FHWA-NJ-2025-004

NJDOT Corrosion Study on Steel Structural Members
FINAL REPORT

August 2025

Submitted by

John Braley, Ph.D.
Research Professor
Rutgers University

Perumalsamy Balaguru, Ph.D.
Distinguished Professor
Rutgers University

NJDOT Research Project Manager
Giri Venkiteela, Ph.D.

In cooperation with

New Jersey
Department of Transportation
Bureau of Research, Innovation and Information Transfer
And
U. S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA NJ-2025-004		

4. Title and Subtitle **FINAL REPORT** NJDOT Corrosion Study on Steel Structural Members	**5. Report Date** August 2025
	6. Performing Organization Code Enter any/all unique numbers assigned to the performing organization, if applicable.
7. Author(s) John Braley (0000-0003-2058-3082). Perumalsamy Balaguru, Seyed Hooman Ghasemi, Saeed Nejad, Caleb Bennett, Kathleen Hawkins	**8. Performing Organization Report No.** Enter any/all unique alphanumeric report numbers assigned by the performing organization, if applicable.
9. Performing Organization Name and Address Center for Advanced Infrastructure and Technology Rutgers, the State University of New Jersey 100 Brett Rd, Piscataway, NJ	**10. Work Unit No.**
	11. Contract or Grant No. 23-60178
12. Sponsoring Agency Name and Address Federal Highway Administration (SPR) 1200 New Jersey Avenue, SE Washington, DC 20590 New Jersey Department of Transportation (SPR) 1035 Parkway Avenue, P.O. Box 600 Trenton, NJ 08625.0600	**13. Type of Report and Period Covered** Final Report, March 2023 – August 2025
	14. Sponsoring Agency Code FHWA, NJDOT

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

Please provide Transportation Research Center information and volume information (subtitles, volume #, etc.), if applicable.

16. Abstract

This report evaluates corrosion of New Jersey's steel bridges, analyzing paint inspection data and weathering steel performance. Findings show deterioration depends on exposure, with three-coat zinc-rich systems performing best. Targeted maintenance, improved detailing, and proactive interventions are recommended to extend service life, reduce costs, and ensure safety.

17. Key Words	18. Distribution Statement
Steel, corrosion, corrosion protection, steel coatings, paint, preservation, maintenance, washing, rust, bridge condition, bridge preservation, exposure, de-icing	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	182	Refers to the price of the report. Leave blank unless applicable.

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The author(s) wish to acknowledge the customer(s), *The New Jersey Department of Transportation*, as well as the research team, without whom this project would not have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Corrosion of steel bridge components poses a significant challenge for asset managers like state Departments of Transportation, where limited budgets must be balanced against the critical need for safe and reliable infrastructure. With more than half of the state's 6,800 bridges composed of steel, New Jersey faces unique challenges due to its dense population, coastal exposure, frequent winter storms, and reliance on de-icing chemicals. Effective corrosion management—through timely inspection, maintenance, and protective measures—extends service life and reduces long-term costs. Prioritizing strategies that mitigate corrosion is essential to preserving public safety while making the most efficient use of available resources.

This report provides a comprehensive analysis of steel corrosion in New Jersey, combining a review of corrosion processes and protective strategies with empirical data from bridge inspections. Statistical analysis of paint condition data is presented to evaluate the performance of various protective systems, while a survey of uncoated weathering-steel bridges offers insight into their long-term durability.

The findings highlight that deterioration rates are strongly dependent on exposure category, with three-coat zinc-rich systems outperforming alternatives, though beam ends, fascia beams, and bearings remain especially vulnerable. Weathering steel generally performs well but exhibits inferior performance in coastal environments and at overpasses subjected to heavy de-icing agent applications.

Based on these findings, the report recommends targeted maintenance strategies, including routine bridge washing and timing of spot- and over-coating based on exposure categories. It further emphasizes the importance of improved detailing to reduce moisture entrapment and refinement of inspection protocols such as adhesion testing for patina evaluation. Policy-focused recommendations include refining Qualified Products Lists (QPL) to better accommodate new coating technologies and developing predictive models based on inspection data to plan maintenance more effectively.

INTRODUCTION

New Jersey has over 6,800 bridges, of which more than 3,600 (53%) have steel superstructures. The state's coastal geography exposes many bridges to airborne chlorides from the ocean, while high traffic volumes, due to its dense population and frequent winter precipitation, necessitate the application of de-icing salts. The salts attack and permeate protective coatings and accumulate at critical details such as beam ends, bearings, and deck joints. These combined environmental and operational factors increase the susceptibility of New Jersey's steel bridges to corrosion and long-term deterioration.

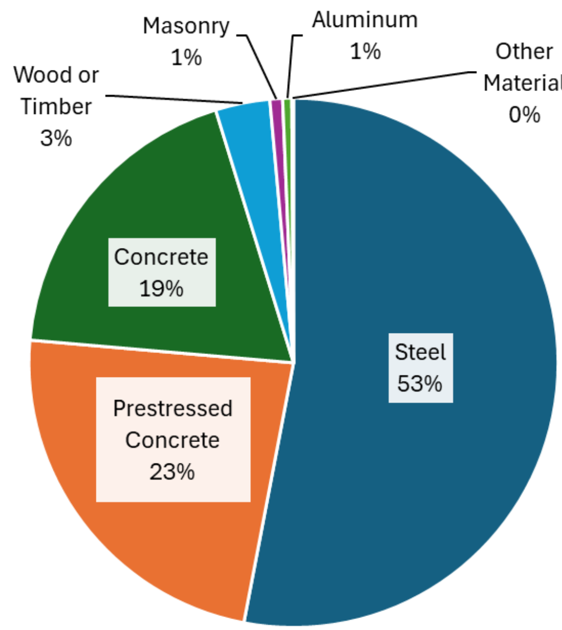

Figure 1. Distribution of Bridge Composition

The presence of corroded elements on bridges poses significant structural and safety concerns. Corrosion reduces the cross-sectional area of steel members, diminishing their load-carrying capacity and altering stress distributions, which can lead to unexpected deflections, fatigue, or even localized failures. Beyond the mechanical implications, corroded elements can affect the serviceability and longevity of a bridge, creating hazards for both traffic and maintenance personnel.

Fortunately, nearly all steel components are protected by some kind of coating and major efforts are made on maintaining the steel members of bridges. As part of this effort, condition evaluation is performed every 2 years. The current project focusses on enhancing these efforts. When steel coatings are well maintained, the service life of the parent members is virtually unlimited.

The objectives of this report are to provide the following:

- An understanding of the corrosion processes and exposures in New Jersey.
- The differences in service life durations of coatings applied to bridges subjected to typical environments in New Jersey (i.e., moderate, marine, industrial and severe).
- The performance of weathering steel bridges in NJ.
- Recommendations on maintenance activities to preserve steel members.

BACKGROUND

Nature of Corrosion

When unprotected iron is exposed to the atmosphere, corrosion initiates with the formation of iron oxides, which subsequently hydrate to produce iron hydroxides. The presence of these hydroxides is particularly detrimental, as they promote localized attack and accelerate pitting corrosion under conditions of elevated humidity.

Corrosion is often classified into one of the following categories:

- Uniform (General) Corrosion: Occurs evenly across steel surfaces due to oxygen and moisture, producing a relatively uniform layer of iron oxide. While predictable, extended exposure can result in significant material loss (Fontana, 1986).

- Pitting Corrosion: Localized cavities or pits develop, often accelerated by chloride ions, such as those from marine environments or deicing salts. Pitting can penetrate deeply while causing minimal overall metal loss, creating high risk for sudden structural failures (Jones, 1996).

- Crevice Corrosion: Develops in shielded or tight spaces (such as under washers, flanges, or fasteners) due to differential aeration that creates localized electrochemical cells (Revie & Uhlig, 2011).

- Galvanic Corrosion: Occurs when two dissimilar metals are electrically connected in the presence of an electrolyte. The more anodic metal corrodes preferentially, while the cathodic metal is protected (Uhlig & Revie, 2000).

- Stress Corrosion Cracking (SCC): Results from the combination of tensile stress and a corrosive environment, often affecting high-strength steels exposed to chlorides or industrial pollutants. SCC can produce brittle fractures with minimal visible corrosion (Jones, 1996).

- Localized Coating-Related Corrosion: Occurs when protective coatings fail due to damage, poor adhesion, or insufficient curing. Rust often initiates at scribed or scratched areas and may propagate beneath the coating (FHWA, 2020).

The progression and severity of steel corrosion are most strongly influenced by environmental factors, including moisture, chloride ions, and atmospheric pollutants. Cycles of wetting and drying, as well as temperature fluctuations, can exacerbate localized corrosion by breaking down protective oxides and introducing mechanical stress within the corrosion products. Marine environments, deicing salts, and industrial pollution further accelerate pitting and crevice corrosion, while freeze-thaw cycles can induce microcracking and delamination in protective coatings (Melchers & Jeffrey, 2010).

Steel composition, microstructure, and surface finish can also influence corrosion susceptibility. Alloyed weathering steels, such as ASTM A588, develop a stable, adherent patina that acts as a natural barrier to further oxidation. Conversely, conventional carbon steels lack this inherent protection and require coating or other mitigation strategies to prevent degradation. Mechanical properties, including tensile strength and hardness, also affect the formation of microcracks, which can serve as initiation points for localized corrosion (Revie & Uhlig, 2011).

Structural features, such as joints, welds, crevices, and edges, may trap water, debris, or salts, thereby promoting localized corrosion. Differential aeration within these areas accelerates crevice corrosion, while sharp edges and poorly coated welds are particularly vulnerable to pitting. Complex geometries can hinder surface preparation and coating application, reducing the effectiveness of protective measures (Jones, 1996).

The quality and type of corrosion protection systems implemented strongly influence corrosion progression. Coating systems serve as physical and chemical barriers to environmental attack. Proper surface preparation, application, and curing are essential to maintain adhesion and prevent corrosion beneath the coating. Additional mitigation strategies, such as galvanic isolation, cathodic protection, and the use of weathering steels, further reduce corrosion risk but require careful implementation and ongoing maintenance to remain effective (FHWA, 2020).

Exposure Categories

New Jersey classifies bridges into environmental exposure categories to guide inspection, maintenance, and protective strategies for steel structures. These categories reflect the relative corrosivity of the environment surrounding the bridge and are primarily based on factors such as proximity to the ocean, industrial activity, traffic density, and exposure to de-icing chemicals. These categories were developed by combining field observations, empirical corrosion data, and expert assessment of environmental factors affecting steel deterioration. The commonly used categories include:

- Category 1 – Rural or Industrial, Mild Exposure: Low levels of airborne salts and pollutants; bridges in less populated or lightly industrialized areas.
- Category 2 – Industrial, Severe Exposure: Higher levels of airborne pollutants from industrial emissions; bridges in heavily industrialized or urban zones.
- Category 3A – Marine, Mild Exposure: Bridges near the coastline with occasional exposure to salt spray, but moderate humidity.
- Category 3B – Marine, Severe Exposure: Coastal bridges directly exposed to salt spray, high humidity, or other aggressive marine conditions.

These categories are not stagnant and the conditions in each category can change over time. In the mid-20th century, New Jersey faced elevated SO_2 levels, particularly in urban and industrial areas, due to emissions from coal-fired power plants and industrial activities. These elevated concentrations contributed to environmental issues such as acid rain and corrosion of infrastructure.

However, since the implementation of the Clean Air Act and subsequent regulations, SO_2 emissions have decreased substantially. Nationally, the annual mean ambient concentrations of SO_2 decreased from 12.0 parts per billion (ppb) in 1980 to 0.7 ppb in 2020, marking a 94% reduction (U.S. Environmental Protection Agency [EPA], 2025).

In New Jersey, similar trends have been observed. For instance, the Newark Firehouse monitoring station, which operated from 2009 until its closure in 2022, reported significant reductions in SO_2 concentrations over its operational period (New Jersey Department of Environmental Protection [NJDEP], 2022). In 2023, all of New Jersey met the national health-based outdoor air quality standard for SO_2 for the first time since 1987 (EPA, 2023).

This improvement is attributed to various factors, including the closure of high-emission facilities and the adoption of cleaner technologies. The reduction in SO_2 concentrations has led to a decrease in acid rain and related environmental issues, thereby reducing the corrosion risk to steel infrastructure in New Jersey. It is expected that NJ bridges in exposure category 2 (industrial) will begin to perform similarly to exposure category 1 as air quality continues to improve.

Hazards of Corrosion on Structures

In structural steel systems, failure at locations of maximum bending moment is uncommon and unlikely due to the inherent reserve capacity of the material and the ability of the structure to redistribute loads to adjacent members. Furthermore, acute corrosion in these regions is less common. Rather, sudden and brittle failures are more often observed at connections, where stress concentrations are exacerbated by corrosion-induced section loss or pitting. Fatigue effects in these regions may further amplify demands, as cyclic loading interacts with corrosion damage to initiate and propagate cracks, possibly resulting in fracture.

Shear failures due to the loss of web capacity is another plausible failure mode, particularly when corrosion reduces the effective thickness of web plates. Unlike some connection failures, these shear deficiencies are generally detectable during routine inspections, allowing for maintenance interventions before catastrophic collapse occurs. Overall, the progression of corrosion significantly influences the susceptibility of steel structures to sudden failure by reducing local member strength and accelerating fatigue damage, underscoring the importance of corrosion monitoring and proactive maintenance strategies (American Institute of Steel Construction [AISC], 2018; American Society of Civil Engineers [ASCE], 2016; Khatri & Ghosh, 2020).

Corrosion Mechanism of Weathering Steel

When weathering steel is subjected to alternating wet and dry conditions, a protective patina gradually develops on the surface. This patina, consisting of a dense and adherent layer of corrosion products, significantly reduces the rate of subsequent corrosion by limiting the transport of oxygen and moisture to the underlying metal. Under optimum exposure conditions—specifically environments that promote controlled cycles of wetting and drying without prolonged moisture retention—the patina forms with enhanced uniformity and stability. This patina is effective at blocking moisture and oxygen to the underlying steel, thereby improving the long-term performance of the component and extending its service life with minimal maintenance requirements.

Field observations indicate that, in general, most weathering steel structures are performing well when situated in environments conducive to patina development (FHWA, 2022). However, performance is not universal, and deficiencies arise particularly in microclimates or exposure conditions where excess moisture is retained.

In such scenarios, the protective layer fails to achieve full impermeability, permitting continued corrosion of the substrate. Over time, this may result in thicker and less adherent corrosion scales that are prone to flaking, thereby exposing fresh steel surfaces to further degradation and undermining the self-protective mechanism upon which weathering steel relies.

To address these vulnerabilities, protective interventions have been employed in critical regions of structures (e.g., supports, bearings, and expansion joints) where the detailing of the structure or the accumulation of water compromises the patina's protective function. In these locations, over-coating systems are frequently used as a supplementary barrier, working in concert with the weathering steel's natural corrosion resistance.

Performance of Uncoated Weathering Steel (UWS) Bridges

Weathering steel (WS) forms a protective patina but can still experience localized corrosion where moisture, chlorides, or debris accumulate. Designs that trap water or debris on horizontal surfaces should be avoided for weathering steel components (FHWA, 2020). Furthermore, the design should seek to minimize direct exposure to de-icing salts (AASHTO, 2019).

The research on uncoated weathering steel (UWS) bridges identified two primary environments of concern: coastal regions and highway overpasses subjected to extensive deicing agent use (FHWA, 2022). Field observations and owner reports indicate that UWS performs reasonably well in coastal areas, although instances of reduced performance were noted within one mile of the coastline. Key contributing factors include high ambient humidity, elevated atmospheric chloride concentrations, localized humidity increases from waterway crossings, and vegetation that inhibits drying. These conditions align with previous research in similar climates, such as Florida (Granata et al., 2017). Despite occasional localized issues, UWS in coastal environments typically remains structurally adequate when applied with proper design and maintenance considerations. Overall, UWS bridges demonstrate strong performance in most environments, with age and maintenance practices as primary determinants of condition.

FHWA's 2022 study also found that bridges spanning roadways with frequent applications of deicing chemicals exhibited the most notable reductions in performance. Inferior performance was most pronounced on structures with high average daily traffic (ADT), substantial snowfall, and low vertical clearance, which collectively increase chloride exposure to the steel. Field measurements indicated section loss on the bottom flanges of I-girders that, while generally not catastrophic, approached levels that could compromise lifecycle cost benefits if not accounted for. For these environments, the research recommends incorporating a sacrificial corrosion allowance of approximately 1/8 inch on horizontal surfaces prone to water accumulation.

In response to a survey conducted as part of FHWA's 2022 study on UWS, owners reported that leaking joints are a frequent contributor to accelerated corrosion. Mitigation strategies such as improved joint design and the adoption of jointless bridges are recommended to reduce localized deterioration. Regular bridge washing also emerged as a significant factor influencing performance on highway overpasses. Statistical analyses demonstrated that maintenance practices, particularly selective washing, play a substantial role in limiting corrosion progression. (FHWA, 2022)

Protective Measures

Steel is widely used in New Jersey's structures. However, it almost always has a protective coating. The most popular and economical coating system uses a zinc rich primer, often followed by one or more topcoats. The inorganic zinc primer (IZR) is preferable to organic. In some cases, only a single zinc coat is applied (galvanized). This layer will produce a corrosion resistant oxide layer if sufficient thickness is applied. However, it may be vulnerable to chemical attacks, especially in areas with prolonged moisture and debris accumulation.

There is very little information on the performance of the zinc primer coat. For instance, little is known about how much of the zinc is consumed; where the oxidized zinc products are transported, and if areas with damage to the coating can cause pitting corrosion.

Sacrificial Protection

The application of zinc-based coatings provides a dual protective mechanism. Zinc serves as a sacrificial anode, preferentially corroding to shield the underlying steel substrate, while simultaneously contributing to the development of a more impermeable barrier. The corrosion of zinc typically stabilizes upon the formation of zinc oxide, which under many service conditions further reacts with atmospheric constituents (e.g., carbonates or sulfates) to form dense, adherent corrosion products. These secondary phases enhance the impermeability of the coating, thereby improving long-term durability and extending the protective function of the system.

Silicate Inorganic Zinc (SIOZ) Systems

Francis and Szokolik (2013) conducted a comprehensive review of the performance of coatings on sixteen bridges located in environments near Melbourne, Australia. The study focused on structures coated with water-based silicate inorganic zinc (SIOZ) systems, with bridge ages ranging from 3 to 37 years. The dry film thickness (DFT) of the SIOZ coatings varied considerably, between 35 and 375 microns (1 to 15 mils), reflecting differences in application and service history (Francis & Szokolik, 2000).

The survey revealed that most of the bridges utilizing SIOZ coatings were highway girder structures, typically functioning as overpasses or water crossings. Most of these coatings were applied during the early to mid-1990s, meaning that, at the time of evaluation, they had been in service for between 20 and 30 years (Francis & Szokolik, 2013). All of the bridges considered were situated in either mixed humid or mixed marine environments, conditions that are typically challenging for the long-term performance of protective coatings (Austroads, 2011). Despite these exposure conditions, the SIOZ coatings were generally performing well. Only one superstructure was rated as being in "fair" condition, while all others were evaluated as "satisfactory" or better.

A more direct indication of SIOZ performance was provided using the National Bridge Element (NBE) condition rating system, specifically Element 515, which is designated for steel protective coatings. Condition states within this framework range from 1 (good) to 4 (severe) and are assigned based on observed coating defects such as chalking, peeling, bubbling, cracking, oxide film degradation, color and texture loss, overall adherence, and evidence of damage. By applying this system, a weighted average condition state was calculated for each bridge. The results showed that all SIOZ coatings fell between “good” and “fair” weighted condition states at their respective service ages (Francis & Szokolik, 2013).

When compared with conventional systems such as red lead and micaceous iron oxide/aluminum pigment coatings, the SIOZ systems demonstrated significantly superior durability. In many cases, service lives of the SIOZ coatings were three or more times longer than those of the alternatives, even when applied at lower film thicknesses (Francis & Szokolik, 2000; Francis & Szokolik, 2013). Maintenance was also found to be less intensive, as corrosion associated with SIOZ systems was generally superficial and limited to surface rusting, whereas alternative systems exhibited deeper and more extensive substrate attack. Together, these findings suggest that SIOZ coatings can have long-term protective advantages in bridge applications, particularly in aggressive atmospheric environments where extended durability and simplified maintenance are critical to lifecycle performance (AISC, 2023).

Single-Coat System

Following encouraging results from a 2002 study, the Federal Highway Administration (FHWA) undertook an extensive evaluation of one-coat systems at the Turner-Fairbank Highway Research Center (TFHRC) to assess their suitability as alternatives to traditional multi-coat systems for steel bridge protection. The study included eight commercially available one-coat systems selected based on their prior performance in FHWA research, inclusion on the Northeast Protective Coatings Qualified Products List, and review of commercially marketed products. For comparative purposes, a conventional three-coat system and a two-coat system, both employing zinc-rich primers, were included as control benchmarks (FHWA, 2011a; FHWA, 2011b).

Results indicated that three-coat systems consistently exhibited high durability across all testing environments, reinforcing their long-established reliability. Among the one-coat systems, several formulations—particularly high-ratio calcium sulfonate alkyd coatings—demonstrated performance comparable to three-coat systems under both laboratory and field conditions. However, the study also highlighted that many commercially available one-coat products exhibited inconsistent performance, with premature blistering or adhesion loss observed in some formulations, emphasizing the need for careful selection and quality control during application.

Application considerations were also critical; for example, adequate curing time was essential to achieving the expected durability, with insufficient curing leading to reduced early performance in the single-coat calcium sulfonate alkyd coatings. Overall, the study demonstrated that, with proper formulation, application, and quality control, one-coat systems can provide a viable alternative to multi-coat systems, offering comparable protection for steel bridge structures while potentially reducing labor and material costs.

2-Coat System

In a 2002 study, the Federal Highway Administration (FHWA) evaluated the performance of two-coat systems as potential alternatives to traditional three-coat systems for steel bridge protection. The study found that two-coat systems, consisting of a zinc-rich primer and an organic topcoat, demonstrated performance comparable to three-coat systems in both laboratory and outdoor exposure tests. These two-coat systems exhibited minimal rust creepage at scribed areas and maintained adhesion strength, suggesting their viability as cost-effective alternatives without significant sacrifice in corrosion resistance (FHWA, 2002).

However, subsequent evaluations in 2011 and 2020 presented a more nuanced perspective. The 2011 study, part of the FHWA 100-Year Coating Study, included four two-coat systems among the eight evaluated. While some two-coat systems performed well, others exhibited reduced adhesion strength and increased susceptibility to corrosion, particularly under aggressive environmental conditions. (FHWA, 2011a; FHWA, 2011b)

The 2020 study further investigated the performance of two-coat systems applied to steel substrates with varying levels of chloride contamination. The results indicated that while some two-coat systems maintained adhesion strength under low chloride levels, they experienced significant degradation at higher contamination levels. This underscores the importance of surface preparation and environmental considerations in the selection and application of coating systems (FHWA, 2020).

FHWA's evaluations over the years suggest that while two-coat systems can offer a cost-effective alternative to traditional three-coat systems, their performance is highly dependent on formulation, application quality, and environmental conditions. Careful selection and proper application are crucial to ensure their effectiveness in providing long-term corrosion protection for steel bridges (FHWA, 2002; FHWA, 2011a; FHWA, 2011b; FHWA, 2020).

3-Coat System

The industry favored 3-coat system contains the self-sacrificing zinc-rich primer, followed by an intermediate coat, often epoxy, to stop moisture ingress, and finally an organic topcoat that is resistant to chemicals and UV light.

FHWA’s 2020 study on coatings found that three-coat systems exhibited minimal rust creepage, even under aggressive chloride exposure. Rust development was negligible in all natural weathering and salt spray conditions, demonstrating the robust barrier properties of the multi-layer system. The 3-coat systems maintained excellent adhesion throughout the duration of testing with no evidence of delamination, blistering, or significant chalking. In addition, the combination of zinc-rich primer and intermediate epoxy provided strong substrate bonding and resistance to mechanical damage, including at edges and corners. Performance was consistent across diverse exposure conditions, including marine, humid, and industrial environments and even when the substrate was moderately contaminated. (FHWA, 2020).

Organic vs. Inorganic Topcoat

Organic coatings are comprised of carbon-based polymeric chains, which may be derived from either natural sources (vegetable or animal materials) or synthetic precursors. A notable advantage of organic coatings is their reduced environmental impact. Many modern formulations are water-based and exhibit low levels of volatile organic compounds (VOCs), contributing to safer indoor air quality and decreased ecological burden.

Unlike organic coatings, which are based on carbon-containing polymers, inorganic coatings rely on mineral constituents such as silica, alumina, and titanium dioxide. These minerals are frequently combined with additional additives to enhance adhesion, flexibility, and other performance characteristics.

Organic coatings are easier to apply and less sensitive to environmental conditions during application. In contrast, inorganic coatings may require more precise application techniques and curing conditions. However, inorganic coatings tend to have longer service lives due to their robust protective mechanisms. (CoatingsDirectory, 2024)

Systems Approved for Use in New Jersey

NJDOT's QPL has only one inorganic-zinc 3-coat system, and three qualified organic zinc systems (Table 8). The New Jersey Turnpike lists several products for each of the 3 coats (Table 9). These products are summarized in the appendix.

Coatings Applied to Weathering Steel

FHWA's (2020) study evaluated coating performance on weathering steel (A588) panels alongside conventional carbon steel (A36) panels to determine how substrate composition affects corrosion protection. The weathering steel panels were exposed under the same accelerated laboratory tests and outdoor exposure conditions as the carbon steel panels, including salt spray, natural weathering, and cyclic ASTM D5894-05 tests.

Their findings showed that weathering steel enhances the performance of coating systems by reducing rust creepage and improving adhesion, particularly for two-coat systems. While three-coat systems remain the most reliable option for all environments, weathering steel may allow for reduced coating complexity in environments with limited chloride exposure, supporting cost-effective maintenance strategies (FHWA, 2020).

Impact of Contaminants on Coating Performance

FHWA's (2020) study found that the presence of chloride contamination significantly influenced the performance of the coating systems. Panels subjected to higher chloride levels exhibited increased rust creepage and adhesion loss, particularly in two- and one-coat systems. For instance, under saltwater spray conditions, the two-coat system developed significant rust creepage, with net creepage measurements between 7.4 and 8.5 mm after 5,040 hours of exposure. The one-coat system also showed considerable rust creepage, with measurements ranging from 3.0 to 9.6 mm under similar conditions. In contrast, the three-coat systems demonstrated excellent resistance to rust creepage development regardless of chloride contamination levels. (FHWA, 2020)

Maintenance: Washing, Spot-Coating, Over-Coating, Re-Coating

Routine inspections are essential to detect early signs of corrosion, coating degradation, or mechanical damage. Visual inspections should be complemented with quantitative testing where possible, such as chloride measurements or adhesion testing for protective coatings. Data-driven inspection schedules allow targeted maintenance and help prioritize critical components for intervention (American Association of State Highway and Transportation Officials [AASHTO], 2019; Federal Highway Administration [FHWA], 2020). Coatings or patina should be inspected periodically; treating areas where the protective layer is compromised with spot-coating if needed (FHWA, 2020).

Bridge washing is one of the most effective preventive measures to remove accumulated salts, dirt, and pollutants that accelerate corrosion. Industry guidance suggests that bridges should be washed at least once per year in areas exposed to deicing salts, or more frequently in high-salt, coastal, or marine environments (FHWA, 2020). Bridges with weathering steel also benefit from annual cleaning to prevent chloride accumulation in crevices.

High-pressure water washing or low-abrasive mechanical cleaning is preferred, ensuring that the steel surfaces are not damaged. Detergents may be used sparingly to remove oily deposits (Steel Structures Painting Council [SSPC], 2017).

Spot-coating involves repairing damaged or worn coating areas before corrosion progresses. Bridges should be inspected for coating defects such as peeling, blistering, or chalking (AASHTO, 2019). Rust or loose coating should be removed with abrasive cleaning. A primer and topcoat may be applied if compatible with the existing system (SSPC, 2017). Spot-coating should be performed promptly after defects are detected to prevent accelerated deterioration.

When coatings reach the end of their service life, full-system re-coating may be required. Re-coating intervals depend on coating type, environmental exposure, and observed condition (typically 15–25 years for high-performance systems under moderate exposure, shorter in harsh environments) (FHWA, 2020). Again, proper surface preparation is important. Surfaces to be painted should be thoroughly removed of rust, scale, and failed coating to ensure adhesion of the new system. Multi-coat systems (primer, intermediate, and topcoat) perform best for long-term protection, particularly in industrial or marine environments (SSPC, 2017).

PERFORMANCE OF STEEL COATINGS IN NEW JERSEY

The New Jersey Department of Transportation provided data compiled from their biannual paint inspections. While this inspection is performed on any structure requiring paint, this study focused only on those structures with steel structural members. This reduced dataset contains the codified results from 1,308 bridges inspected between 2012 and 2022. Each record in the dataset contains comprehensive information regarding the paint condition of beam elements.

The type of elements rated include Fascia Beam, Fascia Bottom Flange, Interior Beam, Interior Bottom Flange, Beam Ends, Connections, Bracings, and Bearings.

The paint condition for these elements is rated on a scale from 0 (poor) to 10 (excellent) based on visual inspection. The rating corresponds to the average area experiencing corrosion. The description for each condition state is provided in Table 1 and taken from the 2003 "Recording and Coding Guide for the Structure Inventory and Appraisal of New Jersey Bridges".

Table 1 – Coding System for Paint Condition Ratings

	CODE DESCRIPTION		CODE DESCRIPTION FOR WS
0	100% Rust	**0**	100% Failed Oxide Protective Layer
1	50-100% Rust	**1**	50-100% Failed Oxide Protective Layer
2	33-50% Rust	**2**	33-50% Failed Oxide Protective Layer
3	16-33% Rust	**3**	16-33% Failed Oxide Protective Layer
4	10-16% Rust	**4**	10-16% Failed Oxide Protective Layer
5	3-10% Rust	**5**	3-10% Failed Oxide Protective Layer
6	1-3% Rust	**6**	1-3% Failed Oxide Protective Layer
7	0.3-1% Rust	**7**	0.3-1% Failed Oxide Protective Layer
8	0.1-0.3% Rust	**8**	0.1-0.3% Failed Oxide Protective Layer
9	.03-0.1% Rust	**9**	.03-0.1% Failed Oxide Protective Layer
10	0-.03% Rust	**10**	0-.03% Failed Oxide Protective Layer

The ages of buildings and coatings in this study range from new (0) to 100 years old. The histograms below represent the entries in the dataset, not the actual bridge population, since there are multiple inspection entries per bridge.

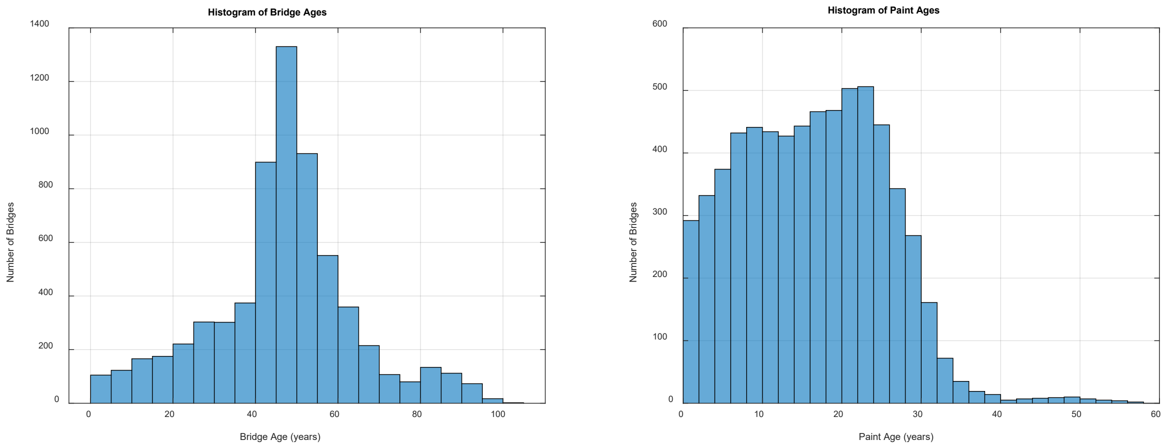

Figure 2. Bridge Age (left) and Paint Age (right) Histograms

Bridges are classified into four environmental exposure conditions: 01 (Rural or Industrial, Mild Exposure), 02 (Industrial, Severe Exposure), 3A (Marine, Mild Exposure), and 3B (Marine, Severe Exposure). The vast majority of New Jersey's bridges reside in category 01 (Figure 3).

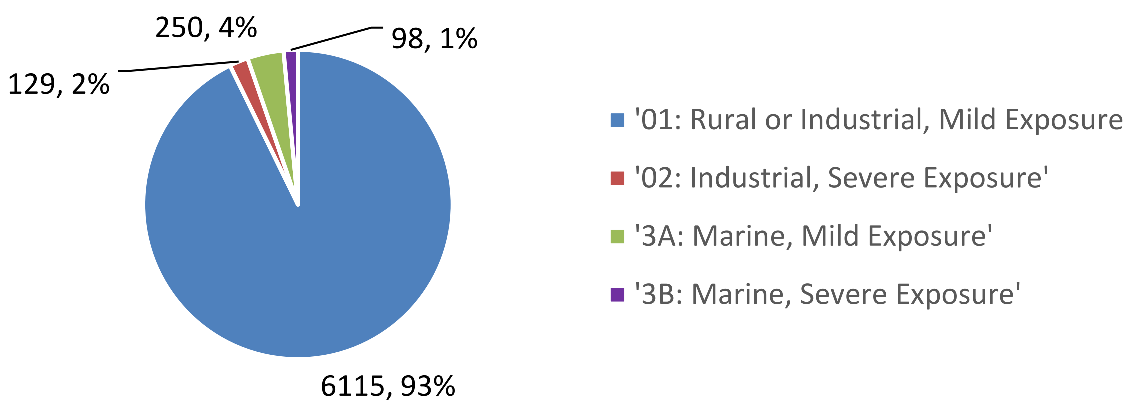

Figure 3. Distribution of Bridges in Various Exposure Environments

Analysis of Paint Inspection Data

The data was plotted with the element paint condition rating on the vertical axis, and the age of the paint on the horizontal axis. A trendline was fit to the data to establish a deterioration curve for each element and exposure category. The trendline was only fit to the data from bridges with paint ages less than 30 years. This is because there are few bridges with paint older than 30 years and we did not want the variability of these data points to influence our estimates on the rate of deterioration. Furthermore, paint that is older than 30 years is not likely to have a similar composition to any paints being applied today, therefore, any deterioration rates experienced by these older paints would not be representative of current coating products.

Quadratic functions were fit to the elements in exposure category 1 (Rural or Industrial, Mild Exposure). The figure below shows the paint ratings and paint age for fascia beams in category 1. The plot also includes the fit model with its coefficients.

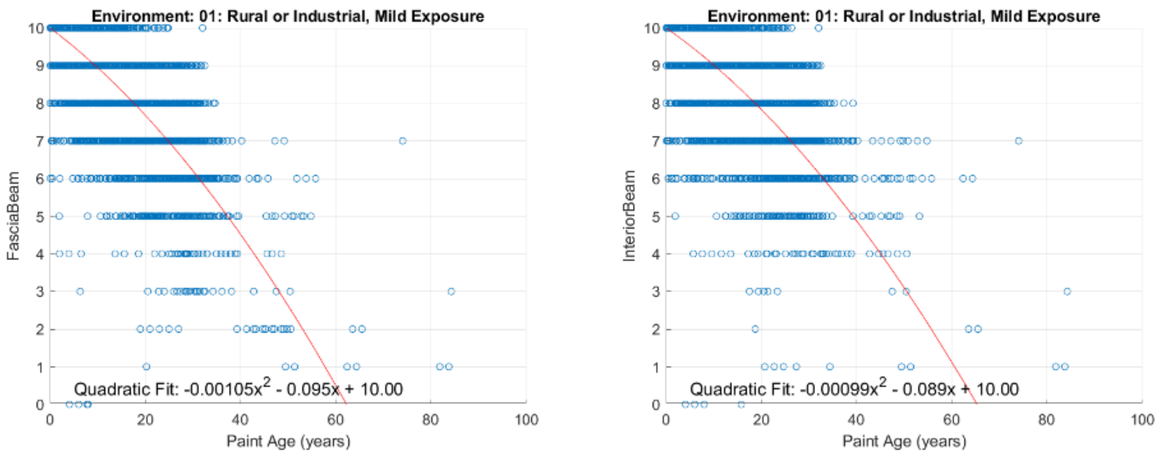

Figure 4. Quadratic Functions Fit to Paint Condition Data

While quadratic functions well fit the data from category 1, for other environments (2 or 3), the number of bridges in the dataset were too few to reliably fit a quadratic function. Instead, a linear function fitted with a fixed y-intercept of 10. This is because at 0 years (new), the paint must be at condition level 10. Examples of this function fit to data are provided in Figure 5. The slopes for the different elements and different environmental exposures are compared in Table 2. The slope values represent the amount the condition rating is expected to change each year (i.e., a slope of -0.5 indicates a drop from a condition state of 10 to 5 in 10 years). Slopes with greater magnitudes indicate a faster rate of deterioration.

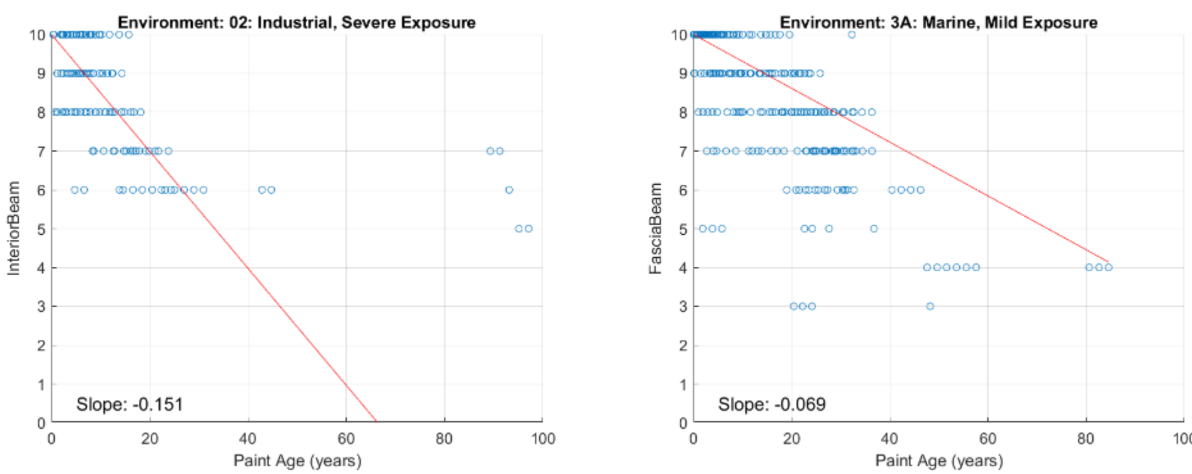

Figure 5. Linear Function Fit to Paint Condition Data

The slopes (or derioration rates) provided in Table 2 are compared in Figure 6.

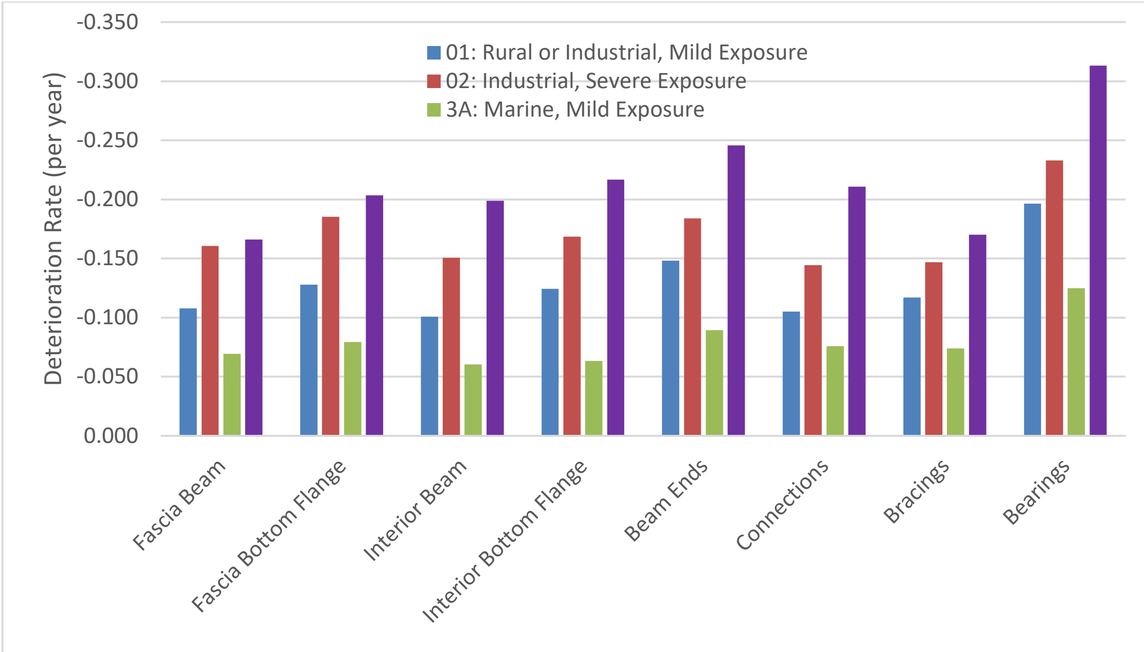

Figure 6. Comparison of Deterioration Rates

Table 2 – Slope of Linear Fit

	01: Rural or Industrial, Mild Exposure	02: Industrial, Severe Exposure	3A: Marine, Mild Exposure	3B: Marine, Severe Exposure
Fascia Beam	-0.108	-0.161	-0.069	-0.166
Fascia Bottom Flange	-0.128	-0.185	-0.079	-0.203
Interior Beam	-0.101	-0.151	-0.060	-0.199
Interior Bottom Flange	-0.124	-0.168	-0.063	-0.217
Beam Ends	-0.148	-0.184	-0.089	-0.246
Connections	-0.105	-0.144	-0.076	-0.211
Bracings	-0.117	-0.147	-0.074	-0.170
Bearings	-0.197	-0.233	-0.125	-0.313

The change in paint condition ratings could also be computed for individual bridges, since the dataset included results from different inspections of the same structure. The same process of fitting a straight line through the ratings with a y-intercept of 10 was performed for each bridge. Figure 7 plots the deterioration rates for the various years that the paint was applied.

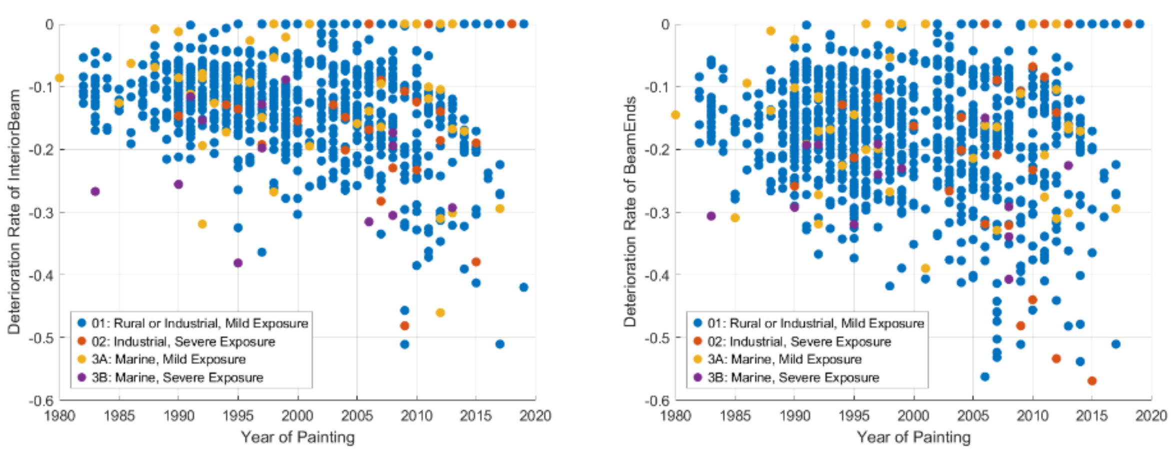

Figure 7. Deterioration Rates of Interior Beams and Beam Ends in Different Environments

From Figure 7, no obvious difference can be observed between the deterioration rates observed in different environments. The same data was examined for differences between different routes (Figure 8).

Again, no obvious difference in deterioration rates is observed between different routes, although it may be observed that certain routes experienced more painting in specific time periods. Furthermore, there appears to be an increase in the spread of the deterioration rate as the year of painting becomes more recent, suggesting that newer paint has greater performance variability, but this may also be attributed to the reduced sample size (number of inspections) for newer paint systems.

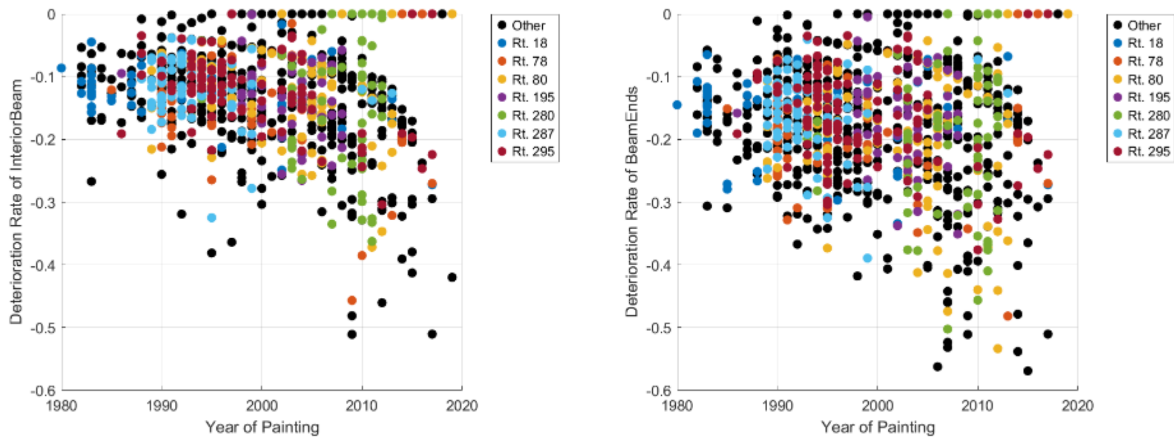

Figure 8. Deterioration Rates of Interior Beams and Beam Ends on Different Routes

The deterioration rate for each element on each bridge was averaged for a given route. These average deterioration rates are compared in the following plots. Only those routes with at least 10 bridges were included in the plot.

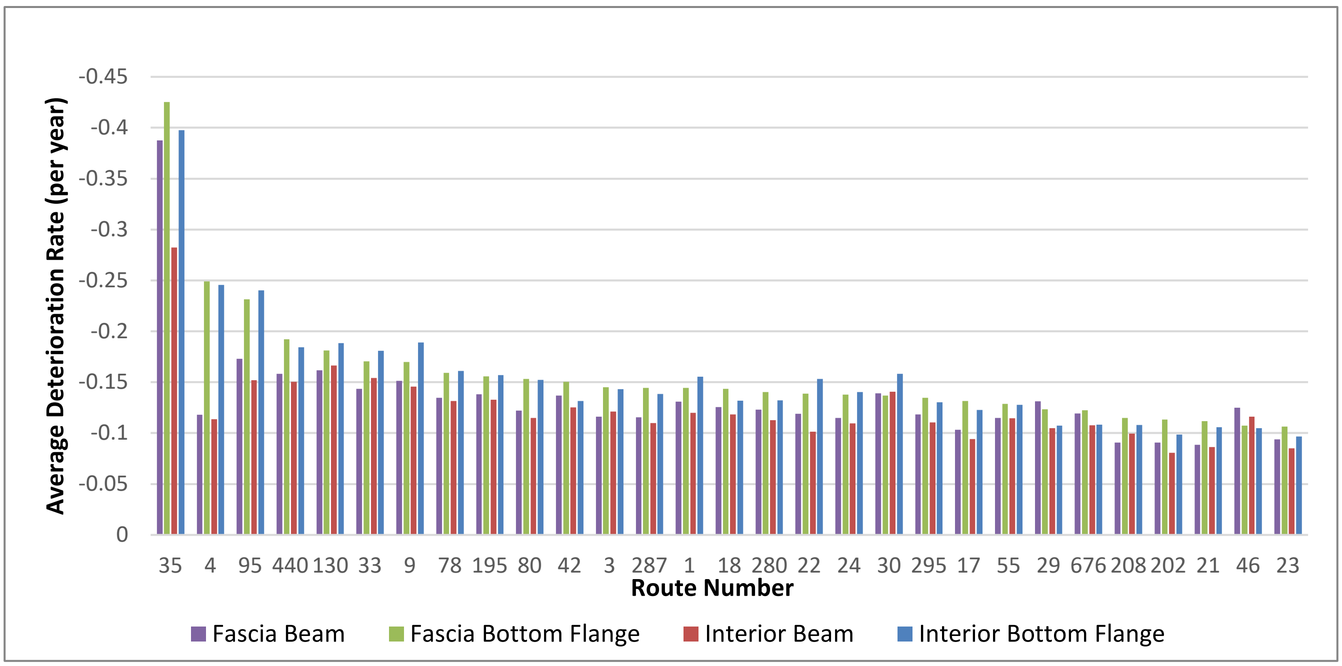

Figure 9. Deterioration Rate for Different Routes

The deterioration rates provided in Figure 9 show that there is some difference in paint performance for different routes. NJ Route 35 consistently performs worst, with the highest rates of deterioration, followed by NJ Route 4 and Route I-95. The percentage of bridges within each route that are in different environments is summarized in Figure 10. From this figure, it is clear that NJ Route 35 has a considerable portion of its bridges in marine exposures, while other routes are predominantly in exposure category: 01.

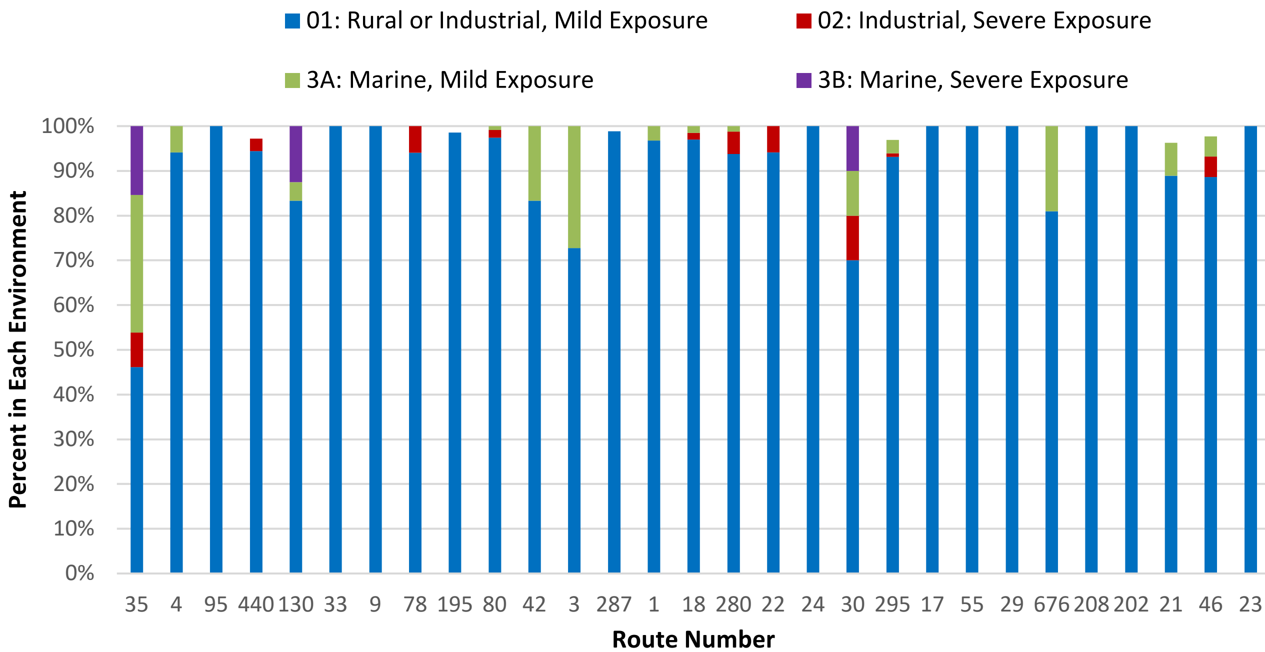

Figure 10. Distribution of Environmental Categories within Routes

The paint inspection data also included two columns of remarks. These remarks were mined to find mentions of the paint system, specifically IEU or OEU, which stand for Inorganic Zinc, Epoxy, Urethane, and Organic Zinc, Epoxy, Urethane, respectively. Other paint systems were also identified, but this only occurred for a handful of entries and thus were too few to perform any statistical inference.

A comparison of these populations is presented in Figure 11, which indicates minimal differences in paint condition distributions across paint systems. A Weibull distribution was fit to each population and included in the distribution plots for easier visual comparison. Additional comparisons for other elements, provided in the appendix, show even less variation among distributions.

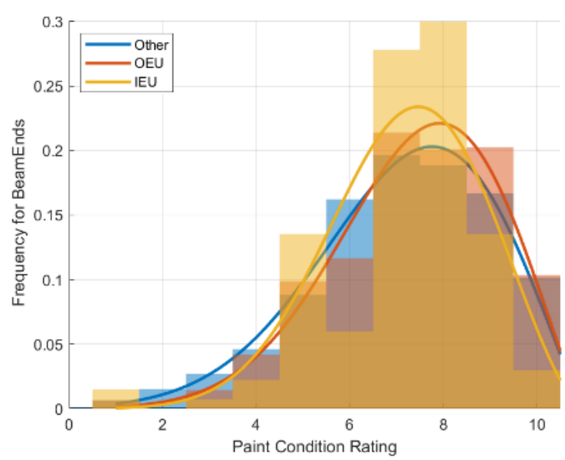

Figure 11. Paint Condition Distribution According to Paint Type for Beam Ends

The plot of paint condition versus age is compared for different paint systems in Figure 12.

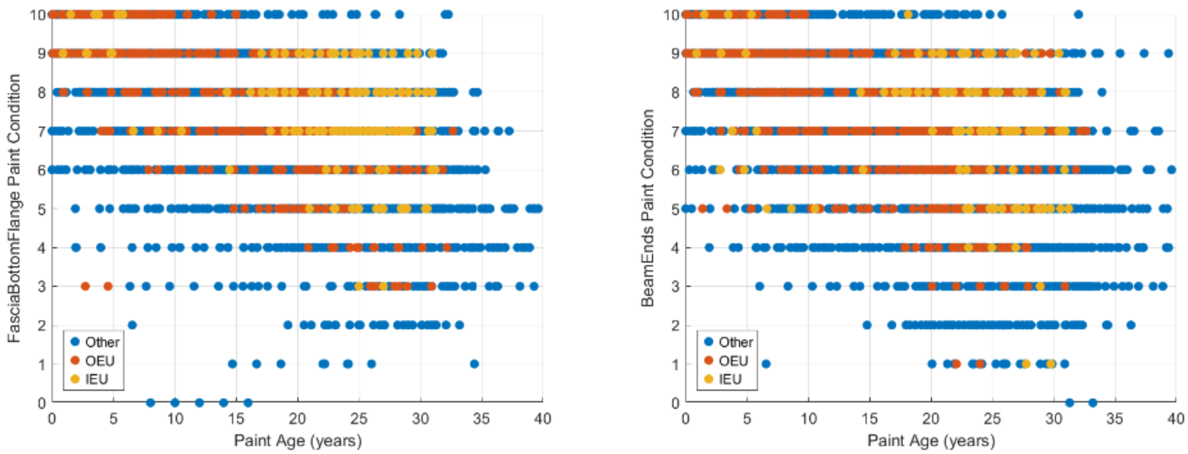

Figure 12. Paint Condition for Fascia Bot. Fl. and Beams Ends, Categorized by Paint System

Regression analysis was performed on the data shown in Figure 12 to obtain the best fit for a straight line with a y-intercept of 10. The resulting deterioration rates are compared in Figure 13. There is not a large difference between deterioration rates for systems with inorganic vs organic zinc primers. The largest difference is observed for the fascia bottom flange and the beam ends. Based on these deterioration rates, the IEU systems achieved, at most, 5 additional years of service life, while OEU systems achieved 2 additional years of service life (compared to “other”). These small differences do not yet warrant consideration of paint system when predicting remaining service life.

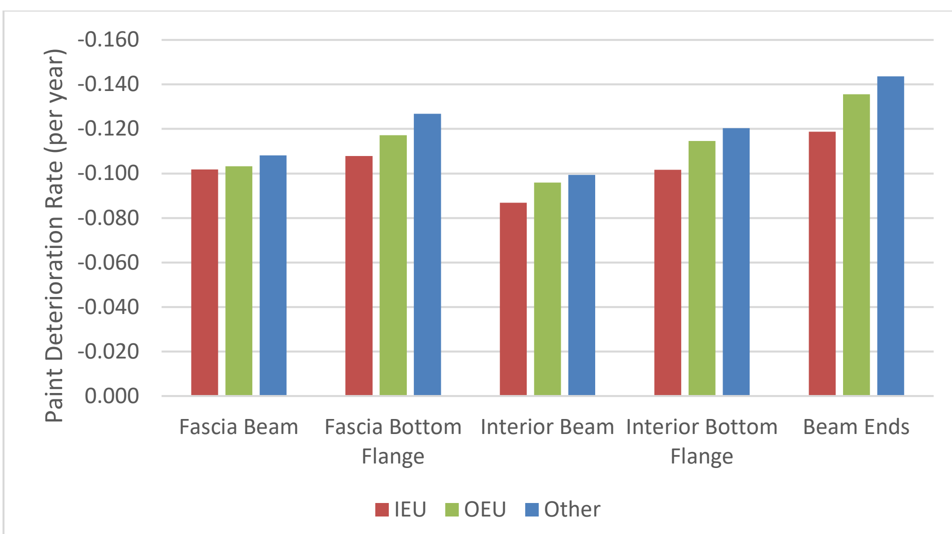

Figure 13. Comparison of Deterioration Rates for Different Paint Systems

The statistical analysis presented in this section showed that while some routes and some paint systems may experience poor paint performance, the exposure category has a stronger influence on paint deterioration. Further, the studies showed that the element type and location have a large influence on paint deterioration, with beam ends, and bearings performing considerably worse than the rest of the beams.

However, the paint condition rating does not reflect the overall condition of the parent element. If the paint can be maintained in good condition, the parent element should remain in good condition (condition state 1). The condition states are defined by *AASHTO Bridge Element Inspection Guide Manual* (2019). The description of the states is provided below for convenient reference.

Table 3 – Condition State Descriptions for Beams and Stringers

Condition State 1 **Good**	No observable defects.
Condition State 2 **Fair**	Freckled rust. Corrosion of the steel has initiated. Minor cracking that has self-arrested or been repaired.
Condition State 3 **Poor**	Section loss is evident, or pack rust is present but does not warrant structural review. Identified cracks exist that are not arrested but do not warrant structural review.
Condition State 4 **Severe**	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.

The average paint condition for the interior and fascia beams, including the bottom flanges, was compared to the condition score for the parent element (steel stringer or steel open girder/beam). The condition score was computed by taking the weighted average of the condition states according to percent area in each state. The resulting plot, provided in Figure 14, shows that while paint condition remains a 5 or better, the majority of the steel elements remain in condition state 1. This reflects the extended service life provided by the coating.

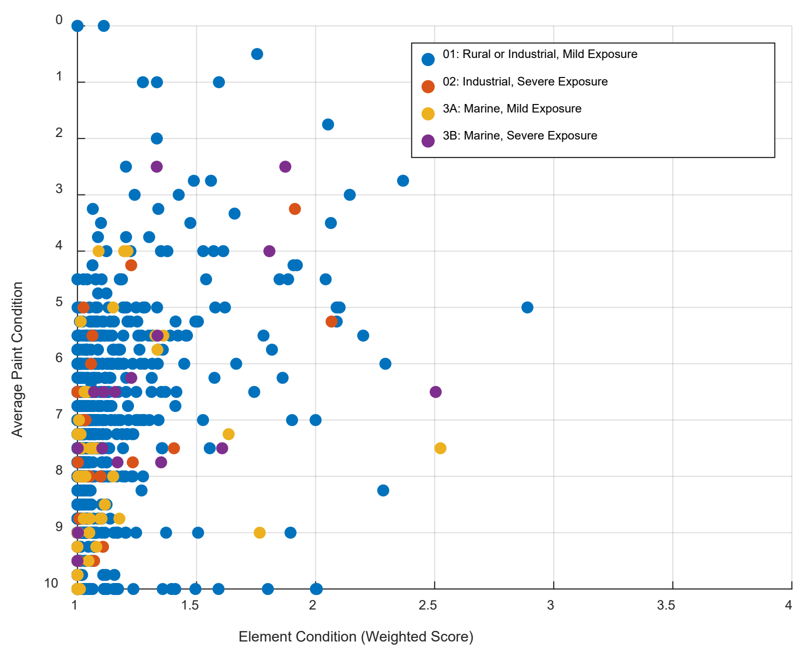

Figure 14. Comparison of Paint Condition and Element Condition

Coating Life Expectancy

The previous section compared the rates of deterioration experienced by bridges across the state. The analysis results showed that the paint condition ratings for beams on most bridges (Exposure Category 1) decreases by 1 every 10 years (-0.10 slope). However, this rate of deterioration increases for different exposure categories. Furthermore, exposure category 3A exhibited the slowest deterioration. Since this is likely due to the small sample size available for this category, it is more conservative to assume it's deterioration rate will be as predicted for exposure category 1.

The final deterioration rates are provided in Table 4. The units for these rates are condition rating per year. The rates for beams in the table were taken as the lesser (more negative) of the values for beams and beam flanges for more conservative service life predictions.

Table 4 – Deterioration Rates

	EXPOSURE CATEGORY: 01 & 3A	EXPOSURE CATEGORY: 02	EXPOSURE CATEGORY: 3B
Fascia Beam	-0.13	-0.18	-0.21
Interior Beam	-0.12	-0.17	-0.22
Beam Ends	-0.15	-0.18	-0.25
Bearings, etc.	-0.2	-0.23	-0.32

Since the previously presented slopes represent rates of deterioration, we may use them to predict the number of years until a coating deteriorates to a specified level. For example, the predicted number of years for a condition rating of 10 to drop to a rating of 7 can be computed by simply dividing the change in rating (3) by the slope. This computation was performed for the elements and environmental categories in Table 4 and is summarized in Figure 15.

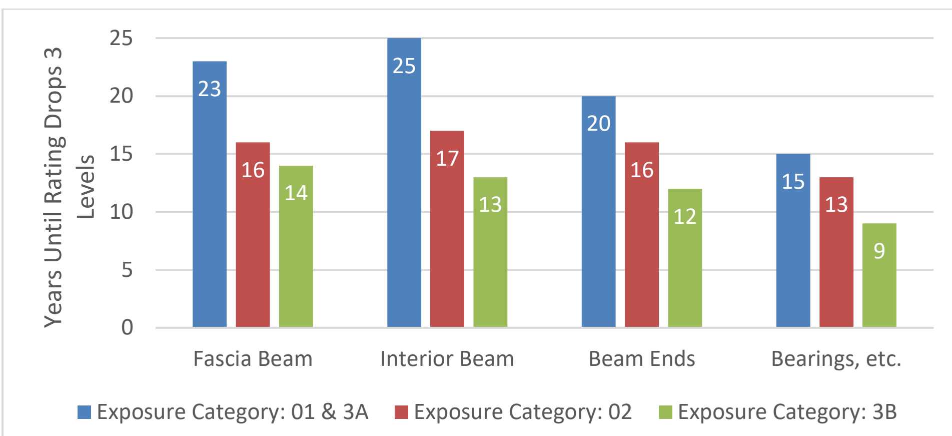

Figure 15. Years for Paint Condition Rating to Decrease 3 Levels

Given that bridge elements are expected to perform for 50 or more years, paint must be kept in adequate condition to prevent any significant corrosion of the underlying steel. Therefore, when 1% of the element is experiencing corrosion, intervention should be undertaken to repair the coating and stop corrosion. Since a condition state of 7 corresponds to 1% corrosion, the coating has begun to fail at state 7 but is performing well when the paint condition state is 8 or greater. With this interpretation, the years presented in Figure 15 also represent time until intervention is required.

PERFORMANCE OF WEATHERING STEEL BRIDGES IN NEW JERSEY

Analysis of Patina Inspection Data

Analysis was also conducted on the coating inspection data for bridges with weathering steel beams. 94% of the weathering steel bridges in our dataset were in Exposure Category 01, 3% were in category 02, and 3% in category 3A. Because so few structures are in category 2 or 3, no meaningful results could be obtained by performing regression analysis on these categories separately. Instead, the population (all exposure categories) was analyzed together.

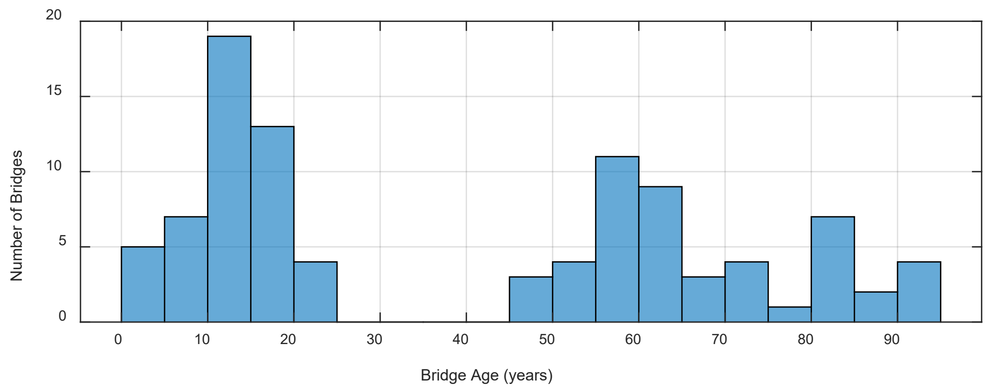

Figure 16. Histogram of Ages of Weathering Steel Bridges

The age of bridges with weathering steel components is a bimodal distribution with a large portion of weathering steel structures less than 30 years old. The calculated rate of deterioration for weathering steel bridges depends on if the older structures are included in the regression analysis. In Figure 17, we see that the older bridges are performing well, and as a result, the estimated deterioration rate (slope) is less when these structures are included, but the estimated deterioration rate triples when only recently constructed bridges are considered in the regression analysis.

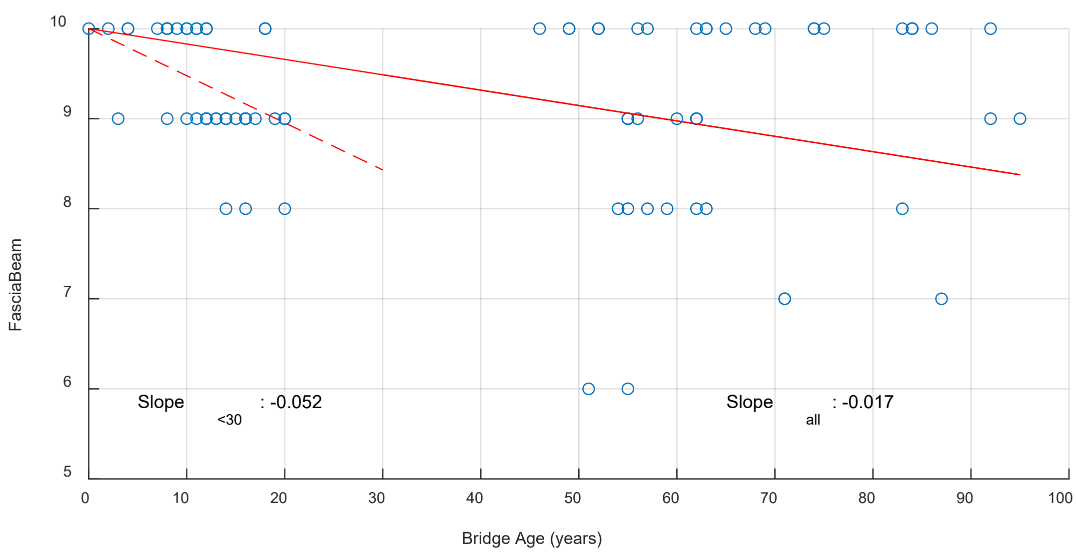

Figure 17. Regression Analysis Comparison of Coating Condition on WS Bridges

In the remaining analyses, the deterioration rates were determined when considering all WS bridges, not just those newly constructed. This is because in proper conditions, weathering-steel produces a stable patina that does not require maintenance. However, in many cases, end-coating or spot-coating may be necessary when consistent moisture enables more aggressive corrosion.

Table 5 – Weathering Steel Deterioration Rates

	ALL	< 30 YRS OLD
Fascia Beam	-0.017	-0.052
Fascia Bottom Flange	-0.021	-0.056
Interior Beam	-0.016	-0.048
Interior Bottom Flange	-0.018	-0.069

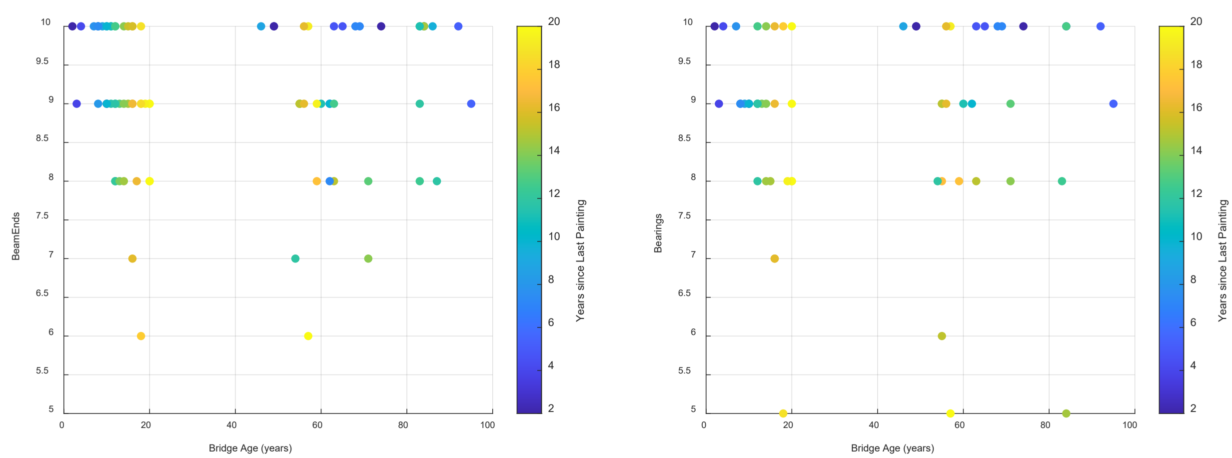

Figure 18. Condition versus Bridge Age of Beam Ends and Bearings on WS Bridges

The plots in Figure 18 show the deterioration of the beam ends and bearings on weathering steel bridges, they also show little correlation between bridge age and coating condition.

However, the time since the last painting does have a significant effect on condition as shown in Figure 19. This is because these elements or portions of elements are periodically painted.

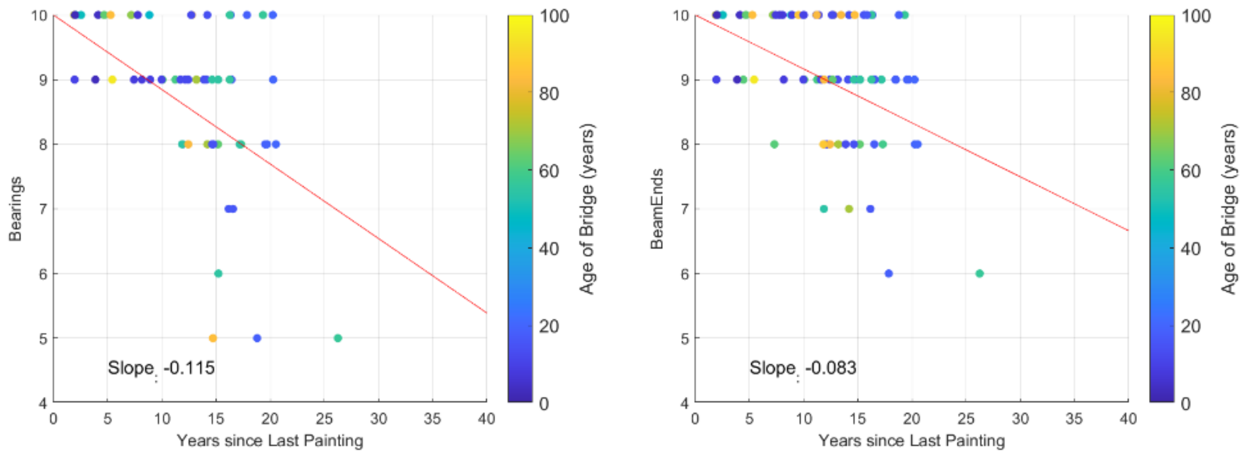

Figure 19. Condition versus Years since Last Painting of Beam Ends and Bearings on WS Bridges

The linear trends provided in Table 5 and Figure 19 were used to estimate the time for elements to drop 3 levels in condition state, as summarized in Figure 20. The values for beam ends and bearings represent the time since the last painting, while the rest represent the age of the structure. These results suggest that weathering steel elements will perform well for over 50 years if the ends and bearings are adequately maintained (painted every 15-20 years). It also suggests that newer weathering steel structures are deteriorating faster.

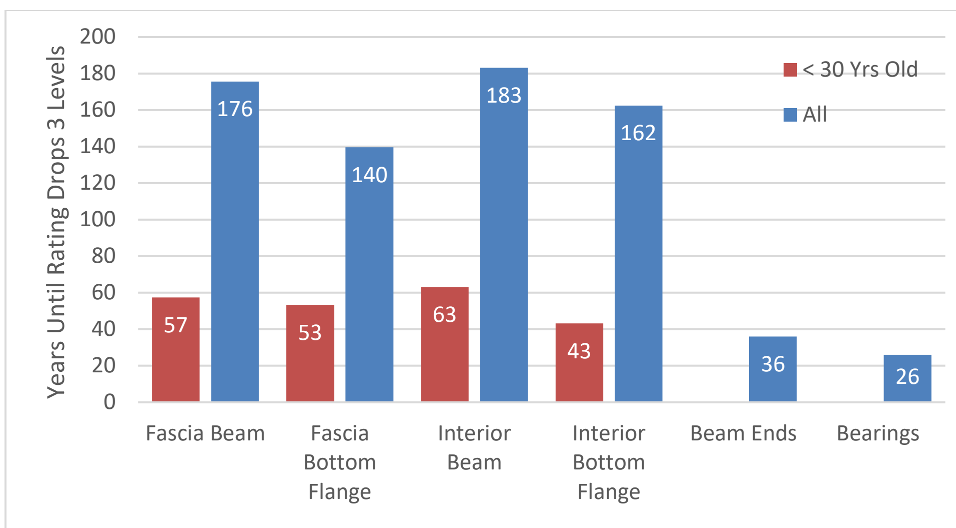

Figure 20. Time for Weathering Steel Condition to Decrease 3 Levels

Field Survey of Weathering Steel Bridges

Members of the research team included personnel from Wiss, Janney, Elstner Associates, Inc., who performed a field survey of weathering steel bridges. Their full report is included in the appendix. A total of 26 weathering steel (WS) bridges in New Jersey were visited and inspected as part of this survey. 25 bridges were sampled for patina analysis to evaluate the condition of the WS surfaces. Most inspected bridges (21 in total) were in rural or industrial areas with mild exposure (Exposure Category 01), reflecting the most common environmental conditions for WS in the state. Two bridges were classified as industrial with severe exposure (Category 02), and another two were situated in marine environments with mild exposure (Category 3A).

Figure 21. Surveyed WS Bridge in Poor Condition (No. 0725167)

Figure 22. Surveyed WS Bridge in Fair Condition (No. 1202152)

Two primary tests were performed on the sampled weathering steel (WS) bridges to evaluate the condition of the patina and the effectiveness of protective coatings. Chloride testing (CHLOR*TEST) was conducted to quantify the concentration of chloride ions on the steel surface, which can accelerate corrosion. Tape adhesion testing (ASTM D3359) was used to assess the adhesion strength of the patina. In this procedure, pressure-sensitive tape is applied over the area and subsequently removed to evaluate the degree of coating detachment.

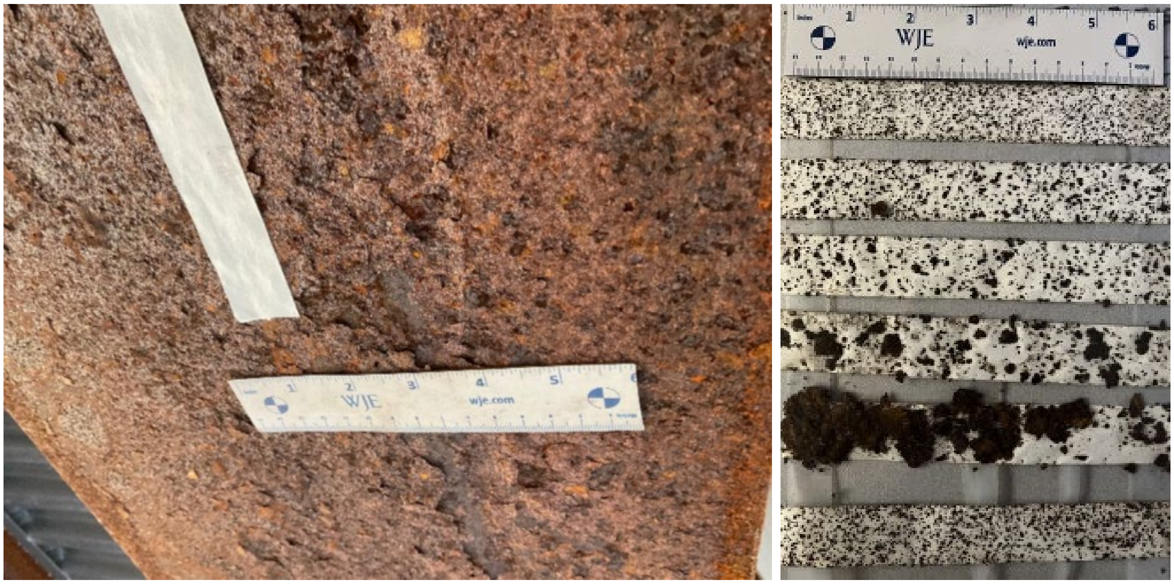

Figure 23. Tape Adhesion Testing on Bottom Flange (Left) and Tape Sample (Right)

In addition, physical samples of the steel surface patina were collected by scraping the beam flanges and webs. One sample was obtained from each bridge member inspected, ensuring that the samples were representative of the patina condition across different sections of the bridge. The samples were subjected to a series of laboratory analyses, specifically: chloride content by ion chromatography and Fourier transform infrared spectroscopy (FTIR) to identify the corrosion products present.

Visual appearance—specifically color, texture, and characteristic flake size—together with the tape adhesion record provided the most reliable and consistent indicators of patina performance. Most of the sampled bridges exhibited satisfactory to good patina development: uniform, dark brown patinas with tightly adherent rust layers.

In-situ chloride concentrations varied widely and did not correlate strongly with element condition ratings or the laboratory chloride measurements but beams with higher concentrations of chlorides often received a lower patina rating. Laboratory chloride measurements were most useful when interpreted alongside exposure and wetness indicators.

The FTIR analysis did not reveal correlation between any condition indicators and the composition of the patina. However, samples with larger proportions of goethite and lepidocrocite also had the highest (best) patina rating

Ultimately, exposure and detailing governed performance. Where water and debris were shed effectively and steel surfaces dried quickly, patinas tended to be finer, tighter, and more uniform. Where leaks, spray, or sheltered recesses prolonged time of wetness (TOW), patinas were coarser, more stratified, and locally unstable.

CONCLUSIONS

Paint system deterioration rates are most strongly correlated with exposure category.

Three-coat systems with an inorganic zinc-rich primer perform marginally better than those with organic primers.

Average deterioration rates were determined based on paint inspection data. These rates were leveraged to estimate the service life of the coatings and expected interval for interventions (Table 6).

Table 6 – Service Life Estimates

	Cat 01 & 3A	Cat 02	Cat 3B
Interior Beams	25 years	17 years	13 years
Fascia Beams	23 years	16 years	14 years
Beam Ends	20 years	16 years	12 years
Bearings	15 years	13 years	9 years

Weathering steel develops its own protective layer and therefore coating may not be needed. The patina on weathering steel beams can last 40–60 years, however, the data shows that the beam ends and bottom flanges, which are often subjected to prolonged periods of wetness, can exhibit unstable patinas and extensive corrosion, requiring intervention after 20–30 years.

Recommendations

Maintenance actions should be planned and implemented to keep paint condition ratings above 7, as corrosion can accelerate when the condition drops further. Based on this objective, Table 7 provides the interval between painting efforts that can be expected for different exposure categories. It is possible that some structures will exhibit signs of distress earlier, warranting intervention sooner. Therefore, appropriate maintenance actions for individual bridges should be determined and scheduled according to the documented performance and condition for that specific structure.

Table 7 – Painting Intervals

	Cat 01	Cat 02 & 3A	Cat 3B
Spot-coating	20 years	15 years	10 years
Over-coating	20 years	15 years	10 years
Over-coating (WS)	10 – 30 years		
Bearings	15 years	10 years	8 years

Recoating, which is essentially repainting the entire element, is expensive and can be postponed to 25 years or even more if the coating is well maintained with spot-coating and over-coating performed as needed.

Over-coating WS beam ends is recommended to protect against poor drainage and moisture accumulation. For the best performance, this should be performed at the factory, so protection is in place as early as possible. FHWA (2022) recommends increasing bottom flange thickness by 1/8 inch for sacrificial corrosion on WS beams.

Bridges on NJ Route 35 deteriorate more rapidly due to marine exposure and the higher concentration of roadway contaminants associated with dense population and traffic; these should receive more frequent inspection, washing and painting.

Annual washing is recommended for all steel bridges, especially those Category 3B and/or exposed to frequent de-icing applications.

Weathering steel, with grades up to 100 ksi, should be considered where appropriate. When detailed and maintained properly, it offers excellent low-cost corrosion resistance.

Routine inspection on weathering steel bridges should also include tape adhesion testing, especially in the first 10 years, to verify patina development and identify vulnerable areas (e.g., near supports) or otherwise signal the need for intervention.

Chloride testing did not prove reliable for characterizing weathering steel patina performance and is therefore not recommended for use in routine inspections. It is preferable, if the exposure severity of a site is to be determined, to employ other methods, such as the wet-candle method and humidity/moisture monitoring.

A three-coat system with zinc-rich primer and inorganic topcoat remains the preferred steel coating system and is recommended for spot-coating, over-coating and recoating.

Two-coat systems have shown some promise, but careful selection and proper application are crucial to ensure their effectiveness in providing long-term protection. Their use may be appropriate for spot-coating.

Single-coat systems have not yet demonstrated reliable long-term performance; further research should identify viable options for spot-coating.

Current Qualified Products Lists (QPL) are effective but should be updated to more flexibly accommodate manufacturer improvements without requiring lengthy and costly testing.

Bridge and element designs should seek to eliminate joints and water-trapping geometries to reduce crevice corrosion risks. Innovative drainage solutions (e.g., gutters) are needed to divert salt-laden runoff away from supports and other vulnerable areas. Scuppers should extend far enough to prevent discharge from being blown back onto bridge components (at least 12 inches below bottom flange) (Stephens, 2019).

Further studies are recommended to identify and evaluate both proprietary and non-proprietary methods that are effective at preventing crevice corrosion. Novel methods to effectively remove pack rust, such as the alternative method proposed by MDOT (Curtis, 2017), should also be evaluated.

It is recommended to develop a data-driven protocol (leveraging the past 10 years of inspection data) to forecast coating maintenance needs for spot-coating, over-coating, and full recoating.

REFERENCES

American Association of State Highway and Transportation Officials. (2019). Manual for bridge element inspection (2nd ed.). AASHTO.

American Institute of Steel Construction. (2023). Single-coat inorganic zinc protection for steel bridges (NSBA Technical Synthesis Report).

American Institute of Steel Construction. (2018). Design of steel structures (15th ed.). McGraw-Hill Education.

American Society of Civil Engineers. (2016). Fatigue of steel structures. ASCE Press.

Austroads. (2011). Potential re-coating treatment for inorganic zinc silicate coating (ABC-SAS007-11). Austroads.

CoatingsDirectory. (2024, April 6). The ultimate guide to organic coatings vs inorganic coatings. https://coatingsdirectory.com/blog/organic-coatings-vs-inorganic-coatings/

Curtis, R. (2017, March). *Bridge development update* [Conference presentation]. Michigan Bridge Conference, Lansing, MI, United States.

Environmental Protection Agency. (2023, September 28). It's official: Air across New Jersey meets national standards for sulfur dioxide. https://www.epa.gov/newsreleases/its-official-air-across-new-jersey-meets-national-standards-sulfur-dioxide

Environmental Protection Agency. (2025). Sulfur dioxide trends. https://www.epa.gov/air-trends/sulfur-dioxide-trends

Federal Highway Administration. (1989). Technical advisory on uncoated weathering steel for bridges. FHWA.

Federal Highway Administration. (2002). Save time and money with two-coat painting systems for steel bridges. https://www.fhwa.dot.gov/publications/focus/06may/02.cfm

Federal Highway Administration. (2011a). Federal Highway Administration 100-Year Coating Study. FHWA-HRT-12-044. https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/12044/12044.pdf

Federal Highway Administration. (2020a). Coating performance on existing steel bridge superstructures (FHWA-HRT-20-065). https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/20065/20065.pdf

Federal Highway Administration. (2020b). Weathering steel in highway bridges: Inspection and maintenance guidelines. U.S. Department of Transportation. https://www.fhwa.dot.gov/bridge/weathering_steel.pdf

Federal Highway Administration. (2022). Performance evaluation of uncoated weathering steel bridges (UWS Special Project, LTBPP InfoBridge Portal).

Federal Highway Administration. (2022b). Bridge Element Inspection Manual. https://www.nj.gov/transportation/eng/structeval/pdf/BridgeElInsManual.pdf

Fontana, M. G. (1986). Corrosion engineering (3rd ed.). McGraw-Hill.

Francis, R. A., & Szokolik, A. (2000). A comparison of the corrosion behaviour of inorganic zinc and conventionally-coated bridges. Proceedings of the ACA Conference 2000.

Francis, R. A., & Szokolik, A. (2013). Inorganic zinc silicate coatings: Fallacies and facts. Corrosion & Prevention, Paper 026. R. A. Francis Consulting Services.

Granata, J. P., et al. (2017). Weathering steel bridges in Florida: Corrosion performance and environmental thresholds. Florida Department of Transportation Research Report.

Jones, D. A. (1996). Principles and prevention of corrosion (2nd ed.). Prentice Hall.

Khatri, S., & Ghosh, S. (2020). Influence of corrosion on fatigue and fracture of steel structures: A review. Engineering Structures, 221, Article 111052. https://doi.org/10.1016/j.engstruct.2020.111052

Melchers, R. E., & Jeffrey, R. (2010). Corrosion of steel in concrete: Understanding, investigation and repair. Woodhead Publishing.

New Jersey Department of Environmental Protection. (2020). 2020 New Jersey air quality report. https://www.nj.gov/dep/airmon/pdf/2020-nj-aq-report.pdf

New Jersey Department of Environmental Protection. (2022). 2022 New Jersey air quality report. https://www.nj.gov/dep/airmon/pdf/2022-nj-aq-report.pdf

New Jersey Department of Transportation. (2022). State of New Jersey Bridge Inspection Program Policy and Procedures. https://www.nj.gov/transportation/eng/structeval/pdf/BridgeInspectionProgramPolicyandProcedures.pdf

Revie, R. W., & Uhlig, H. H. (2011). Corrosion and corrosion control: An introduction to corrosion science and engineering (4th ed.). Wiley.

Steel Structures Painting Council. (2017). Steel bridge coating systems: Application and maintenance. SSPC. https://www.sspc.org

Stephens, M. T., Gleeson, B., Mash, J., & Li, B. (2019, August). *Steel bridge corrosion prevention and mitigation strategies: Literature review* (IRISE-19-P19-01-01). University of Pittsburgh, Swanson School of Engineering. IRISE Consortium Technical Report. https://www.engineering.pitt.edu/IRISE/Research-Projects/Completed/

Uhlig, H. H., & Revie, R. W. (2000). Corrosion and corrosion control (3rd ed.). Wiley.

APPENDIX

Table 8 – Coating Systems Provided in NJDOT QPL

	Product Name	Manufacturer	System Name
Organic Zinc Systems	Carbozinc 859	Carboline Co.	OEU-37 CARBOLINE SYSTEM SSC(12)-04
	Carbogard 893		
	Carbothane 133 VOC		
	Zinc Clad 4100 Organic Zinc Rich Epoxy	Sherwin Williams Co.	OEU-38 SHERWIN WILLIAMS SSC(18)-09
	Macropoxy 646 Fast Cure Epoxy		
	Acrolon 218 HS Acrylic Polyurethane		
	Zinc Clad 4100 Organic Zinc Rich Epoxy	Sherwin Williams Co.	OEU-39 SHERWINWILLIAMS SSC(15)-07
	Macropoxy 646 Fast Cure Epoxy		
	Hi-Solids Polyurethane 250		
Inorganic Zinc Systems	Carbozinc 11 HS	Carboline Co.	IEU-25 CARBOLINE SYSTEM
	Carbogard 893		
	Carbothane 133 LV		

Table 9 – Coating Systems Provided in NJ Turnpike QPL

	Product Name	Manufacturer
Zinc Primers	Zinc Clad III HS Zinc-Rich Primer	Sherwin Williams Co.
	Zinc Clad II Plus	
	Carbozinc 859	Carboline Co.
	Carbozinc 11 HS	
	Amercoat 68HS	PPG Industries
	Dimetcote 9H	
	Interzinc 52	International Paint
	Interzinc 22HS	
Intermediate Coats	Macropoxy 646 FC	Sherwin Williams Co.
	Carboguard 60	Carboline Co.
	Carboguard 825	
	Carboguard 888	
	Carboguard 893	
	Amerlock 2	PPG Industries
	Amerlock 400	
	Amercoat 385	
	Interseal 670HS	International Paint
	Interguard 475HS	
Finish Coat	Acrolon 218 HS	Sherwin Williams Co.
	Carbothane 133 LH	Carboline Co.
	Amercoat 450H	PPG Industries
	Interthane 870 UHS	International Paint

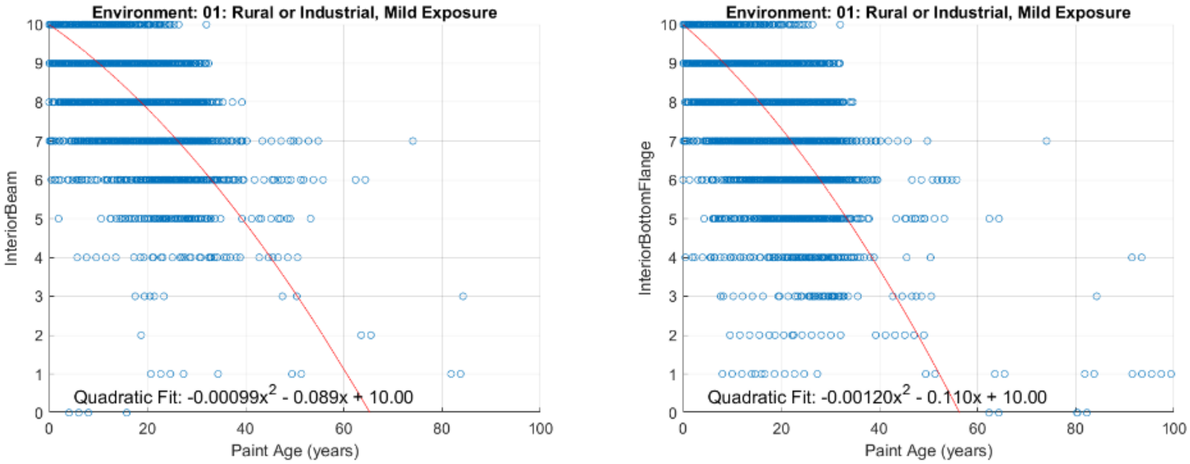

Figure 24. Plot of Interior Beam Paint Condition vs Age for Cat. 01

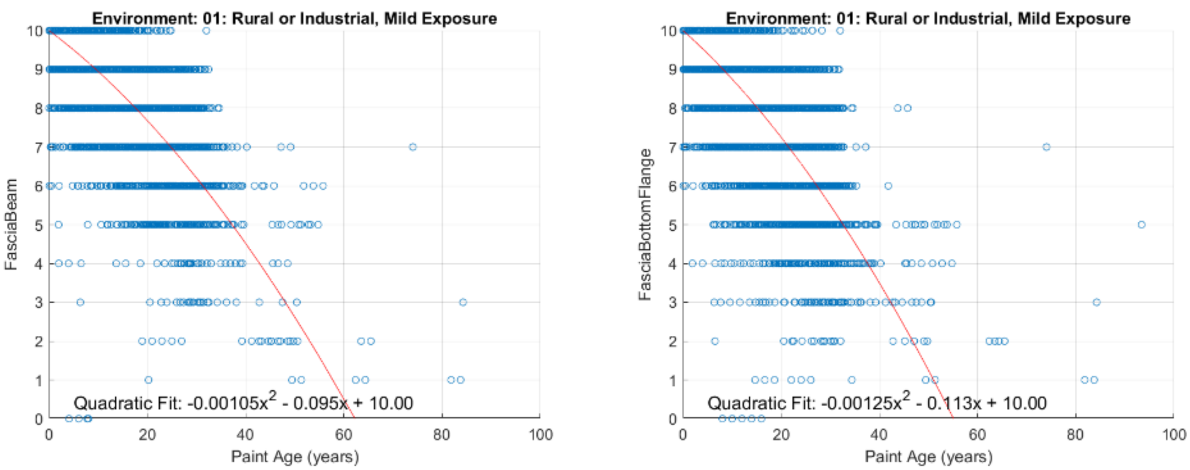

Figure 25. Plot of Fascia Beam Paint Condition vs Age for Cat. 01

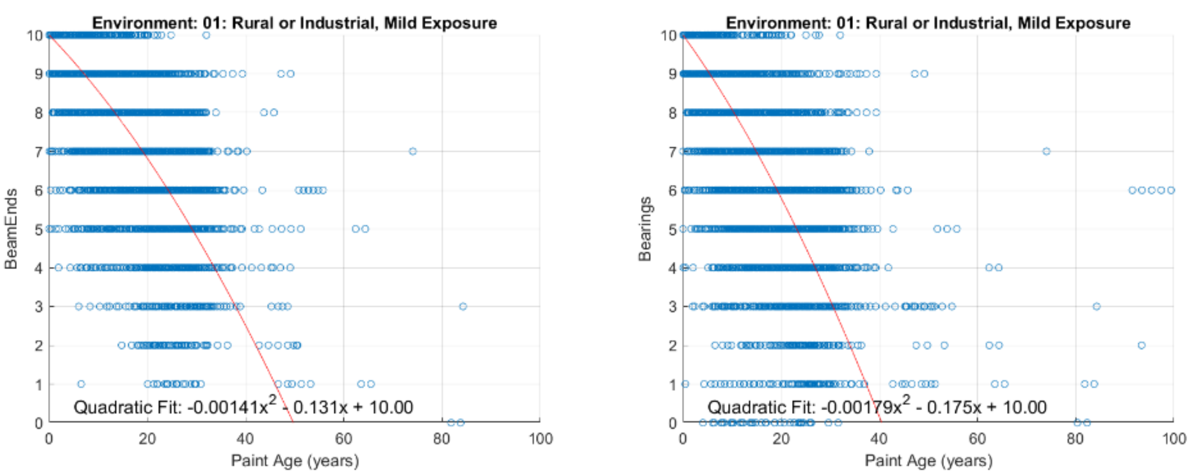

Figure 26. Plot of Paint Condition vs Age for Beam Ends and Bearings for Cat. 01

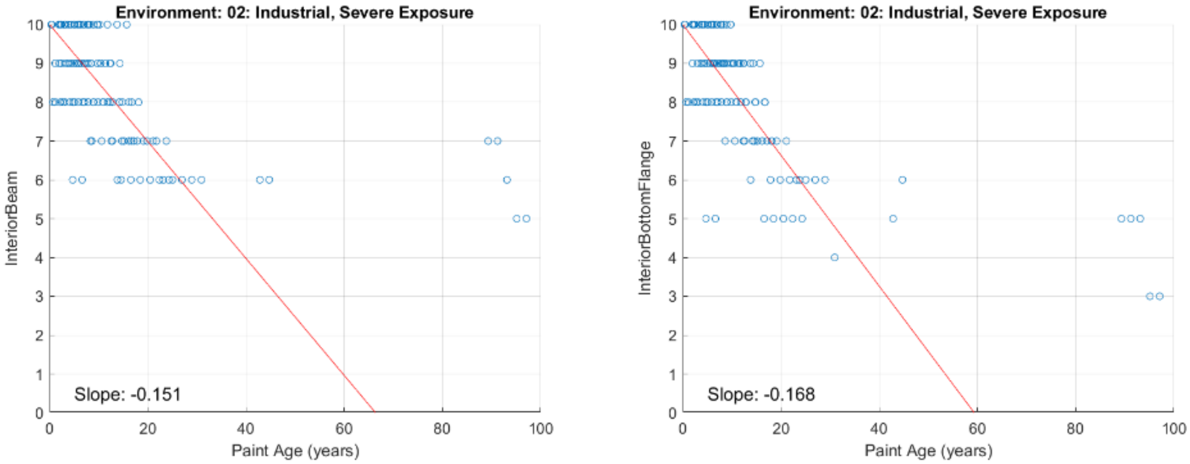

Figure 27. Plot of Interior Beam Paint Condition vs Age for Cat. 02

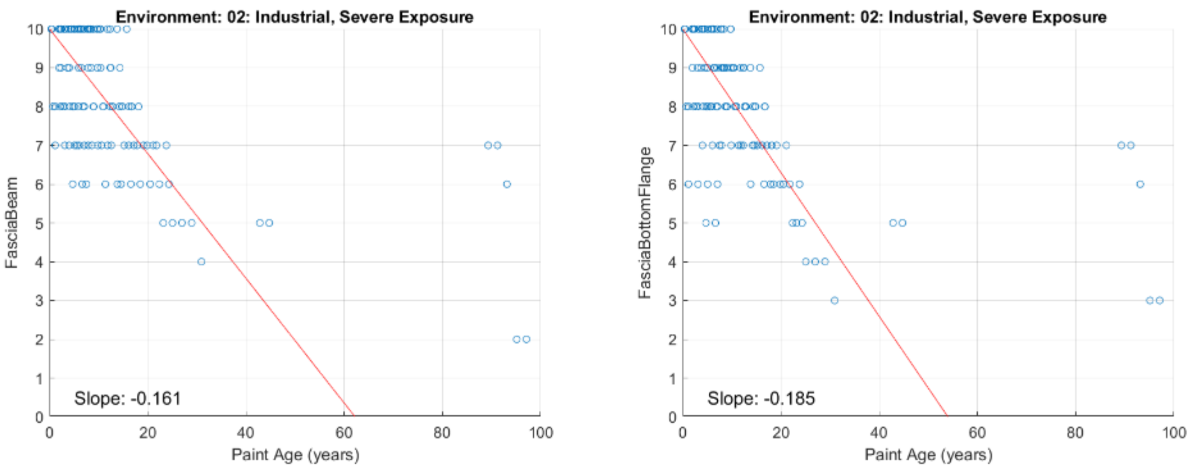

Figure 28. Plot of Fascia Beam Paint Condition vs Age for Cat. 02

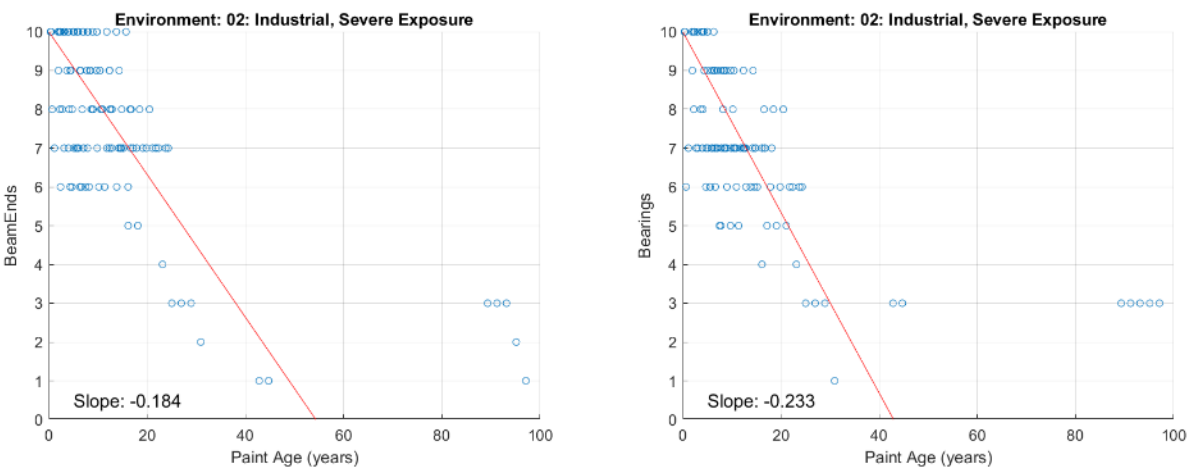

Figure 29. Plot of Paint Condition vs Age for Beam Ends and Bearings for Cat. 02

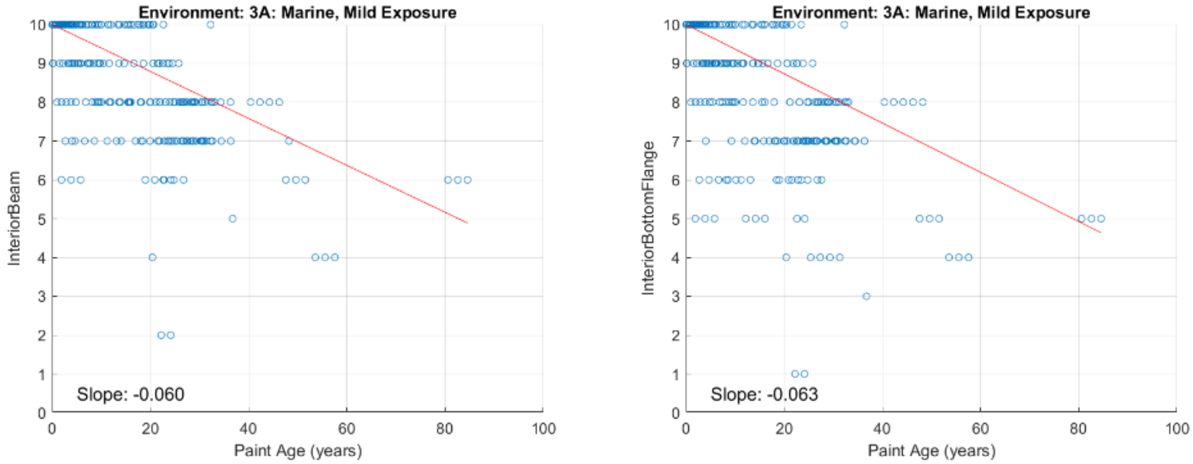

Figure 30. Plot of Interior Beam Paint Condition vs Age for Cat. 3A

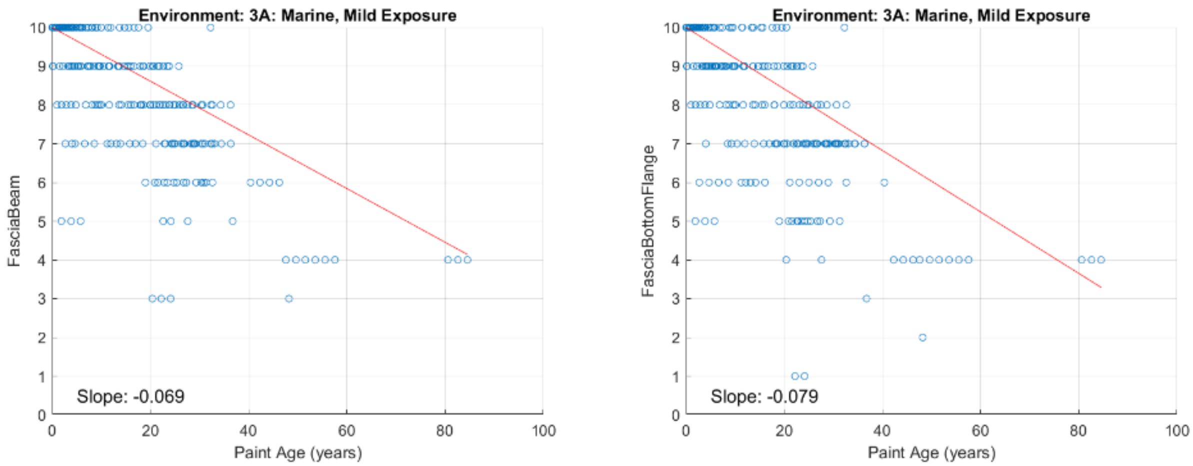

Figure 31. Plot of Fascia Beam Paint Condition vs Age for Cat. 3A

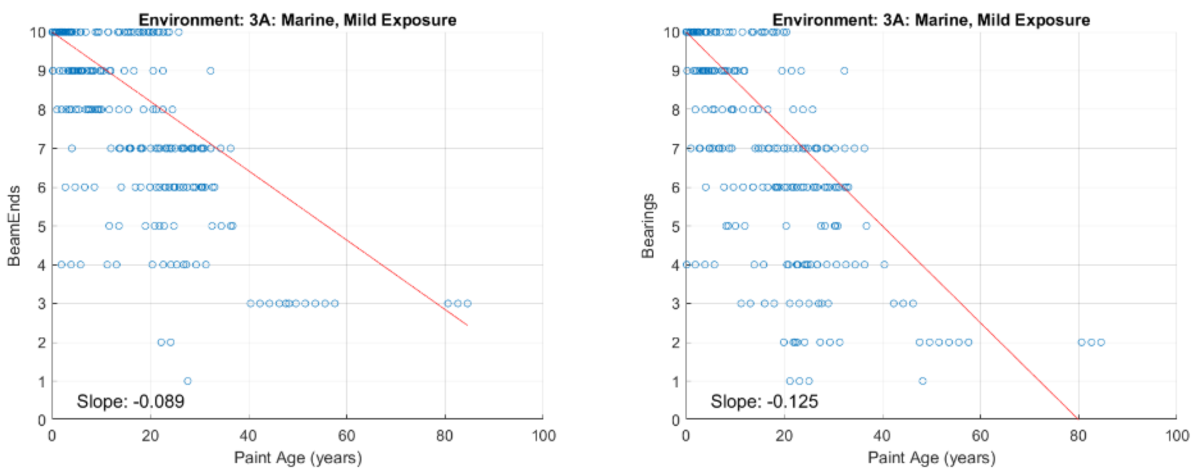

Figure 32. Plot of Paint Condition vs Age for Beam Ends and Bearings for Cat. 3A

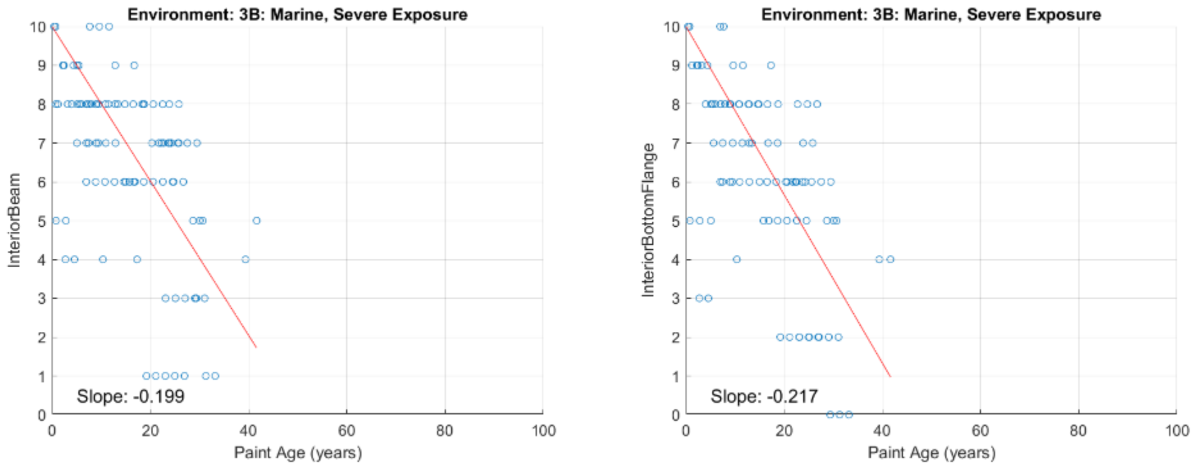

Figure 33. Plot of Interior Beam Paint Condition vs Age for Cat. 3B

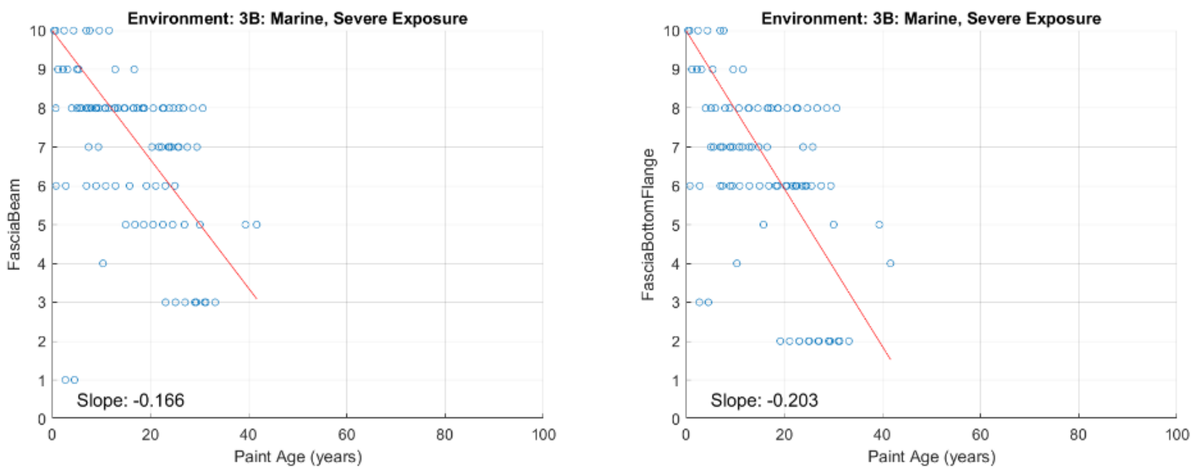

Figure 34. Plot of Fascia Beam Paint Condition vs Age for Cat. 3B

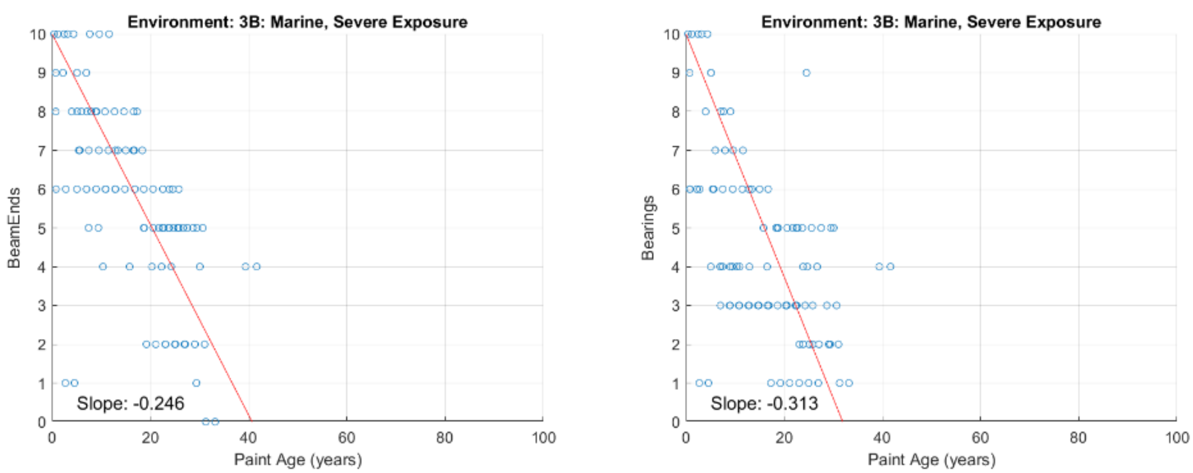

Figure 35. Plot of Paint Condition vs Age for Beam Ends and Bearings for Cat. 3B

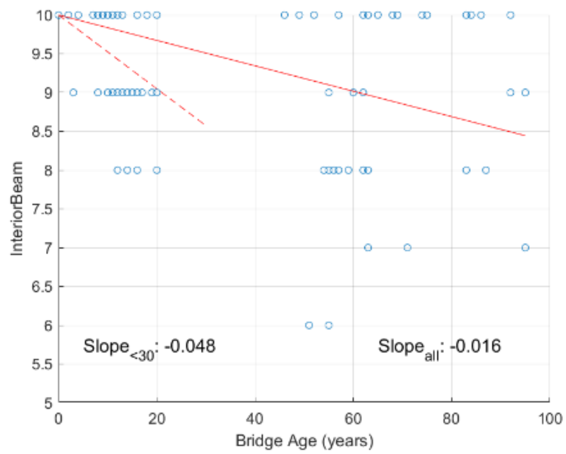

Figure 36. Plot of Interior Beam Paint Condition vs Age for WS Bridges

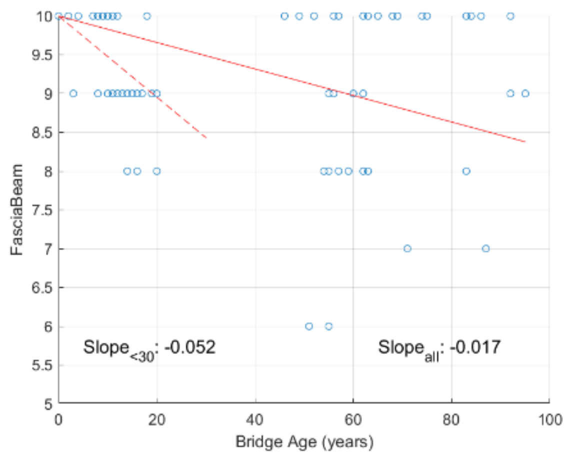

Figure 37. Plot of Fascia Beam Paint Condition vs Age for WS Bridges

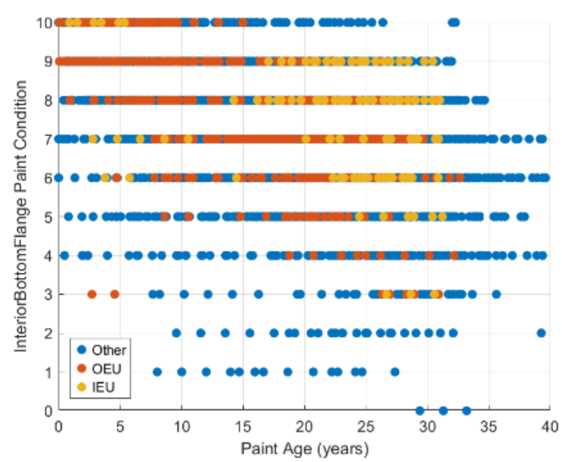

Figure 38. Plot of Interior Beam Paint Condition for Different Paint Systems

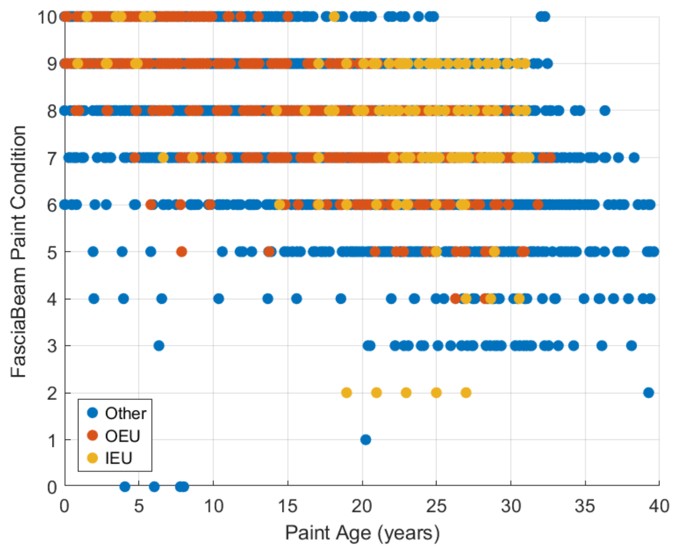

Figure 39. Plot of Fascia Beam Paint Condition

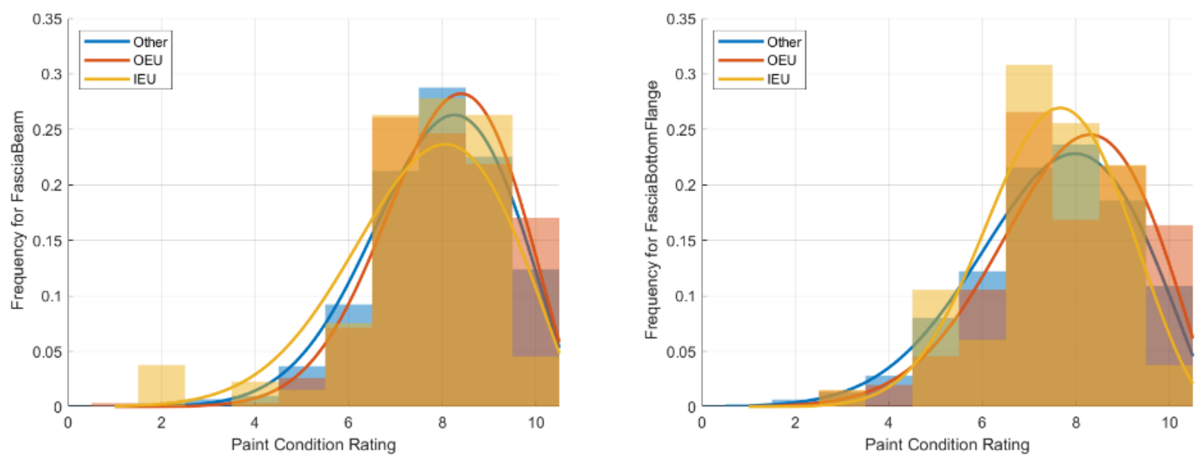

Figure 40. Paint Condition Distribution According to Paint Type for Fascia Beams

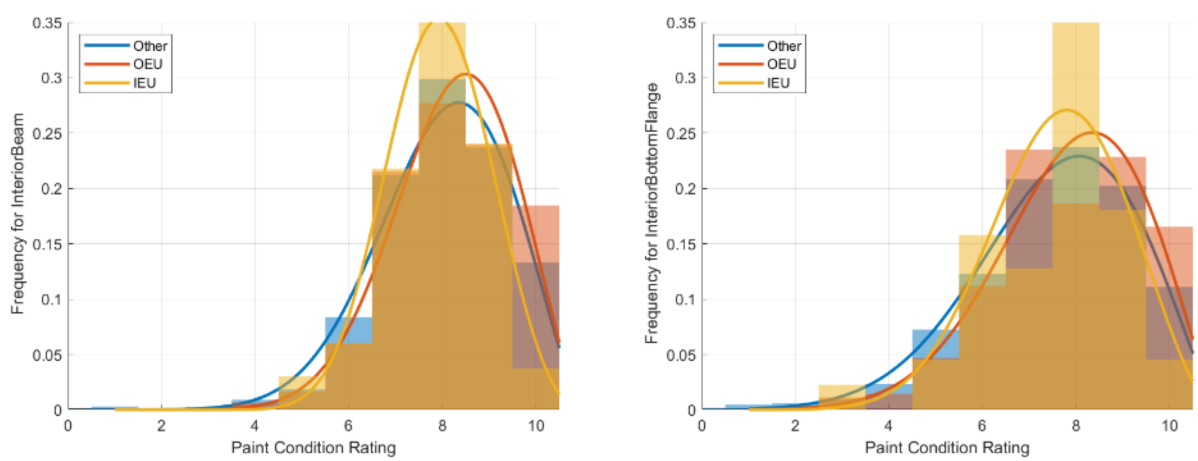

Figure 41. Paint Condition Distribution According to Paint Type for Interior Beams

WJE Report on Weathering Steel Bridges in NJ