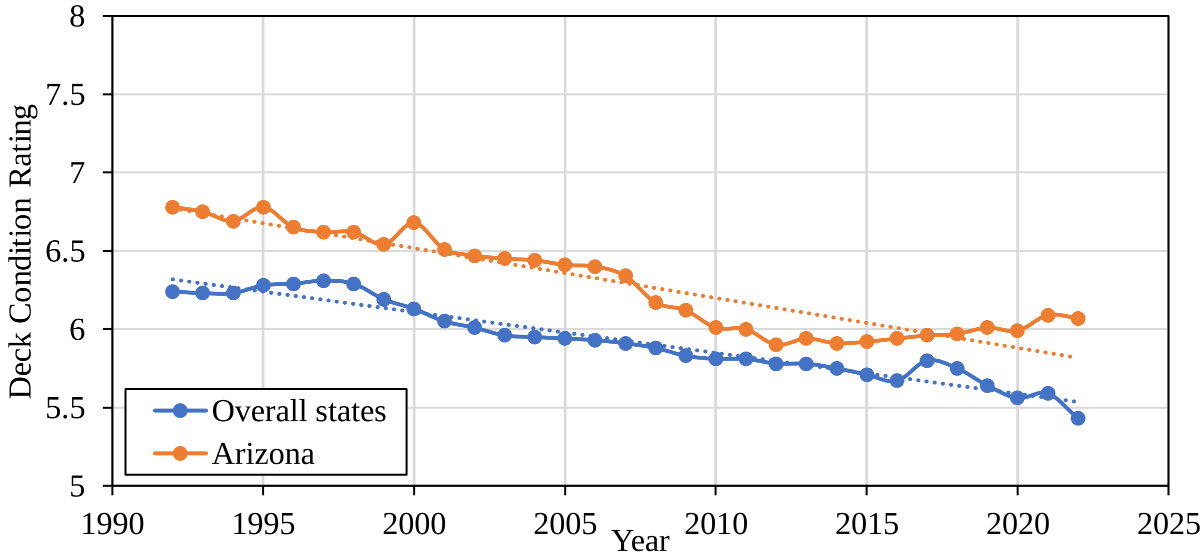

Figure 4.10: Deterioration trends for bridges in AZ and the U.S. with a steel superstructure material

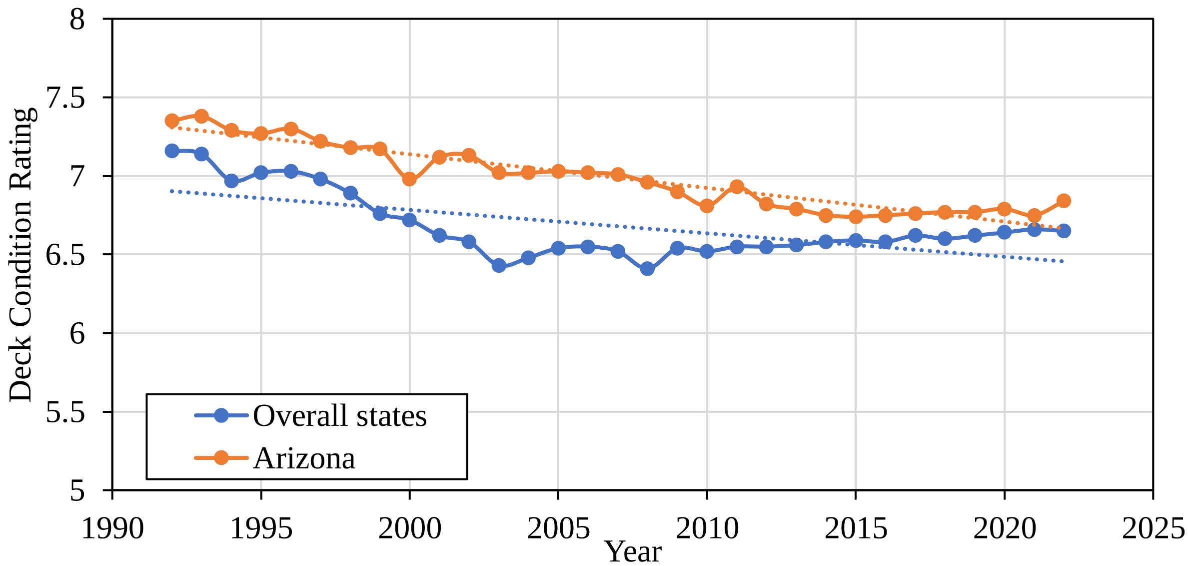

Figure 4.11: Deterioration trends for bridges in AZ and the U.S. with a prestressed material superstructure material

4.2.2 Superstructure Cross-Sectional Geometry (NBI Item 43B)

In slab bridge superstructures, AZ structures typically have higher magnitude ratings. Furthermore, the deterioration rate of AZ slab bridges is slower than that of the equivalent U.S. inventory, as shown in Figure 4.12. Deterioration trends for bridges in AZ and the U.S. with a stringer superstructure cross-sectional geometry are shown in Figure 4.13; AZ structures typically have higher magnitude ratings as well as a slower rate of deterioration compared to the equivalent U.S. inventory. Figure 4.14 shows the deterioration trends for bridges in AZ and the U.S. with box beam superstructure cross-sectional geometry; AZ structures typically have higher magnitude ratings but are experiencing a much faster rate of deterioration compared to the equivalent U.S. inventory. In culvert structures, AZ structures typically have higher magnitude ratings. Furthermore, the deterioration rate of AZ culverts is approximately the same as that of the equivalent U.S. inventory (but slightly faster), as shown in Figure 4.15

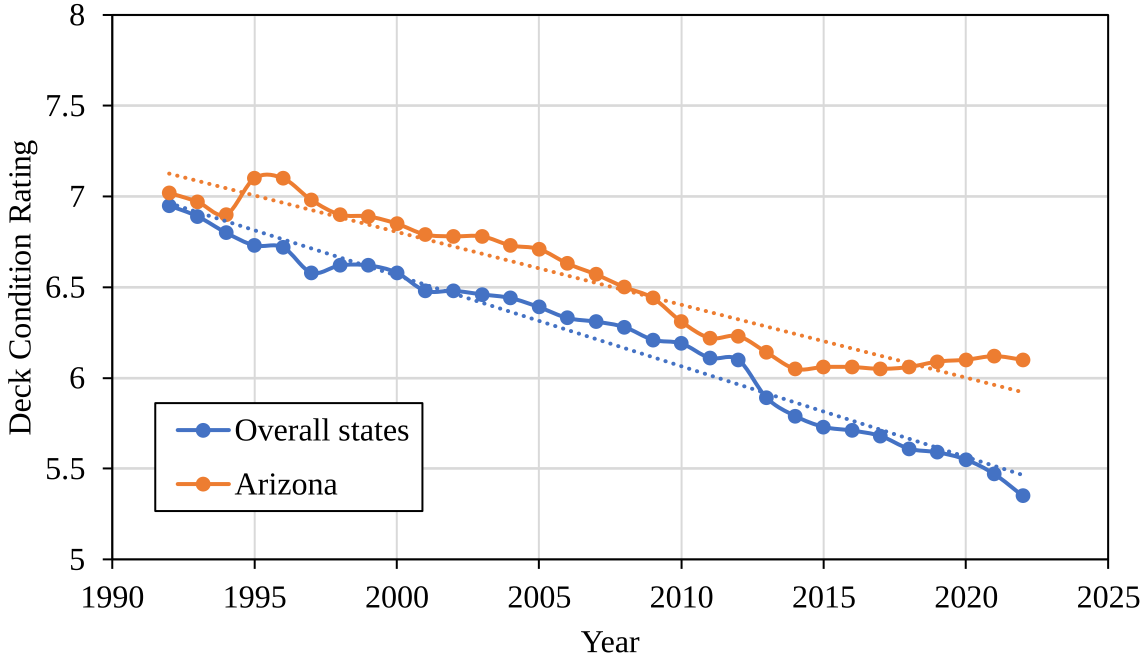

Figure 4.12: Deterioration trends for bridges in AZ and the U.S. with a slab superstructure cross-sectional geometry.

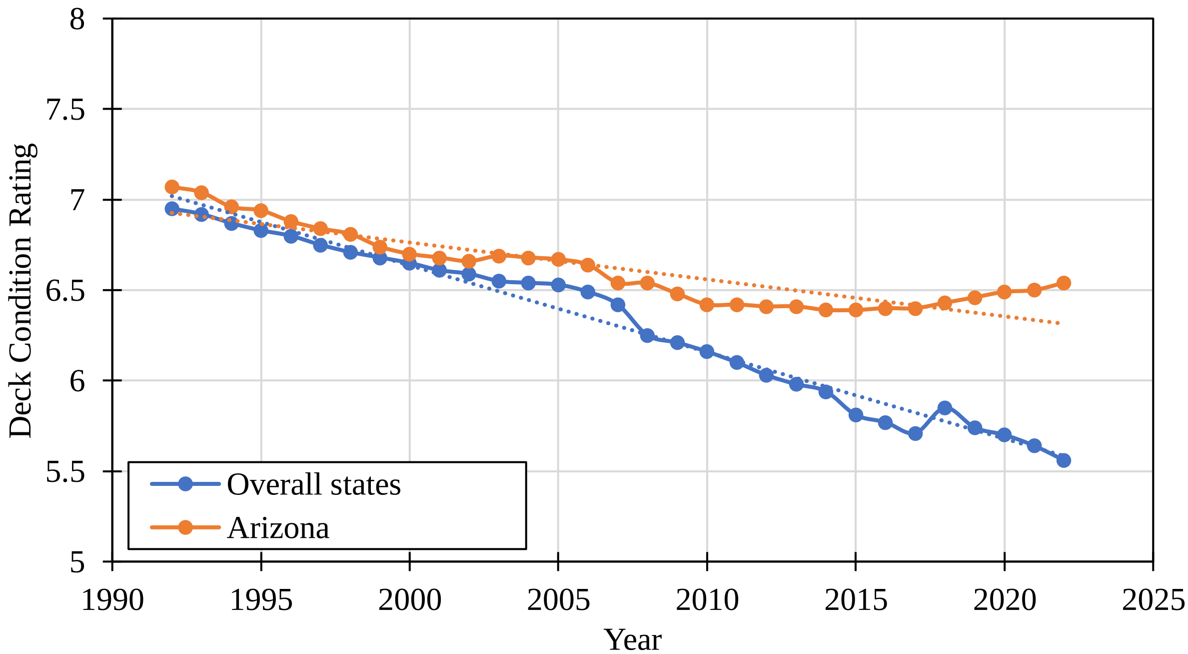

Figure 4.13: Deterioration trends for bridges in AZ and the U.S. with a stringer superstructure cross-sectional geometry.

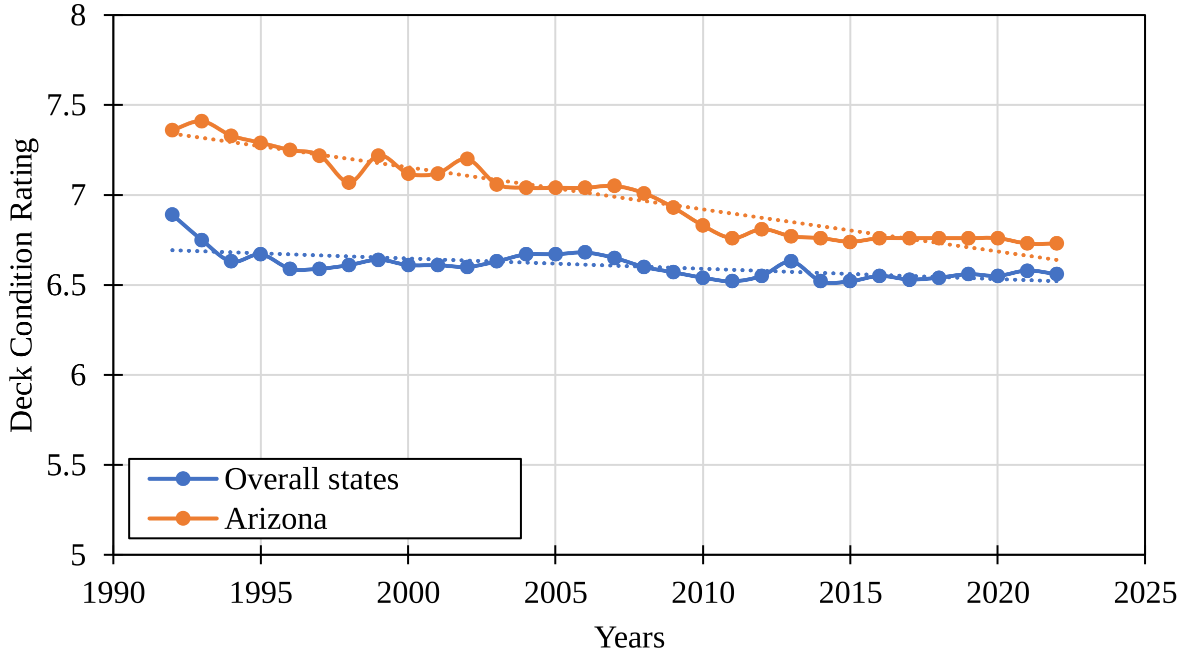

Figure 4.14: Deterioration trends for bridges in AZ and the U.S. with box beam superstructure cross-sectional geometry.

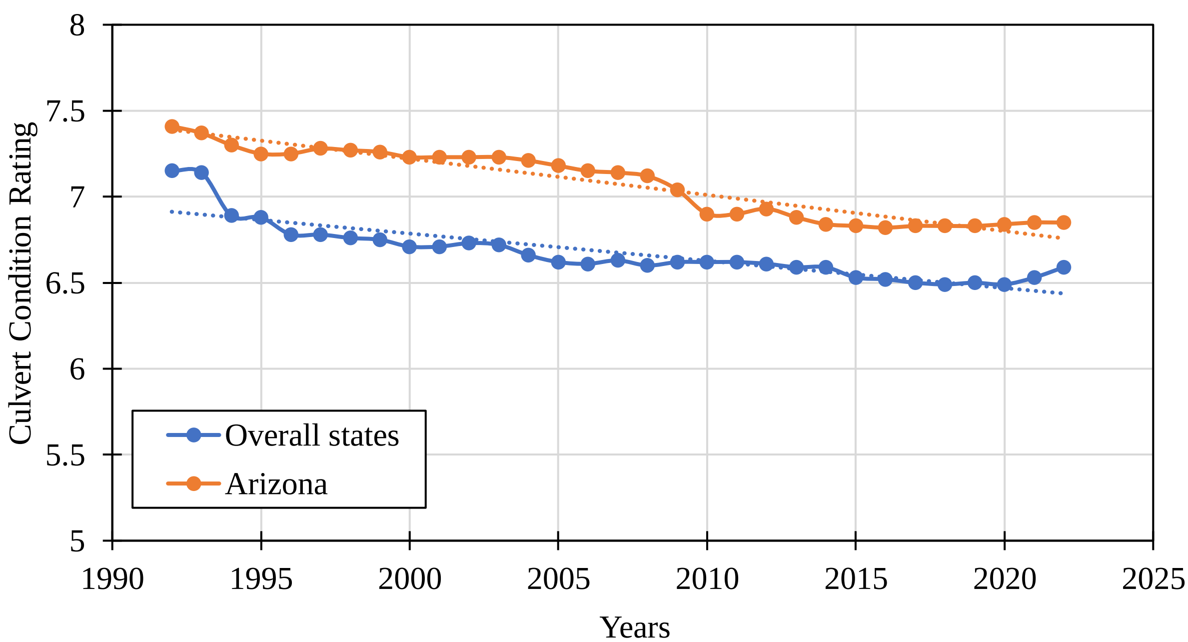

Figure 4.15: Deterioration trends for culverts in AZ and the U.S.

4.2.3 Annual Daily Traffic (ADT) (NBI Item 29)

Figure 4.16 through Figure 4.18 compare the deterioration of bridge decks in AZ and the entire U.S. based on ADT. Due to high volumes of traffic, the Nation's high ADT bridge decks have a lower rating but are not deteriorating as fast as those in AZ. Medium and low traffic bridge decks in the U.S. have lower ratings compared to AZ bridge decks from 1992 to 2022, but the rate of deterioration of AZ bridge decks carrying an ADT < 5000 is faster compared to the U.S.

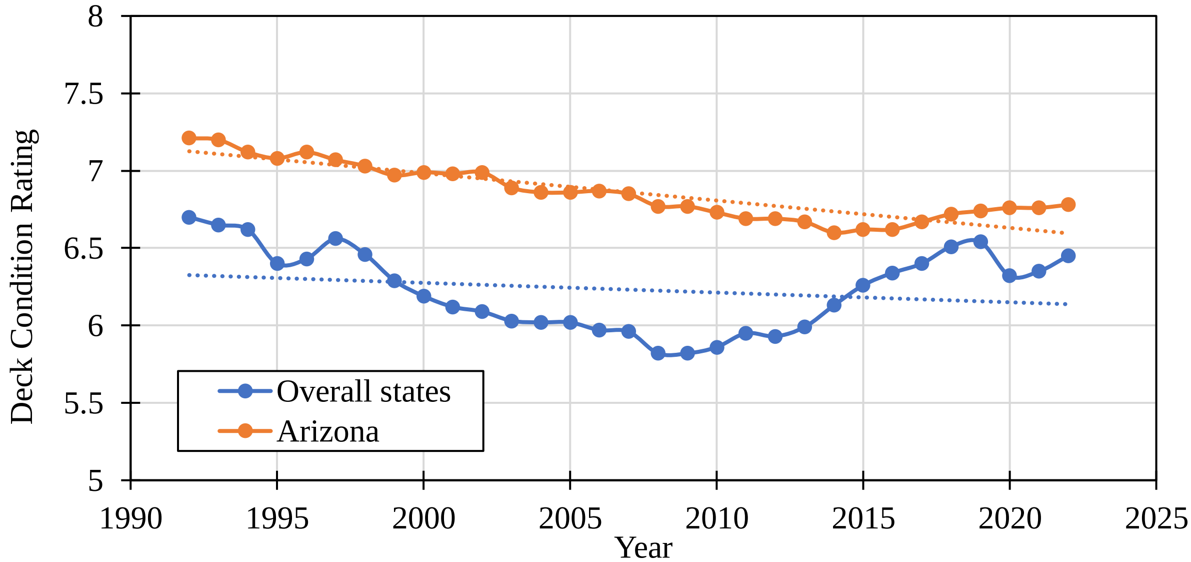

Figure 4.16: Deterioration trends for bridges in AZ and the U.S. with ADT > 10000.

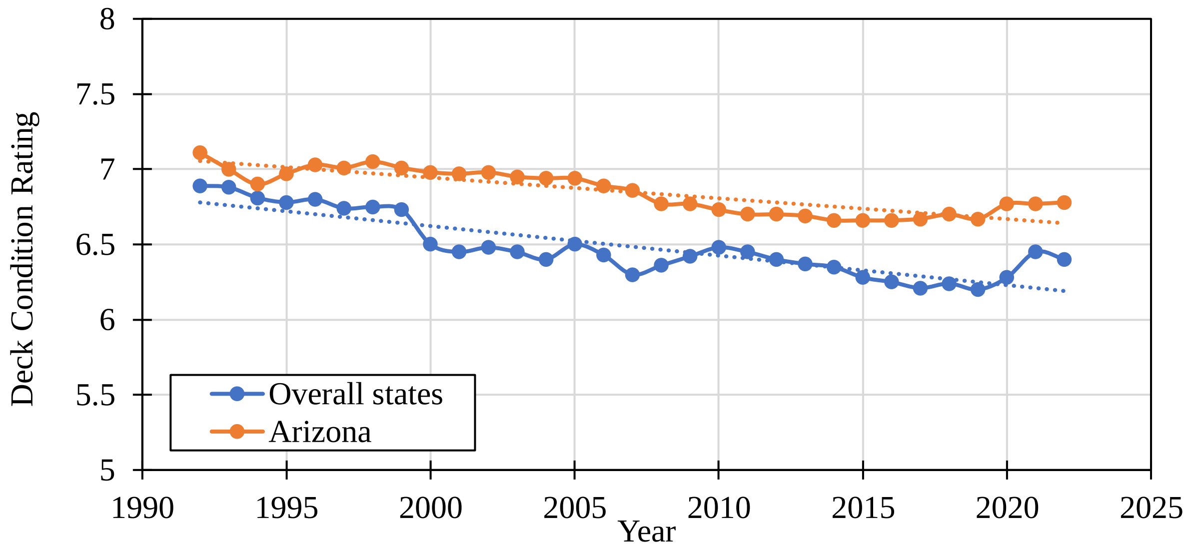

Figure 4.17: Deterioration trends for bridges in AZ and the U.S. with 5000 ≤ ADT ≤ 10000.

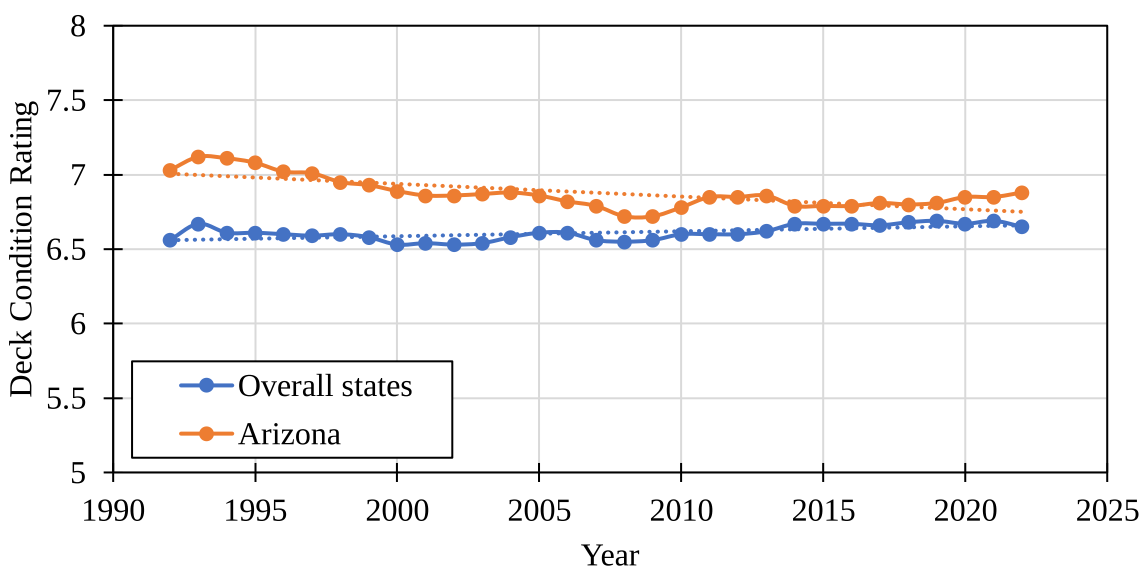

Figure 4.18: Deterioration trends for bridges in AZ and the U.S. with ADT < 5000.

4.2.4 Wearing Surface Material (NBI Item 108A)

The deterioration trends for bridge decks in AZ and the U.S. with a monolithic concrete wearing surface are shown in Figure 4.19. U.S. monolithic concrete decks typically have had a lower rating than the AZ inventory but converged to have approximately the same rating values after

2011. However, the deterioration rate in AZ has been higher, as the gap in rating magnitude was higher in 1992 compared to 2022 when compared to the U.S. Furthermore, the deterioration rate of bridge decks with a bituminous wearing surface is approximately the same, as shown in Figure 4.20. Arizona bridge decks with a bituminous wearing surface had higher magnitude ratings when compared to the equivalent U.S. inventory.

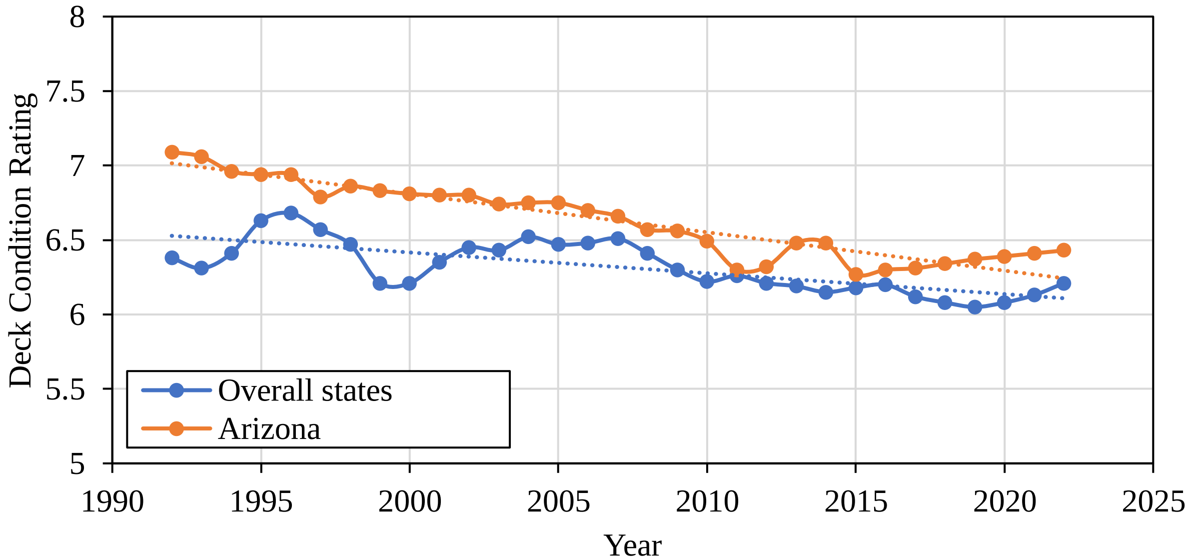

Figure 4.19: Deterioration trends for bridge decks in AZ and the U.S. with a monolithic concrete wearing surface.

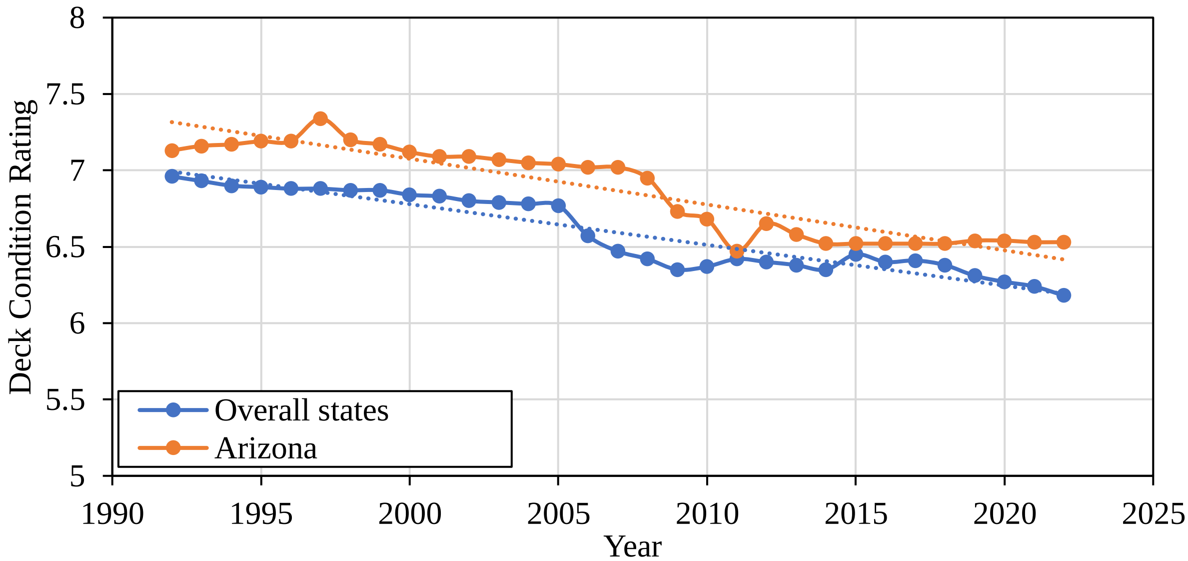

Figure 4.20: Deterioration trends for bridge decks in AZ and the U.S. with a bituminous wearing surface.

4.2.5 Location Considering Latitude (NBI Item 16) and Longitude (NBI Item 17)

The temperatures in the West and South (and AZ) are often milder, with less extreme winters and less exposure to chemicals used to remove ice. In these regions, bridge deck ratings are typically higher because of less corrosion and thermal stress cycles, as shown in Figure 4.21. Even though the Northeast has hard winters, timely maintenance and efficient snow and ice management techniques help improve bridge performance. Preventative steps like snow removal and de-icing techniques helps to reduce the possibility of degradation problems. The Mid-West frequently experiences more difficult weather, with bitterly cold winters marked by ice, snow, and freezing temperatures. The use of de-icing chemicals more frequently and exposure to freeze-thaw cycles may accelerate the deterioration of bridges in this area.

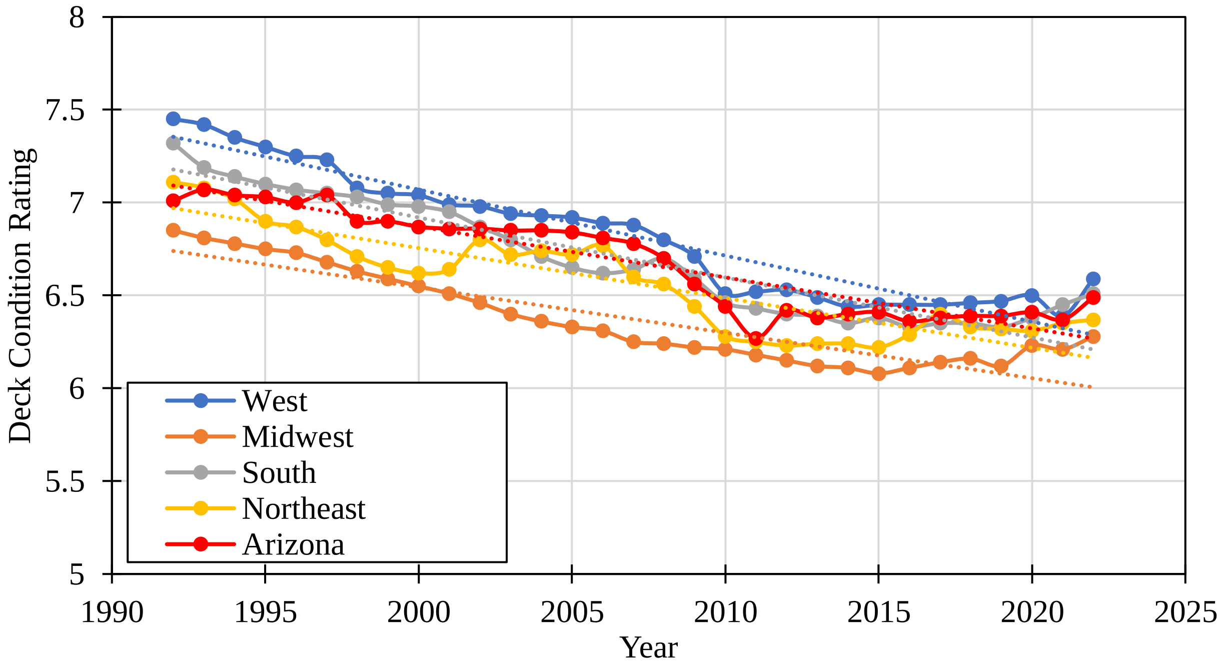

Figure 4.21: Deterioration trends for bridges the United States based on geographic region. Arizona data is shown for comparison.

4.3 Determination of Good, Fair, and Poor Condition for Bridges in all U.S. States

For further comparison and analysis, the count of bridges classified as Good (NBI 7-8), Fair (NBI 5-6), or Poor (NBI 4) condition in every state was determined and evaluated on a percentage basis. Arizona rankings in these analyses was noted. Plots showing the percentage of bridges with Good, Fair, and Poor condition states in all 50 states are shown in Appendix A. The following are the top five states with the lowest percentage of Poor rated structures:

1. Arizona — 1.2%
2. Texas — 1.3%
3. Nevada — 1.4%
4. Delaware — 1.6%
5. District of Columbia — 1.6%

States with highest percentage of Poor rated structures:

1. West Virginia — 19.9%
2. Iowa — 19.3%
3. South Dakota — 16.8%
4. Rhode Island — 16.5%
5. Maine — 14.1%

States with highest percentage of bridges rated Good:

1. Georgia — 74.7%
2. Arizona — 45.4%
3. Florida — 61.7%
4. Ohio — 60.8%
5. Minnesota — 57.5%

States with lowest percentage of bridges rated Good:

1. Rhode Island — 21.4%
2. West Virginia — 23.3%
3. Hawaii — 24.1%
4. Massachusetts — 25.3%
5. New Jersey — 26.3%

States with lowest percentage of bridges rated Fair:

1. Georgia — 23.2%
2. Ohio — 34 %
3. Florida — 34.6%
4. Mississippi — 35. 9%

5. Arizona — 35.9%

States with highest percentage of highest rated Fair:

1. Utah — 70 %
2. Hawaii — 69.5%
3. New Jersey — 66.9 %
4. District of Columbia — 66.9 %
5. Massachusetts — 66.2 %

Some interesting patterns can be seen in the data on bridge conditions across the United States. Of all the states, Arizona has the lowest percentage of bridges evaluated as being in Poor condition, just 1.2%. This likely indicates that, in comparison to states with more significant weather variations, Arizona's arid climate and absence of harsh winter weather impose less burden on bridge deck infrastructure. Although Arizona has the best scores for bridge conditions, other states have far more difficult issues. The five states with the greatest percentages of poorly maintained bridges are characterized by an aged infrastructure and issues related to geography/climate. With 19.9% of its bridges in poor condition, West Virginia ranks first despite having a bridge inventory that had good deck ratings in 1992. Bridge damage is further accelerated by severe winters and flooding incidents. Similarly, saltwater may cause bridge corrosion in Rhode Island, which suffers from extremely cold coastal winters. These illustrations demonstrate how aging infrastructure and the environment contribute to a greater percentage of bridges with Poor ratings.

Georgia has likely made significant infrastructural investments and maintains bridges on a regular basis; Georgia also likely has fewer freeze/thaw cycles, which lessen wear and tear. Rhode Island is a small state by the sea that is exposed to the sea and harsh winters. Another important factor is insufficient financing for extensive repairs. Utah likely extends the useful life of its bridges through routine maintenance and rehabilitation initiatives, ensuring that they remain in reasonable condition as they age; the state's arid climate is also beneficial.

Chapter 5. Summary, Conclusions, and Recommendations

5.1 Summary

The goal of this study was to quantitatively analyze the deterioration of concrete bridge decks and culverts in AZ between the years of 1992 and 2022 using publicly available NBI data from the FHWA. Two NBI coding items were used, Item 58 Deck and Item 62 Culverts that describe the overall condition rating of the deck and of a culvert, respectively. Furthermore, the effect of several key parameters on deck or culvert condition were evaluated, such as superstructure material, superstructure cross-sectional geometry, ADT, wearing surface material, and geographical location. Specifically, detailed results associated with the state of Arizona, as well as broad results associated with the entire United States were investigated.

5.2 Conclusions

The following conclusions were reached based on the results of this research program:

- In Arizona, bridge decks carried by prestressed superstructures outperform those carried by steel and reinforced concrete, according to data and deterioration curves.
- Decks carried by culverts and box beams outperformed those carried by stringer and slab cross-sectional superstructure geometries in AZ.
- Average Daily Traffic affects how well bridges operate in terms of deck ratings. Bridge decks subjected to ADT < 5000 vehicles/day in AZ typically had a superior rating compared to those subjected to heavy and moderate traffic volumes. The correlation that exists between traffic volume and deck condition is inverse, emphasizing the significance of focused maintenance and allocation of resources.

- Bridge decks with a bituminous wearing surface performed better those with monolithic concrete wearing surface, in AZ. This may be because bituminous wearing surfaces can survive the extreme temperature changes and the resulting stress on road surfaces.
- In Arizona, bridge decks in the southern region are deteriorating at a slower rate than the bridges in the northern region. Moreover, the performance analysis shows that bridge decks in Arizona's East region had high ratings approximately 30 years ago. But, with time, there is a notable change in deck rating over the past 30 years, and bridge deck ratings in the West region increasingly exceed those in the East.
- In general, the magnitude of the bridge deck and culvert condition ratings are higher in AZ compared to the U.S. for each of the categories investigated in this study. In fact, Arizona had the lowest percentage of Poor bridges in the United States, 1.26%. However, a detailed analysis of deterioration rates indicated that bridge decks and culverts in AZ have been deteriorating at a faster rate from 1992 to 2022 for almost all the key parameters investigated in this study when compared to the equivalent inventory across the entire U.S. This is a complex issue and likely impacted by a myriad factors; Arizona is reported to be 30th out of 50 states in terms of capital and bridge disbursements (associated with spending to build new and widen existing highways and bridges) but 10th out of 50 states in terms of maintenance disbursements (associated with spending to perform routine upkeep such as filling in potholes and repaving roads, but not necessarily significant bridge deck maintenance) (Feigenbaum et al. 2023).

5.3 Recommendations

From this study, due to their subpar performance, it is recommended that bridge owners give priority to maintenance and rehabilitation plans for the structures that are deteriorating faster, such as bridge decks carried by reinforced concrete superstructures, bridge decks carried by steel superstructures, bridge decks with a monolithic concrete wearing surface, and bridge decks carried by slab and stringer cross-sectional geometries.

In terms of ADT, it is recommended that top priority for rehabilitation projects be given to bridge decks that have ADT > 10,000 vehicles/day so they can endure the additional strain caused by vehicles. With respect to location within the state, it is recommended that bridge decks in the Northern and Eastern regions of AZ be prioritized for maintenance, taking into consideration region-specific issues and the wide temperature variations associated with the mountainous regions of AZ.

It is recommended that an in-depth investigation be conducted to determine why bridge decks and culverts in AZ have been deteriorating at a faster rate than the equivalent inventory across the entire U.S. Additional insight into this trend will allow bridge owners to better deploy resources. They can concentrate maintenance and repair activities by focusing on regions most vulnerable to deterioration, including deciding which bridges to repair first, which maximizes their budgetary expenditures for maximum impact.

5.3.1 Future Research

In terms of future study paths, the NBI bridge deck condition data in AZ should be processed using a more sophisticated predictive modeling approach to project future rates of degradation and bridge lifespans. More intricate linkages and patterns in the data may be found using techniques like neural networks and machine learning algorithms. Furthermore, the accuracy of the models may be increased by broadening the study to include additional variables like maintenance tasks, the caliber of the construction, and meteorological elements like temperature and precipitation.

Creating cost-effective maintenance and repair plans and strategies for the most susceptible bridge types and components is another possible direction to pursue. This could help transportation departments prioritize restoration projects and allocate resources more effectively. The analysis done in this thesis only used NBI data, but inspectors may differ in their subjective opinions. Improved and validated deterioration models could be achieved with more quantitative condition assessments via structural health monitoring.

Further research into project-level evaluations, cost-benefit analyses, quantitative condition data, and more sophisticated predictive modeling may produce even more insightful findings for infrastructure management.

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Appendix A: Percentage of Good, Fair, and Poor Bridges in the United States

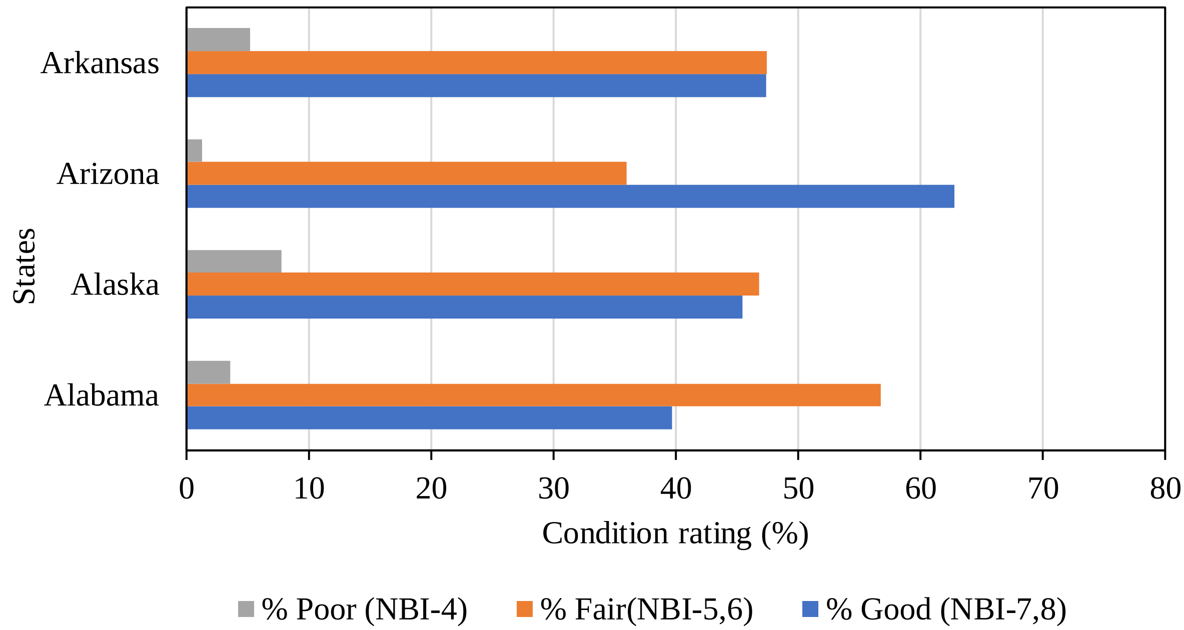

Figure A.1: Percentage of Good, Fair, and Poor Bridges in the United States

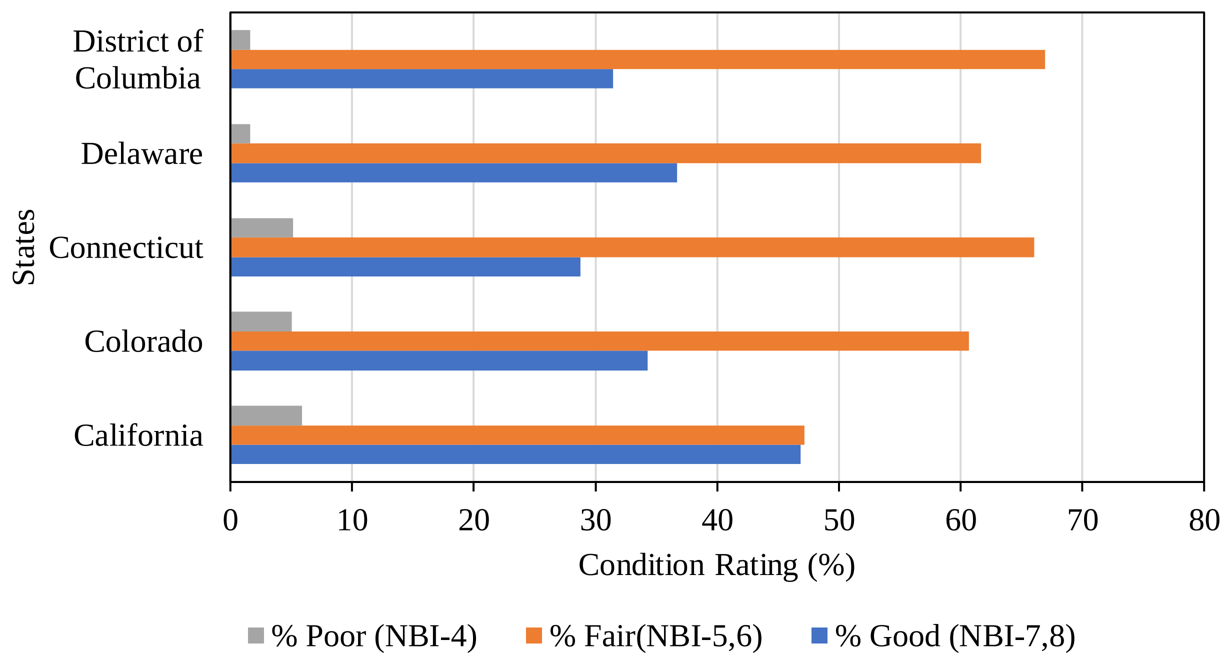

Figure A.2: Percentage of Good, Fair, and Poor Bridges in the United States

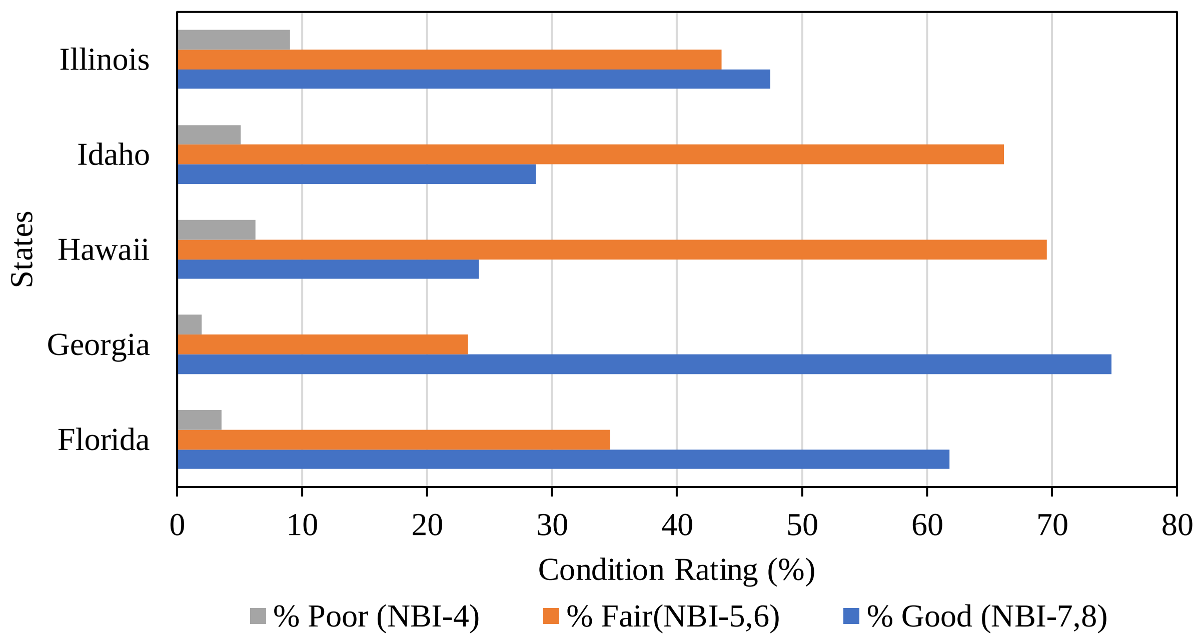

Figure A.3: Percentage of Good, Fair, and Poor Bridges in the United States

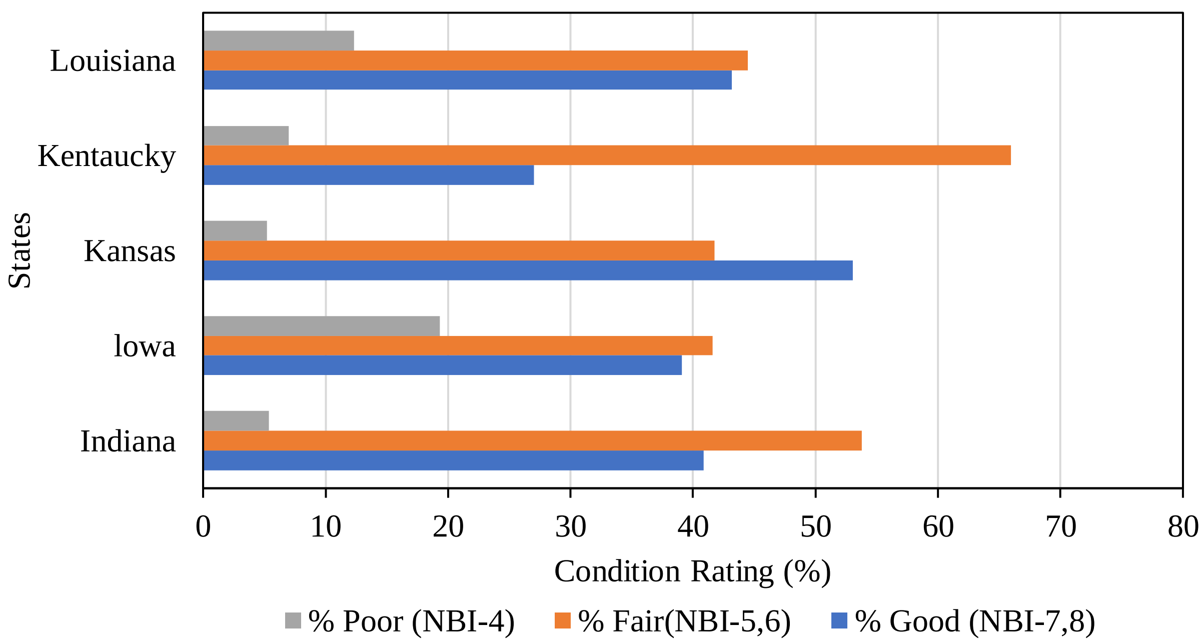

Figure A.4: Percentage of Good, Fair, and Poor Bridges in the United States

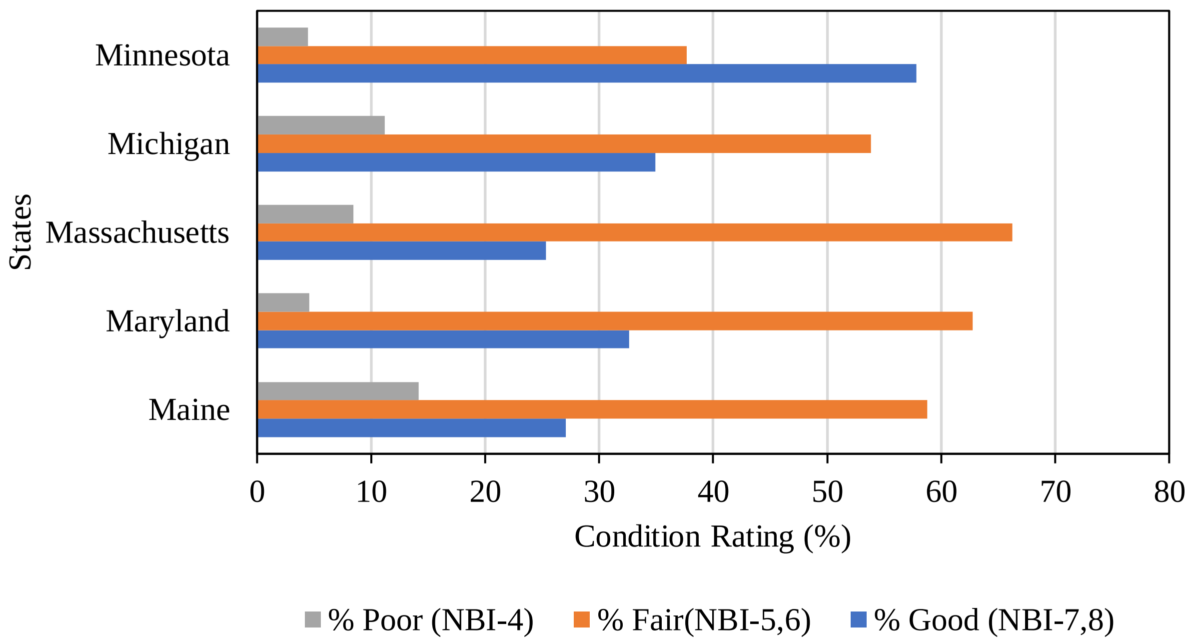

Figure A.5: Percentage of Good, Fair, and Poor Bridges in the United States

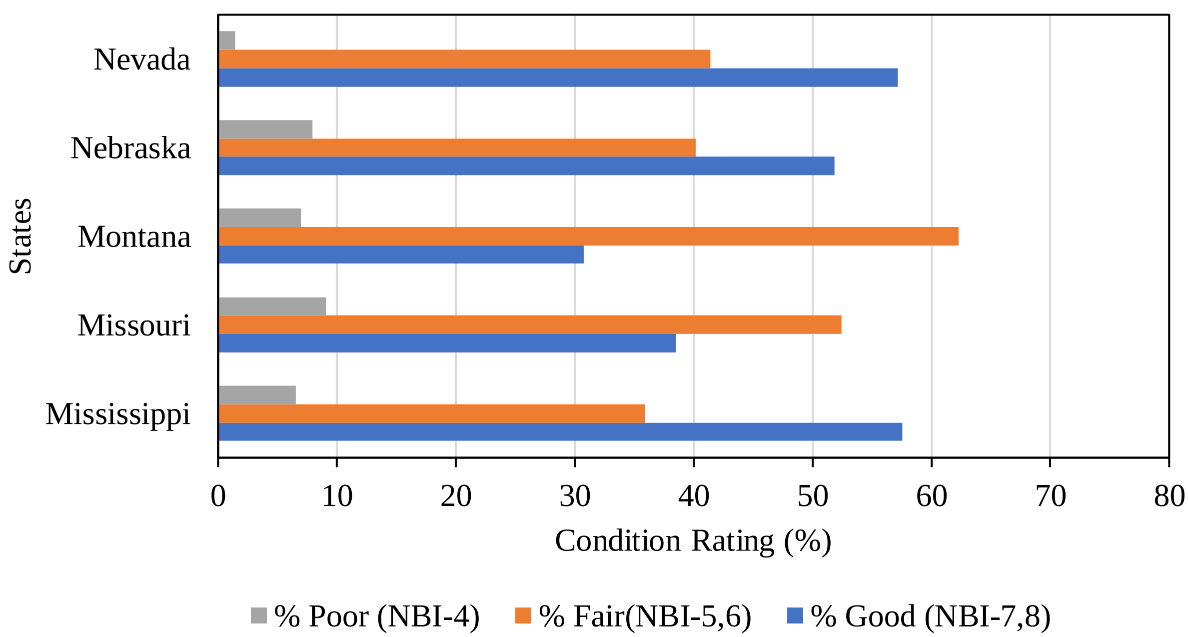

Figure A.6: Percentage of Good, Fair, and Poor Bridges in the United States

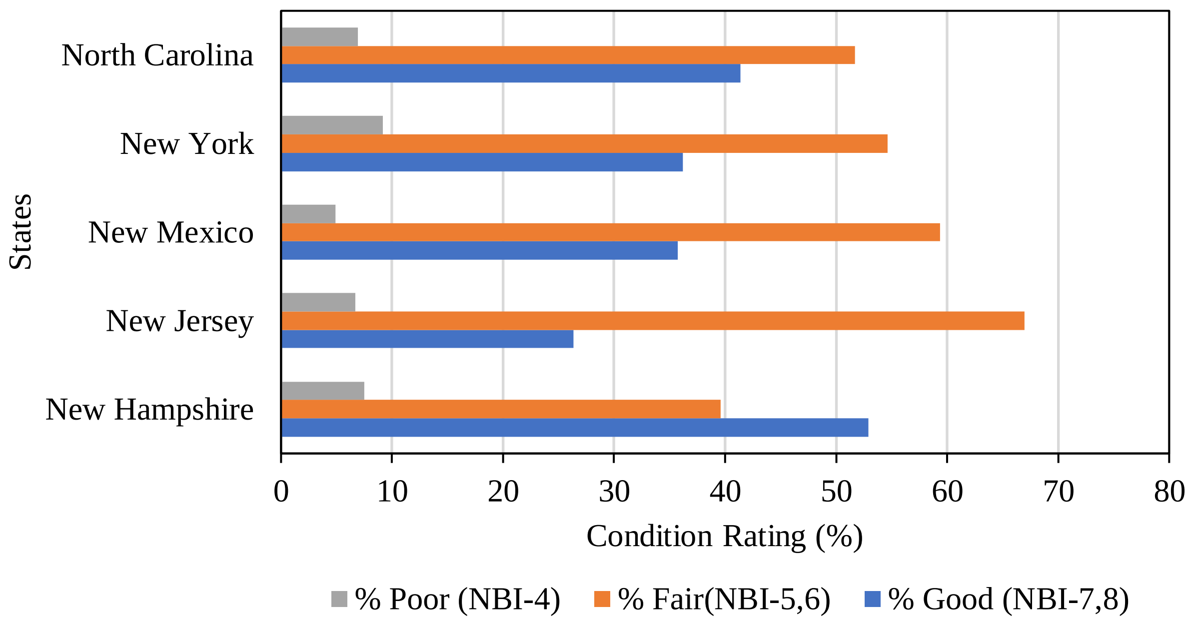

Figure A.7: Percentage of Good, Fair, and Poor Bridges in the United States

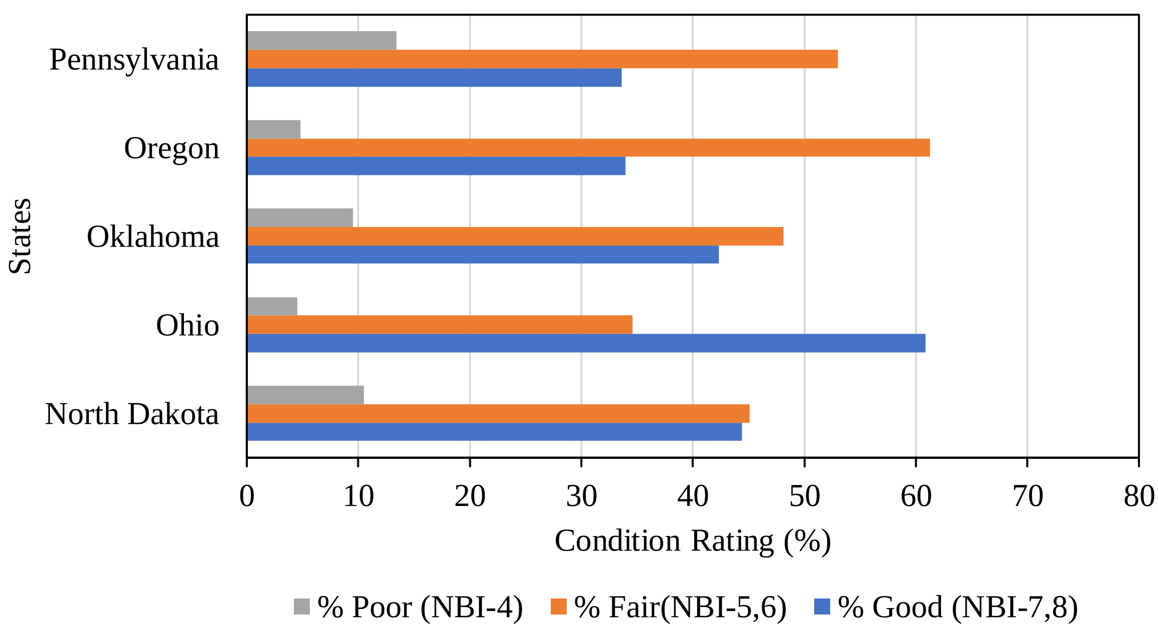

Figure A.8: Percentage of Good, Fair, and Poor Bridges in the United States

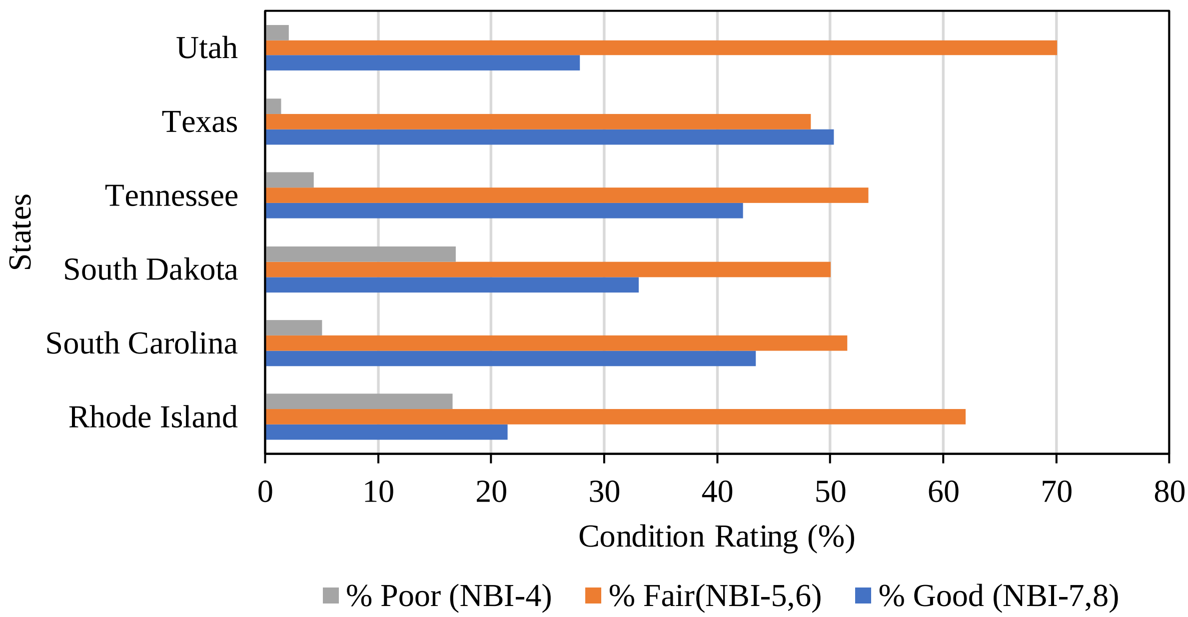

Figure A.9: Percentage of Good, Fair, and Poor Bridges in the United States

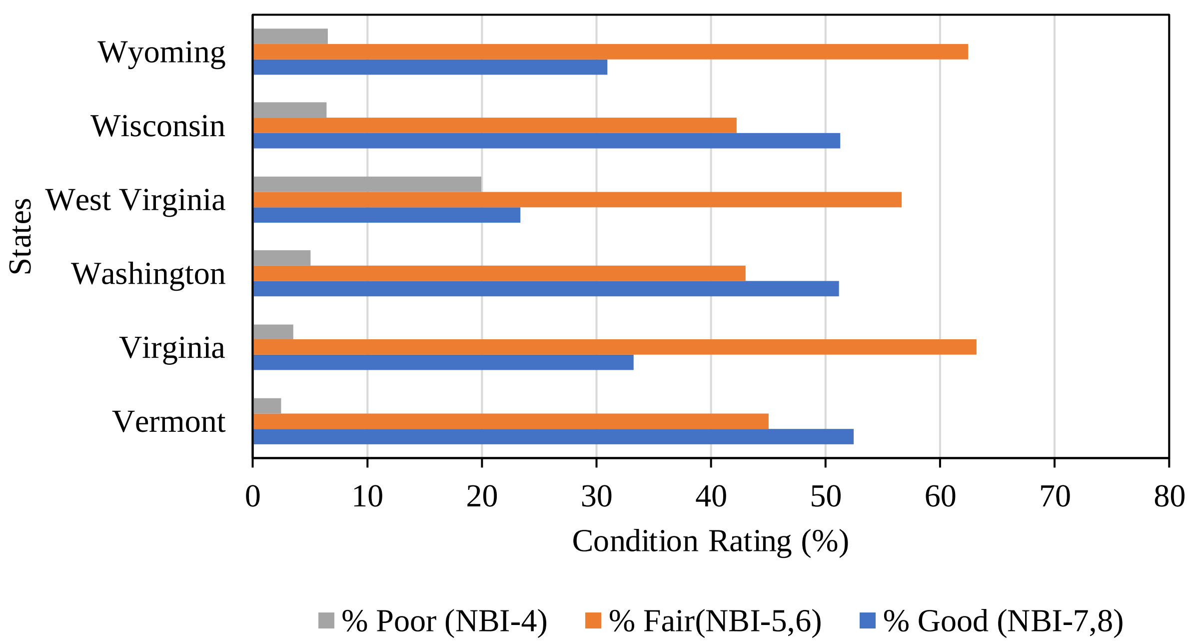

Figure A.10: Percentage of Good, Fair, and Poor Bridges in the United States