JOINT TRANSPORTATION RESEARCH PROGRAM

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Strategic Scheduling of Infrastructure Repair and Maintenance

Volume 1

Decision Tree for Steel Bridge Painting

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16. Abstract

Even for the right treatment, improper timing can have consequences: premature application (treatment is applied too early) could mean wasteful spending even if users enjoy the benefits of higher pavement condition; deferred or delayed application (treatment is applied too late) could result in higher user costs due to poor condition and even reduced asset longevity.

The objectives of this research were to establish the optimal condition or timing for each of the standard M&R treatment types typically used by INDOT; quantify the consequences of departures from such optimal conditions or timings; and to establish the optimal M&R treatment schedule for each asset family. The study focused on three asset types and their treatments:

1. Painting of Steel Bridges. A painting decision tree was developed, to serve as a framework that would enable INDOT to consider other maintenance treatment types, namely spot repair/painting and overcoating.
2. Bridge Deck Maintenance and Rehabilitation. Life-cycle condition-based deck M&R strategies based on different trigger results were proposed and presented.
3. Pavement Maintenance, Rehabilitation, and Replacement. A framework was established to find the optimal scheduling for multiple treatments and recommend appropriate long-term M&R strategies for flexible and rigid pavements on different functional classes.

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EXECUTIVE SUMMARY

STRATEGIC SCHEDULING OF INFRASTRUCTURE REPAIR AND MAINTENANCE: VOLUME 1—DECISION TREE FOR STEEL BRIDGE PAINTING

Introduction

INDOT seeks to apply appropriate treatments for its bridge and pavement assets at the right time. Even for the right treatment, improper timing can have consequences: premature application (treatment is applied too early) could mean wasteful spending even if users enjoy the benefits of higher asset condition; deferred or delayed application (treatment is applied too late) could result in higher user costs due to poor condition, and even reduced asset longevity.

The objectives of this research were to establish the optimal condition or timing for each of the standard maintenance and rehabilitation (M&R) treatment types typically used by INDOT; quantify the consequences of departures from such optimal conditions or timings; and establish the optimal M&R treatment schedule for each asset family. The study focused on:

1. Painting of steel bridges
2. Bridge deck maintenance and rehabilitation
3. Pavement maintenance, rehabilitation, and replacement

Findings

1. The study established a cost-effective way of timing the painting of steel highway bridges.

   a. Deterioration models were developed for painted steel superstructures of highway bridges on routes of various functional classes.
   b. A painting cost model was developed using INDOT's painting contract records. Scenario analyses were conducted by varying the relative weights of agency and user costs.
   c. A painting decision tree was developed to serve as a framework that would enable INDOT to consider other paint maintenance treatment types—namely, spot repair/painting and overcoating. Based on the results, it would be appropriate for INDOT to continue applying complete recoating at trigger value 4, or to include spot repair and overcoating for its highway bridge steel superstructures.

2. The study established appropriate performance thresholds for triggering bridge deck M&R activities.

   a. Statistical models were developed to describe bridge deck and wearing surface deterioration, and performance jump (condition improvement) due to deck overlays. The agency cost models for latex-modified concrete (LMC) and polymeric overlays took into account the pre-treatment deck condition and the impact of scale economies. Two types of bridge user costs were considered: travel time costs due to work zone delays and the incremental vehicle operating costs (VOCs) during normal operations due to the increased roughness of the bridge deck surface.
   b. A life-cycle cost analysis optimization framework was proposed. The analysis used data for bridges on the state-owned routes in Indiana. Various weights were assigned to the agency and user costs for sensitivity analysis purposes. The results indicated that different weighting would have an impact on the optimal trigger or the threshold associated with the lowest equivalent uniform annual cost. In addition, the life-cycle condition-based deck M&R strategies based on different triggers were presented.
   c. Some modifications are recommended to be made to the original decision tree (DTREE) used in the Indiana Bridge Management System (IBMS) in order to incorporate the triggers for specific deck overlay treatments in the DTREE flow paths.

3. The study established a framework for determining the appropriate (condition-based) performance triggers for pavement maintenance, rehabilitation, and replacement activities.

   a. Fourteen types of treatments were considered. Statistical models were developed in terms of performance jump due to each maintenance and rehabilitation (M&R) treatment. Models were also developed for post-treatment performance, agency costs, and user costs.
   b. An optimization approach was proposed to determine the optimal International Roughness Index (IRI) trigger for each type of treatment on different families of assets that maximize the cost-effectiveness. The life-cycle cost analysis incorporates both agency cost (AC) and user cost (UC). Sensitivity analysis indicates that changing the relative weights of agency and user costs has a significant impact on the optimal trigger. The results of sensitivity analysis in terms of other important variables (e.g., AC:UC ratio, traffic load, discount rate, IRI upper bound, and pre-treatment performance) are also provided. The results show how the change in these factors can influence the optimal condition trigger results. This provides asset managers with greater flexibility in making M&R decisions.
   c. The study established a framework to determine the optimal schedules for multiple treatments and recommended appropriate long-term M&R strategies for flexible and rigid pavements on different road functional classes.

Implementation

The methodologies used in this study can help INDOT and other agencies enhance their M&R decisions in terms of the performance threshold of individual assets, as well as long-term M&R scheduling. The findings for each of the three parts of this study provide INDOT asset managers with an enhanced basis for making programming decisions and estimating the consequences of premature or delayed treatments. Possible limitations are:

1. The optimal triggers for pavements are given for surface roughness (IRI). Other important performance indicators such as rutting and cracking are not considered in this study due to the lack of data availability.
2. The lack of quality data limited this study to finding only general relationships between the variables. As more accurate and reliable data become available, the models can be refined, creating a stronger basis for optimal triggers and long-term M&R strategies.

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1. INTRODUCTION

1.1 Background

Highway agencies seek to apply appropriate treatments at the right time. Even for the correct treatment, improper timing can have consequences: premature application could mean wasteful spending even if users enjoy the benefits of higher pavement condition; deferred or delayed application could result in higher user costs due to poor condition, and even reduced asset longevity. The present study was carried out to establish a cost-effective way of painting steel highway bridges. Using nine years of steel bridge paint condition rating data and other variables collected from Indiana Department of Transportation and other agencies, deterioration models were developed for painted steel highway bridges on NHS and NNHS routes. The models were used to compute the effectiveness of current INDOT practice for painting steel highway bridges. Also, a painting cost model was developed to estimate agency unit cost values. In order to include user-related costs in the state of practice, scenarios were tested based on the relative weights for agency cost and user cost. After evaluating the current practice, a painting decision tree was developed. Based on the results, it would be more cost-effective to include spot repair and overcoating in the management of steel highway bridges based on the proposed painting strategy.

1.2 Organization of Volume 1

Volume 1 has five chapters. Chapter 1 discusses the background and problem statement, study objectives and the organization of this report. Chapter 2 provides a detailed literature review covering steel bridge painting and bridge joints. This chapter will focus on the state of practice of steel bridge painting, methodological frameworks available for modeling painting activities on steel highway bridges, and the cost for painting steel highway bridges. In addition, the effectiveness concept of measuring the benefits of an infrastructure would be presented. Chapter 3 presents the adopted methodology, data collection efforts, developed models for steel bridge painting and cost models for steel highway bridge painting activities. The analysis and results from the adopted method are presented in Chapter 4. The report's conclusions and recommendations are discussed in Chapter 5.

2. LITERATURE REVIEW

2.1 Introduction

In order to develop a decision tree for steel bridge painting, this chapter reviews the various steel bridge paint treatment types, some factors that influence steel bridge paint deterioration, models from past studies that have been used to investigate the pattern of steel bridge paint deterioration, and the costs of steel bridge painting activities. Also, this chapter investigates the factors that affect the effectiveness of steel highway bridge paints, the cost values, and how to establish cost-effective trigger values to ensure that steel bridge paints are adequately managed.

2.2 Steel Bridge Painting Treatment Strategies

The American Society for Testing Materials (ASTM) recommends three broad treatment types for steel bridge painting: spot painting, overcoating and complete recoating. These treatment types are intended to protect and enhance the appearance of steel highway bridges. The next sections discuss the three various types of treatments.

2.2.1 Spot Painting

Spot repair or painting for a steel highway bridge surface is considered when there is a small section on the bridge surface that is rusted or delaminated. A section can be considered for spot painting when spot rusting occurs on a steel highway bridge surface. Spot rusting takes place when the majority of the rusting is focused in a few localized areas of the painted section. The rusted or delaminated surface section can be repaired by painting the identified spots.

Spot painting is only applicable to existing coatings that have limited corrosion, by area, and adequate adhesion. In this type of treatment, painting is done on isolated rust spots, observed on the bridge, after which these rust spots are eradicated. The difficulty associated with this type of treatment is that the contractor may have difficulty ensuring that the adjacent coatings, which are in good condition, are not damaged when the isolated rust spots are being removed. In addition, a better coating can be achieved by ensuring that there is a transition zone between the edges of the blast-cleaned areas and the existing coatings. There should be a quality control check to ensure that there is an increase in the mechanical connection between the existing and the new coating. The selection of the proper treatment type at the most economic time is very important in steel highway bridge coating maintenance (Tam & Stiemer, 1996). This type of steel bridge paint treatment applies to defects, which have deteriorated to a specific condition.

The possible degrees of spot rusting that can occur on a steel highway bridge section are presented in Figure 2.1. In the figure, a rust grade of 9-S indicates that the percentage of surface area rusted is greater than 0.01% and no more than 0.03%, while a rust grade of 4-S indicates that the surface has rust condition between 3% and 10% of the total steel bridge surface area. Based on the rust conditions illustrated in Figure 2.1, the recommended actions to be taken for each of these scenarios on a steel bridge surface would be to spot repair/paint.

2.2.2 Overcoating

Overcoating or encapsulation is carried out when the total defective painted area on a steel highway bridge surface is removed and the surface is painted with a

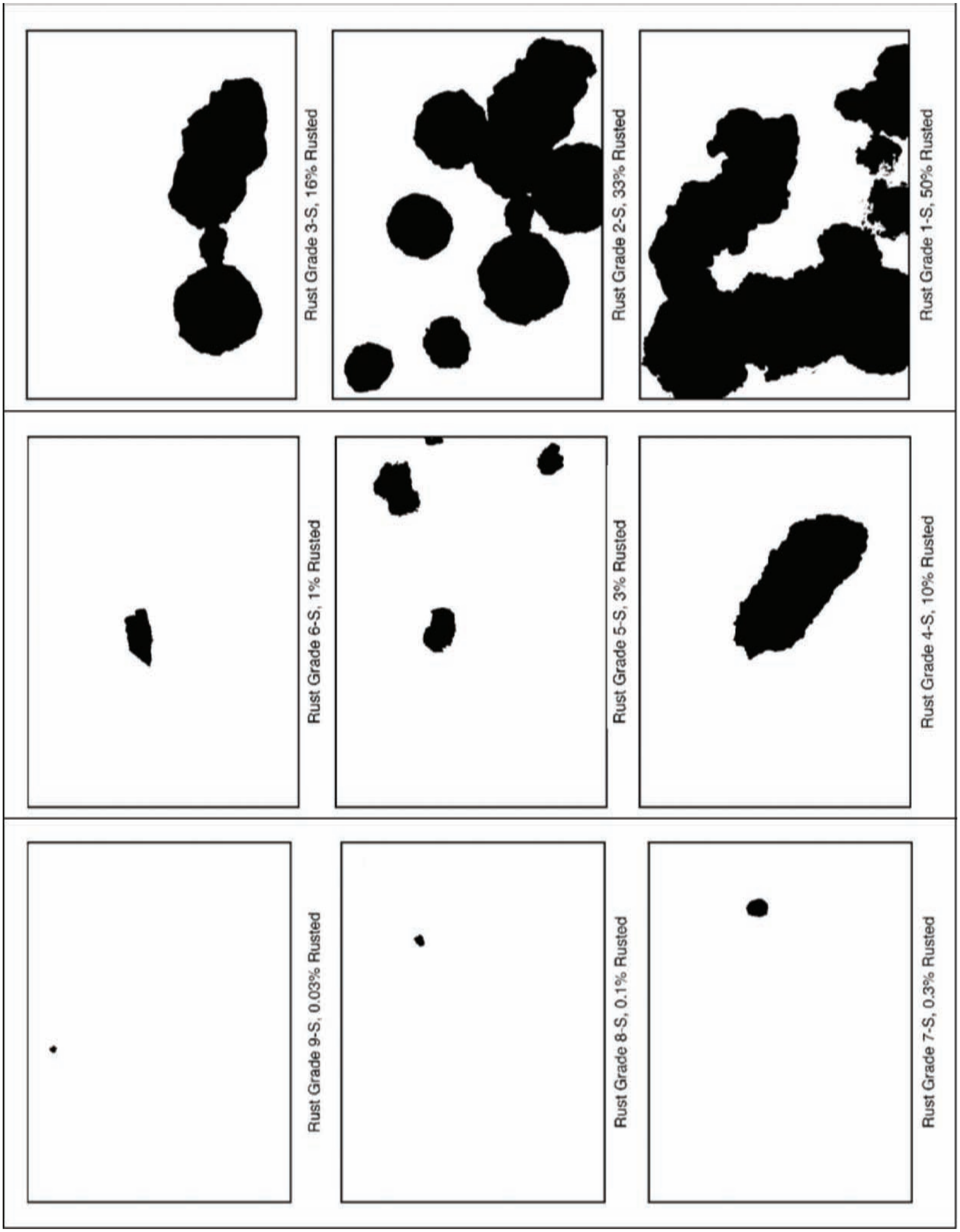


Figure 2.1 Spot rusting on steel bridge surfaces (ASTM, 2009).

new system that is congruous with the present coating system. This painting strategy has application constraints that are similar to spot repair or painting. The primary concern associated with overcoating is the possibility of shrinkage throughout the curing action of the new coating system. If the new system has excessive shrinkage, it would result in cracking when applied close to the existing coating system that is in good condition. The second concern in relation to overcoating is the softening of the underlying layer from solvent penetration. The agency or contractor can significantly reduce this challenge by adopting or applying coatings with high solids content. Kline and Corbett (1992) found that five different types of coatings, when tested for excessive shrinkage, performed far better on steel surfaces cleaned with air blowdown cleaning method compared to surfaces cleaned with brush-off blast-cleaning.

In the past, corrosion experts assumed that an elevated degree of surface preparation ensured the removal of loose rust, thereby achieving an enhanced performance. However, this assumption has been found to be inaccurate. In accordance with ASTM Standard 0610 (Table 2.1), it was found that surfaces cleaned by brush-off blast (Table 2.2) have performances ranging from 4 to 5, while these values are from 5 to 7 for air-blowdown cleaning (Kline & Corbett, 1992). This unexpected result was attributed to the shattering of the alkyd paint due to the impact of the abrasives. Thus, the results from the ASTM study indicate that limited surface preparation is recommended, compared to a more costly brush-off blast for coating systems. In addition to improved performance, expense and health concerns were resolved due to the removal of lead-contaminated abrasives.

Overcoating a steel highway bridge prior to the appearance of significant rusting on the bridge surface would be uneconomical and could damage the existing coating, due to the eventual delamination and cracking of the heavy buildup of the new coating over the existing one.

2.2.3 Complete Repainting

The previous sections discussed two (spot repair and overcoating) of the three painting types, and this section will focus on complete repainting or recoating. Complete repainting is the proper treatment type when the existing coating system has deteriorated until structural damage to corrosion is imminent. At this worst condition of the existing coating system, the entire steel highway bridge surface is cleaned before application of the new coating system. Although some highway agencies practice this treatment strategy and replicate it during the bridge's life, it has been found to be less-cost effective than to spot paint or overcoat, due to the disposal of lead-contaminated abrasives and the excessive cost of the containment (Tam & Stiemer, 1996).

2.3 Steel Bridge Painting Costs

The cost associated with painting steel highway bridges is a critical component in the management of highway infrastructures, especially bridges. During the past decades, the costs of maintenance and rehabilitation (M&R) of existing coating systems for steel bridges continued to increase. The increase was attributed to three broad elements: environmental constraints, reduced governmental funding resulting in suboptimal maintenance

TABLE 2.1
Coating Systems Based on ASTM Standards

ASTM Standard	Description
D610	Test methods for evaluating degree of rusting on painted steel surfaces
D660	Test method for evaluating degree of checking of exterior paints
D661	Test method for evaluating degree of cracking of exterior paints
D662	Test method for evaluating degree of erosion of exterior paints
D4214	Test methods for evaluating the degree of chalking of exterior paint films
D5043	Test methods for field identification of coatings
D5064	Practice for conducting a patch test to assess coating compatibility
D5065	Guide for assessing the condition of aged coatings on steel surfaces

TABLE 2.2
Prior Painting Cleaning Methods

SSPC Standard	Cleaning Method	Description
SP-1	Solvent cleaning	Removes oil, grease, wax, dirt
SP-2	Hand tool cleaning	Removes loose rust, mill scale, and coating
SP-3	Power tool cleaning	Removes loose rust, mill scale, and coating
SP-5	White-metal blast	Complete removal of all visible residue
SP-6	Commercial blast	Minimum for most government agencies for bridge maintenance, leaves 66% of surface area free of all visible residue
SP-7	Brush-off blast	Does not remove tightly adhering mill scale, rust, or old coating
SP-10	Near-white metal blast	95% free of all visible residue

schedules, and improved safety standards for workers (Zayed, Chang, & Fricker, 2002).

In many highway agencies across the USA, asset managers responsible for bridges tend to allow the coating systems on steel highway bridges to deteriorate until they have to be completely repainted. (Dadson, 2001; Tam & Stiemer, 1996). For example, from the data on steel highway bridges painted in Indiana, the service life (i.e., time between treatments) of the paint ranges from 20 to 35 years, depending on the environmental conditions.

In Figures 2.2 and 2.3, it can be observed that steel bridge paint service life ranges from as low as 11 years to a high of 21 years, depending on the traffic and environmental conditions. Knowledge of the service life for steel bridge paint would enable the agency to develop better strategic schedules, based on available cost information.

2.3.1 Agency and User Costs

In order to consider a long-term view of managing steel highway bridges, it would be appropriate to include M & R activities during the service life of the painted steel bridge. This calls for a life-cycle cost analysis (LCCA) for steel highway bridge painting. The broad

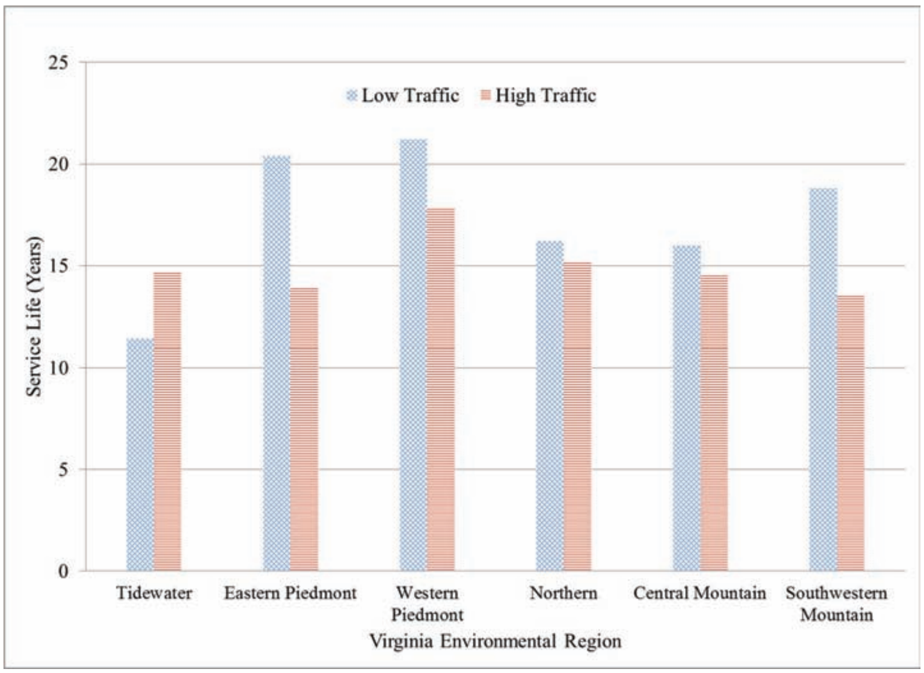


Figure 2.2 Bridge paint service life versus region (Dadson, 2001).

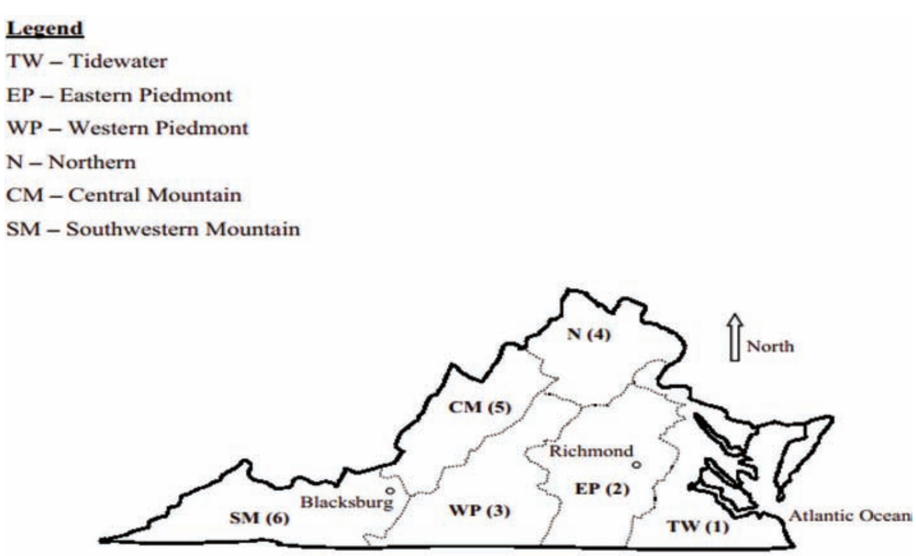


Figure 2.3 Virginia environmental regions (Dadson, 2001).

objective of LCCA is to establish all the relevant costs associated with the corrosion protection of a steel highway bridge throughout the service life. Applying LCCA to different treatment strategy combinations would indicate the alternative that has the treatment schedule with the least cost. To implement LCCA for steel highway bridges, knowledge of steel bridge deterioration models, and the costs associated with M & R of the steel bridge are essential.

The cost of painting steel highway bridges ought to consider both user and agency costs. Agency cost is the cost incurred for the painting of the bridge, and cost of maintenance of traffic. The user cost components for painting a steel highway bridge are associated with detours, work zone duration, work zone safety, and delays. The highway user may incur higher vehicle operating costs, higher likelihood of crashes at work zones, and loss of productivity due to delays.

Currently, many highway agencies do not include user cost in their analysis, which results in the underestimation of total cost associated with steel bridge coating system management. Also, in the absence of user cost in the analysis, the agency would typically wait for the condition of the steel bridge paint to get to the worst acceptable state before any action is taken. For example, an agency that considers complete repainting of its steel highway bridges at condition 4 would always wait for the paint condition to get to condition 4 before an action to paint is taken. However, including user cost in the evaluation tends to encourage a shorter time to a maintenance activity, instead of a longer time. This is because paint deterioration takes place simultaneously with the corrosion of the steel members. If an agency allows the paint to deteriorate to the "worst acceptable state," not only will the bridge require repainting, but the bridge steel members may have to be replaced. This more extensive process will time a longer time to complete, costing road users additional delay in the meantime.

Data from Fricker and Zayed (1999) indicate that the initial agency cost for painting a steel bridge varies from $180 to $220 per ton for paint types 1 (lead-based paint) and 2 (zinc/vinyl paint) (Table 2.3). The study also found that M&R agency costs vary from $20 to $220 per ton. Using data from Michigan Department of Transportation, the study also found that initial agency painting cost for a three-coat system paint system (inorganic/organic zinc epoxy urethane) was $4 and the rehabilitation agency cost varied from $\$1.50/ft^2$ to $\$4/ft^2$ (Table 2.4).

In order to compare the agency cost of steel bridge painting across some departments of transportation, Zayed et al. (2002) found that the cost varies from $\$2.50/ft^2$ to $\$16.81/ft^2$, as presented in Table 2.5. The cost numbers observed in the literature may serve a benchmark for the agency cost numbers in the present study.

The literature is replete with agency cost information but has almost nothing about the user cost components for steel bridge painting. In Chapter 4 of this report, a number of scenario analyses are carried out to include possible user cost values for steel highway bridge painting.

2.4 Bridge Paint Deterioration Models

Deterioration models for steel bridge coating systems attempt to describe the path of decline of the coating condition based on factors that include aging of the coating system, environment, and the state of maintenance practices. In the past, experimental or empirical data have been used as the basis for modeling steel bridge paint deterioration. The experimental framework considered painted steel plates in which the environmental conditions were controlled. Temperature, precipitation, humidity, and even the loading on these plates were controlled. The empirical approach uses data from the field, where the environment is not controlled. The next subsections present past work carried out using the two approaches for modeling coating system deterioration.

2.4.1 Experimental Deterioration Models

Kim and Itoh (2005) performed an accelerated experimental exposure test using steel plates of dimensions 150 mm long, 70 mm wide and 9 mm thick. The study used Japan Industrial Standards (JIS) SM490A structural steels, and the plates were treated using a common surface treatment procedure used for steel bridge painting in Japan. In order to test for how different paint types would perform, the plates were coated with five types of painting systems: A-painted system (applied for a mild environmental condition), C-painted

TABLE 2.3
Estimated Unit Cost of Indiana's Steel Bridge Paint Rehabilitation (Zayed et al., 2002)

Description of Rehabilitation Process	Every *n* Years (*n*)	Alternative Number	Paint State	Initial Cost ($/ton) at Paint Types		Rehabilitation Cost ($/ton) at Paint Types	
				1	2	1	2
Complete repainting	30	1	5	$220	$180	$220	$180
Spot repair	10	2	2	$220	$180	$25	$20
Spot repair	18	3	3	$220	$180	$50	$40
Overcoating	18	4	3	$220	$180	$110	$100
Overcoating	24	5	4	$220	$180	$180	$150
Bridge reconstruction	60						

TABLE 2.4
Estimated Unit Cost of Michigan's Steel Bridge Paint Rehabilitation (Zayed et al., 2002)

Description of Rehabilitation Process	Every *n* Years (*n*)	Alternative Number	Paint State	Initial Cost ($/ft^2) Three-Coat Paint System	Rehabilitation Cost ($/ft^2) Three-Coat Paint System
Complete repainting	25	1	5	$4	$4
Spot repair	15	2	3	$4	$1.5
Spot repair	20	3	4	$4	$2.5
Bridge reconstruction	60				

TABLE 2.5
Agency Unit Costs and Service Life of Paint Systems (Zayed et al., 2002)

	Cost/ft^2 and Service Life for Different Paint Systems							
Paint System	INDOT	ODOT	MDOT	ILDOT	KDOT	CTDOT	FHWA	Service Life (Years)
Zinc-Vinyl	$2.50	x	x	x	x	x	x	15–25
Three-Coat/Lead	$3.96	$4.0–6.0	$9.29	$5	x	x	x	25–30
Three-Coat/Zinc	$2.80	$4.0–6.0	$9.29	$5	x	x	x	25–30
Metallization	$16.81	x	x	$6.0–9.0[a]	x	$12.0–15.0	$14.75	40–60

NOTE: INDOT numbers calculated from data (Georgy & Chang, 1999). ODOT numbers collected from Mr. Herald Schultz and Mr. R. Bauer. MDOT numbers collected from Mr. Sonny Gduan, Mr. Brion Back, Mr. Craig A. Russell, and Mr. Glenn Bukosky. ILDOT numbers collected from Mr. Gary Kowalski. CTDOT numbers collected from Mr. Eric Lohrey. FHWA numbers collected from Rep. No. FHWA-RD-96-058. Service life numbers for cinz-vinyl from Mr. Ted Hopwood; for three-coat system from ILDOT and MDOT; and for metallization from ILDOT and CTDOT.

[a]This number is for new bridges only.

systems (for severe corrosive condition), and I-painted system (considered for severe corrosive condition) in Japan. The I-painting system was subdivided into three groups (I-1, I-2, and I-3), and the divisions were made on the basis of the top coats being applied as presented in Table 2.6.

From the results of the study (Kim & Itoh, 2005) presented in Figure 2.4, it can be observed that the rusting area propagates as time increases, regardless of the type of painted system. Also, using the ordinary least squares method, regression curves (Figure 2.4) were developed. The regression curves were of the form, $C=\alpha\beta^x$, where α and β are constants. However, the difficulty with this study is that it allowed α to be fixed at 0.314 and this parameter was not allowed to vary across observations, and this would give a biased result if the deterioration model were used to assess any other coating system.

In the past, other experimental studies (Doherty & Sykes, 2004; Funke, 1981; Reddy, Doherty, & Sykes, 2004; Reddy & Sykes, 2005) have been carried out on steel plates to investigate how corrosion propagates and what can be established to reduce corrosion. The results from these studies suggested that, at the site of coating breakdown, the elimination of rust will reverse the pattern of electrochemical activity. Thus, when steel has rust deposits at the affected areas, anodic sites are developed and the rust serves as the cathode reactant.

The Federal Highway Administration (FHWA) carried out a study (Kodumuri & Lee, 2012) to investigate the possibility of discovering steel bridge coating systems that can ensure a maintenance-free service life for a century, regardless of the environmental conditions. The study considered eight coatings systems – three were 3-coat systems comprising organic, inorganic, and moisture-cured zinc-based primers, four 2-coat systems with numerous combinations of zinc-based primers and organic top coats, and a single-coat system of calcium sulfonate alkyd. These systems were examined with an accelerated laboratory testing (ALT) and three outdoor exposure environments: natural weathering (NW), natural weathering with salt spray (NWS) in McLean, VA, and outdoor testing at the Golden Gate Bridge (GGB) in San Francisco, CA. The test panels used for the study were coded "type II" because "type I" identified the test panels used in the previous FHWA study. The type II panels had dimensions of 18 in by 18 in. In order to simulate the conditions encountered by bridges in the field, the panels had welded joints and angle attachments. Table 2.7 presents a summary of the coating systems, while Figure 2.5 graphically illustrates the rust propagation observed during the accelerated laboratory testing. The rust creepage data from TSZ/LE panels were not measured due to the development of excessive surface deterioration after only 1,080 hours of ALT.

The results show that the type I panels did not develop any rust separation for NW and NWS testing except for ZnE/LE. When Type II panels in NW and NWS were exposed for a minimum duration of 6 months, the ZnE/LE system displayed identifiable rust separation as presented in Figure 2.6.

TABLE 2.6
Coating Systems Used (Kim & Itoh, 2005)

Symbol of Test Specimens	Painting Process	Treatment and Material	Designed Film Thickness (mm)
A-painted steel	Surface preparation	Power tool, SIS-St3 Class	–
	1st undercoat	Lead anticorrosive paint	35
	2nd undercoat	Lead anticorrosive paint	35
	Intermediate coat	Alkyd resin	30
	Top coat	Alkyd resin	25
C-painted steel	Surface preparation	Blast, SIS-Sa2 1/2 Class	–
	1st undercoat	Inorganic zinc-rich paint	75
	–	Mist coat	–
	2nd undercoat	Epoxy resin	60
	3rd undercoat	Epoxy resin	60
	Intermediate coat	Polyurethane resin	30
	Top coat	Polyurethane resin	25
I1-painted steel	Surface preparation	Brush Off Blast, SIS-Sa1 Class	–
	Undercoat	Organic zinc-rich paint	75
	Intermediate coat	Polyurethane resin	30
	Top coat	Polyurethane resin	25
I2-painted steel	Surface preparation	Brush Off Blast, SIS-Sa1 Class	–
	Undercoat	Organic zinc-rich paint	75
	Intermediate coat	Silicone acrylic resin coating	30
	Top coat	Silicone acrylic resin coating	25
I3-painted steel	Surface preparation	Brush Off Blast, SIS-Sa1 Class	–
	Undercoat	Organic zinc-rich coating	75
	Intermediate coat	Fluorine resin	30
	Top coat	Fluorine resin	25

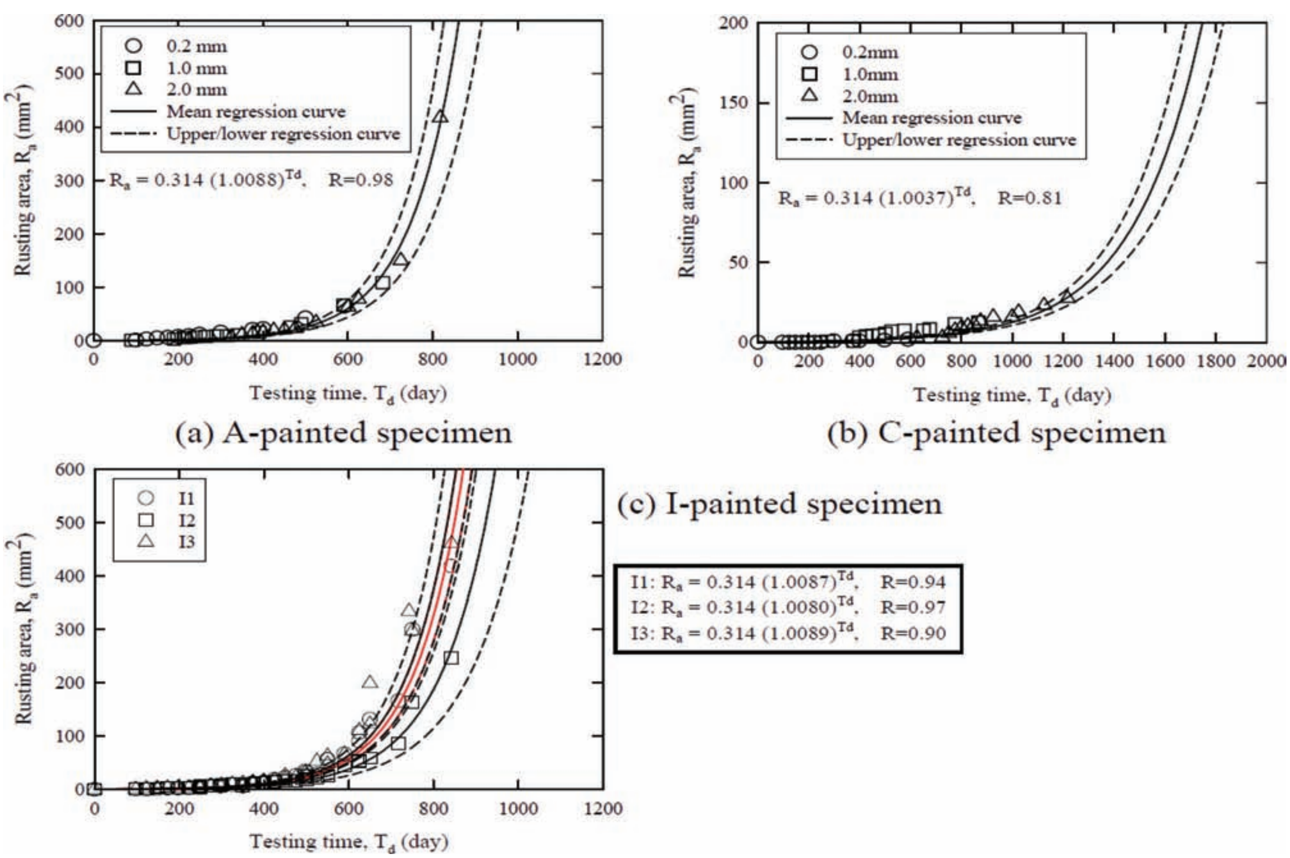


Figure 2.4 Rust propagation (Kim & Itoh, 2005).

TABLE 2.7
Summary of Coating Systems (Kodumuri & Lee, 2012)

		Coating Type		
System Number	**System ID**	**Primer**	**Intermediate**	**Top**
1	Three-coat (control)	Inorganic zinc-rich epoxy (IOZ)	Epoxy (E)	Aliphatic polyurethane (PU)
2	Three-coat (control)	Zinc-rich epoxy primer (ZE)	E	PU
3	Three-coat	Moisture-cured urethane zinc primer (MCU)	E	Fluorourethane (F)
4	Two-coat	ZE		PU
5	Two-coat	Inorganic zinc primer (Zn)		Polysiloxane (PS)
6	Two-coat	Thermally sprayed zinc primer (TSZ)		Linear epoxy (LE)
7	Two-coat	Experimental zinc primer (ZnE)		LE
8	One-coat	High-ratio calcium sulfonate alkyd (HRCSA)		

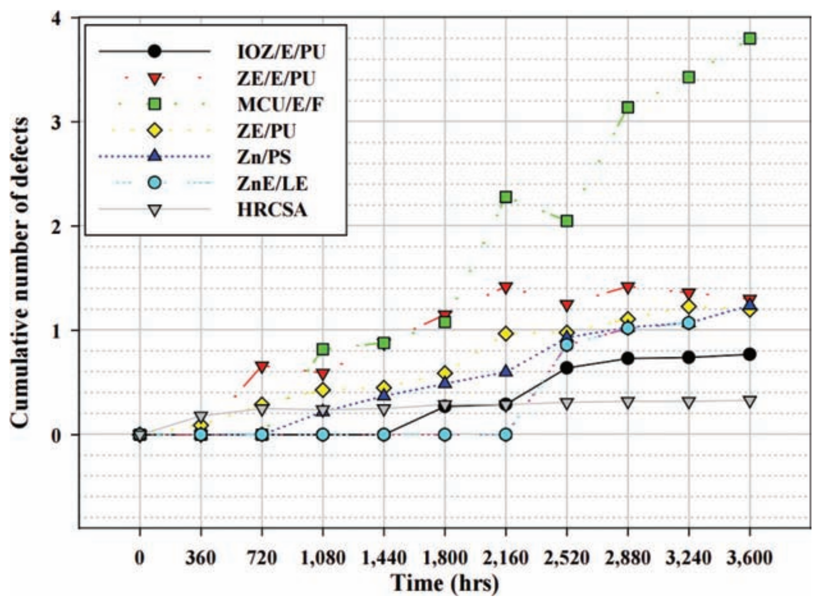


Figure 2.5 Rust creepage growth with time during ALT (Kodumuri & Lee, 2012).

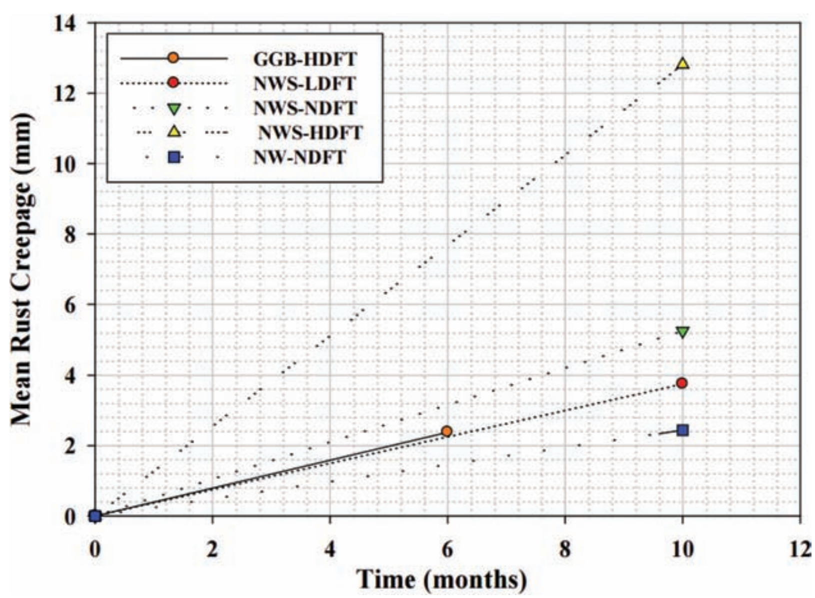


Figure 2.6 Rust creepage growth of ZnE/LE (Kodumuri & Lee, 2012).

The test results made possible these three observations:

- Steel highway bridge maintenance-free corrosion protection for a century could not be achieved from the selected coating systems.
- IOZ/E/PU, ZE/E/PU, and HRCSA performed well and were better than the other coating systems.
- TSZ/LE and ZnE/LE failed prematurely and had a worse performance than the other coating systems.

The previous section presented and discussed how evaluations of steel bridge coating systems were carried out using experimental data. In the next section, evaluations of steel bridge coating systems based on empirical data are presented and discussed.

2.4.2 Empirical Modeling Data

The empirical modeling of steel bridge coating system can be broadly classified into two methods: deterministic and probabilistic. These methods, which are not mutually exclusive, are discussed below.

Deterministic Methods. These models describe the relationship between bridge paint condition and possible deterioration factors. In the past, these models have been used to predict the condition of the paint on steel highway bridges with the assumption of perfect knowledge of the relationship between the factors and the paint condition. In a study conducted by Zayed et al. (2002), a regression analysis was carried out to relate steel bridge painted condition to the paint age. The age of a steel bridge when it was painted was the only independent variable found to be statistically significant, while the other factors, including traffic load, and environmental conditions, were statistically insignificant. The developed models were clustered into two highway types: interstates and state (non-interstate) roads. Using a polynomial functional form, the study developed models for lead-based paints (paint type 1) and zinc/vinyl-based paints (paint type 2), as illustrated in Figure 2.7. The models are indicated in Equations 2.1 to 2.4 as follows:

Paint type 1for interstate roads:

$$Paint\ rating = 9.06 - 0.0821(Age) - 0.00178\left(Age^2\right) \quad (2.1)$$

Paint type 2 for interstate roads:

$$Paint\ rating = 9.06 - 0.201(Age) - 0.0103\left(Age^2\right) - 0.000348\left(Age^3\right) \quad (2.2)$$

Paint type 1 for state roads (non-interstate):

$$Paint\ rating = 9.06 - 0.007(Age) - 0.00517\left(Age^2\right) \quad (2.3)$$

Paint type 2 for state roads (non-interstate):

$$Paint\ rating = 9.03 - 0.0753(Age) - 0.00489\left(Age^2\right) - 0.000054\left(Age^3\right) \quad (2.4)$$

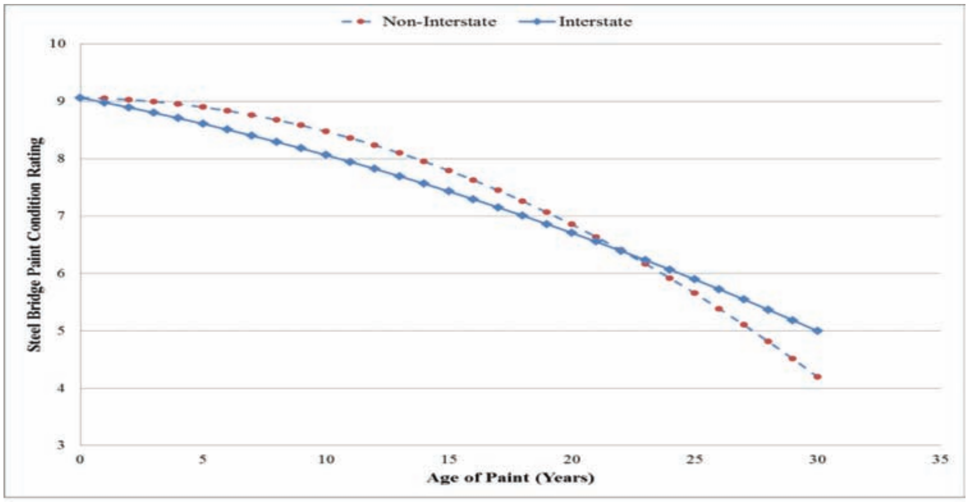
Probabilistic Methods. The probabilistic models are stochastic, and may be able to capture the deterioration of infrastructure in a manner considered to be more robust than the deterministic method, due to the probabilistic manner of infrastructure deterioration (Qiao et al., 2016). One of the widely used stochastic methods in bridge deterioration analysis is the Markovian model, because it is able to approximate the subsequent conditions using transition probabilities. Transition probabilities describe the probability that a system will move from one condition state to another in specified duration. This model is based on a discrete data technique because deterioration of bridges can be considered as a discrete phenomenon rather than continuous. One primary limitation of the method is that it ignores the future performance of the steel bridge paint because it does not capture the time that the steel bridge paint was in the present condition state. In a study by Zayed et al. (2002), the Markov model was used to predict the future performance of bridge paint condition. The Markov probability transition, which was determined using a regression model, was used to model how steel bridge paint deteriorates with time. The study assumed that the condition of the bridge paint would not change by more than one state in one year. The adopted probability transition matrix used was in this form:

$$\mathbf{P} = \begin{bmatrix} p(1) & q(1) & 0 & 0 & 0 \\ 0 & p(2) & q(2) & 0 & 0 \\ 0 & 0 & p(3) & q(3) & 0 \\ 0 & 0 & 0 & p(4) & q(4) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

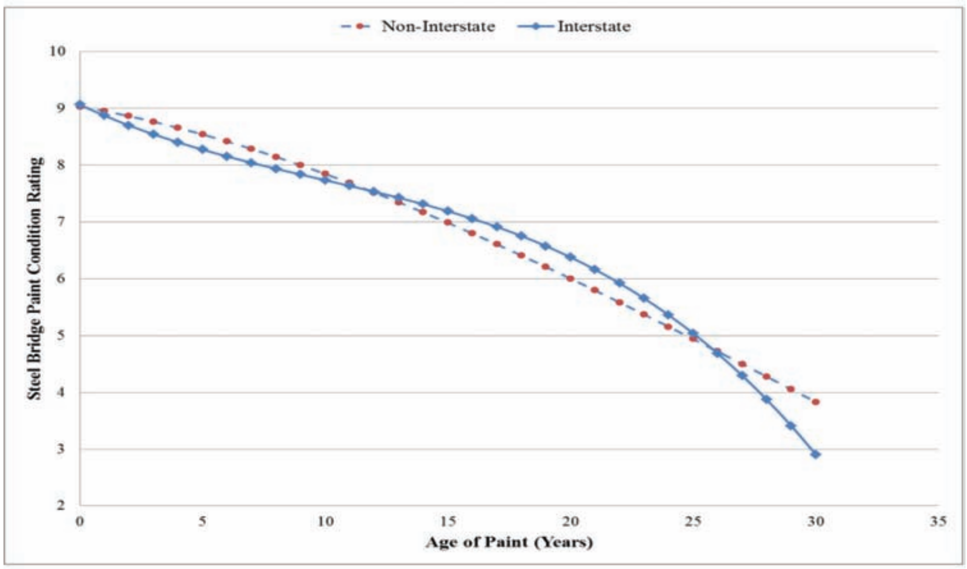
where p(j)=probability of steel bridge paint continuing in state *j* during one inspection cycle; and q(j) = 1 – p(j) is the probability of the bridge paint dropping to the next lower state (j + 1) during one inspection cycle. A comparison of the results from both the probabilistic methods (e.g., Markovian model) and the deterministic methods (e.g., regression model) is presented in Figure 2.8. It can be observed that the trend of deterioration from these two methods was not significantly different.

2.5 Treatment Effectiveness

In order to determine the most cost effective strategic schedule for steel bridge painting treatments across the life cycle, the cost and effectiveness of each treatment have to be determined. Effectiveness of steel bridge painting preservation is the reduced rate of painted condition deterioration due to a preservation action. Effectiveness can be either short-term or long-term. Short-term treatment effectiveness enables the comparisons of the benefits of alternative preservation interventions for different attributes, including treatment type (Labi & Sinha, 2003). However, many highway agencies make their plans, programs and budgets based on long-term effectiveness, rather than short-term effectiveness. The three possible measures of long-term effectiveness include: (a) treatment



(a) Performance curves for steel highway bridge painting (lead-based paints)



(b) Performance curves for steel highway bridge painting (zinc/vinyl paints)

Figure 2.7 Performance curves for steel highway bridge paint systems.

service life (measures the extension in paint life on a steel highway bridge due to a preservation treatment), (b) rise in average asset condition in the post-treatment period, compared to the condition prior to the treatment, and (c) increase in area under the paint performance curve due to the preservation treatment. For the present study, the long-term effectiveness of painted service life will be established using option (c), which is the rise in area under the paint performance curve due to the preservation treatment (Figure 2.9).

The area bounded by the paint performance curve and the threshold line, at which a treatment action is taken, are critical in the computation of the effectiveness and the service life of a particular treatment. Using the area bounded by the paint performance curve represents an appropriate approach to quantity the long-term effectiveness of preservation treatments. One way of computing the area under the performance curve is to use annual measurements of the performance indicator for each asset that received the treatment under investigation, plot a graph of the condition measurements versus time, determine each asset's area under the performance plot, and compute the arithmetic mean of these areas. An alternative approach is to develop a performance curve for the treated assets and compute the area bounded by the curve between treatment time and the threshold. In both approaches, the area bounded by the curve can be computed by coordinate geometry. In the present study, the paint performance function would be determined and used to compute the effectiveness of a specified treatment type. The equation governing the effectiveness computation would be in this form:

$$PTE = \int_{i=0}^{j} g(x) \tag{2.5}$$

where PTE= paint treatment effectiveness; i = time interval; j = service life of the paint maintenance

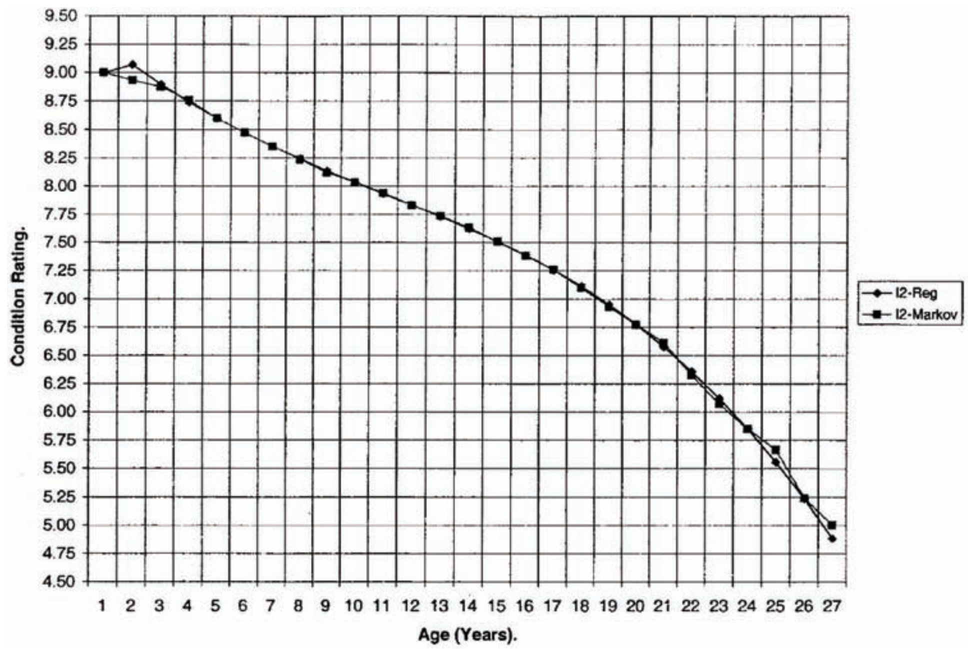


Figure 2.8 Paint deterioration curves: regression versus Markov models (Zayed et al., 2002).

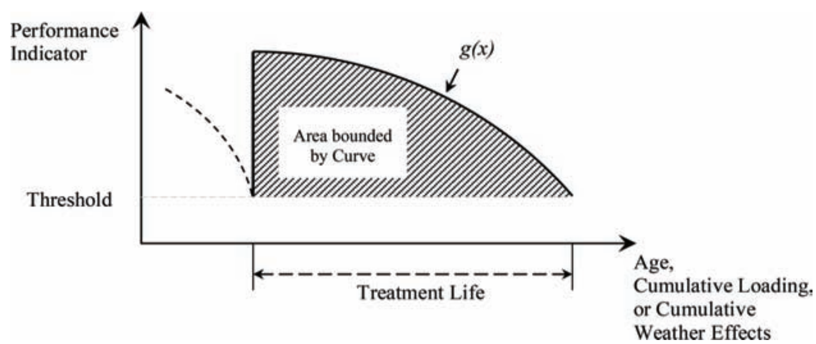


Figure 2.9 Determination of long-term effectiveness.

treatment; and $g(x)$ = deterioration model or function of the paint treatment.

2.6 Cost-Effectiveness

After computing cost and effectiveness values related to the identified treatments, the next step would be to determine the best treatment. One way to select the best treatment would be by comparing the various cost-effectiveness ratios (Hass, Turay, & Austin, 1991; Labi & Sinha, 2005). In the present study, the cost-effectiveness ratio is used to compare various maintenance strategies and establish the appropriate treatment type and strategic schedule of treatment types. The concept embedded in the cost-effectiveness computation is analogous to the benefit-cost ratio, which has been used to compare alternative projects based on economic efficiency analysis. For a comparison of many treatments, the treatment with the highest cost-effectiveness ratio can be considered as the most cost-effective treatment, and ought to be selected. Thus, a treatment with a higher cost-effectiveness ratio is a better treatment. A cost-effectiveness ratio greater than unity indicates that the benefits outweigh the cost associated with the treatment. The cost-effectiveness ratio for a paint treatment type can be computed using the form:

$$PTCE = \frac{PTE}{EUAC} \tag{2.6}$$

where $PTCE$ = paint maintenance treatment cost-effective ratio; PTE = annualized paint treatment effectiveness; and $EUAC$ = equivalent annual cost of paint treatment.

3. METHODOLOGY

This chapter discusses the methodologies used for data collection, selection of statistical variables, statistical analysis framework to investigate the factors affecting steel bridge paint condition and cost. In addition, the chapter presents the development of the effectiveness and cost-effectiveness methods for steel bridge paint treatment, and the recommended decision framework for steel bridge painting.

3.1 Data Collection

Steel bridge paint-related data were available from Indiana Department of Transportation (INDOT) and the National Bridge Inventory, Federal Highway Administration. In order to investigate the possible measureable factors influencing paint conditions on steel highway bridges, the items listed in Table 3.1 were collected.

3.1.1 Agency Cost and Bridge Surface Area

Agency cost data came from the contract letting information website of INDOT. This cost information is the cost incurred by the agency for the actual painting of the entire steel bridge surface. The steel bridge surface area painted was also available to the present study from INDOT. Based on the data on surface area painted and the agency cost, the unit agency cost for painting steel highway bridges was calculated.

3.1.2 Expected Service Life

The expected service life of a paint treatment is the number of years it takes for a painted steel bridge to deteriorate to the trigger value, at which it was last painted. The expected service lives were computed from INDOT's database. Using the database, the difference between the date a steel bridge was painted and the next painting date was computed to estimate the treatment service life.

3.1.3 Maintenance of Traffic Cost

The cost information associated with maintenance of traffic facilitated the computation of cost per day for management of traffic during a painting period. This variable assisted in the determination of the cost the agency incurs for maintenance of traffic only during a steel bridge painting activity.

3.1.4 Percentage of Corrosion

Percent of corrosion on the steel bridge when a painting treatment is being done was needed to analyze the corrosion level at which a particular type of painting treatment would be necessary. However, there was no empirical data from INDOT regarding the fraction of corrosion on the steel bridge surface prior to painting. Therefore, the present study consulted the ASTM standard (Table 3.2), to determine the extent of rust or corrosion that would need a type of treatment. For example, when between 3% and to 10% of a steel bridge surface is observed to be rusted, then the bridge surface is considered to have a rust grade of 4. In order to improve this condition, the area to be painted would be approximately 40% (Table 3.3) of the total steel bridge surface. This procedure was included in the decision tree for steel bridge painting treatment.

3.1.5 Bridge Location and Highway Functional Class

Bridge location and highway functional class data were available from INDOT and the National Bridge Inventory website from FHWA. The bridge location was used to identify the type of bridge that was analyzed and the corresponding environmental factors associated with the location. In addition, highway functional class (NHS-interstate, NHS-non interstate and non-NHS) data were needed to investigate and identify the appropriate highway classes that significantly affect the cost of steel bridge painting activity.

3.1.6 Steel Bridge Paint Condition Data

Steel bridge paint condition data were available to the present study from INDOT, specifically from Bill Dittrich. The data provided the condition of paints on all steel bridges on the state highway system. The data were from years 2006 to 2015, except year 2009, which was missing.

TABLE 3.1
Data Collection

Data Description	Remarks	Source
Agency cost	Quantify cost of surface area painted	INDOT
Expected service life	Paint life	INDOT
Surface area of the structure painted	Compute total paint cost for each painting activity	INDOT
Maintenance of traffic (MOT) duration, and cost per day for maintenance of traffic	Estimate cost of maintenance of traffic	INDOT
Percent of corrosion	Indicate the type of painting activity to be carried out	ASTM/SSPC
Bridge location/functional class	Located on NHS (NNHS) highway class	INDOT/FHWA
Steel bridge paint condition	Indicates the paint condition of the steel bridge, 1 being the worst, and 9 the best	INDOT
Environmental factors	Precipitation, temperature	NOAA
User cost	Traffic delays, safety cost & loss productivity due to painting activity	Literature

TABLE 3.2
Scale and Description of Rust Ratings (ASTM, 2012)

Rust Grade	Percentage of Surface Rusted	Visual Examples		
		Spot(s)	General (G)	Pinpoint (P)
10	≤0.01%		None	
9	>0.01% and up to 0.03%	9–S	9–G	9–P
8	>0.03% and up to 0.1%	8–S	8–G	8–P
7	>0.1% and up to 0.3%	7–S	7–G	7–P
6	>0.3% and up to 1.0%	6–S	6–G	6–P
5	>1.0% and up to 3.0%	5–S	5–G	5–P
4	>3.0% and up to 10.0%	4–S	4–G	4–P
3	>10.0% and up to 16.0%	3–S	3–G	3–P
2	>16.0% and up to 33.0%	2–S	2–G	2–P
1	>33.0% and up to 50.0%	1–S	1–G	1–P
0	>50%		None	

Rust Distribution Types:

S: Spot Rusting—Spot rusting occurs when the bulk of the rusting is concentrated in a few localized areas of the painted surface. The visual examples depicting this type of rusting are labeled 9–S through 1–S.

G: General Rusting—General rusting occurs when various size rust spots are randomly distributed across the surface. The visual examples depicting this type of rusting are labeled 9–G through 1–G.

P: Pinpoint Rusting—Pinpoint rusting occurs when the rust is distributed across the surface as very small individual specks of rust. The visual examples depicting this type of rusting are labeled 9–P through 1–P.

H: Hybrid Rusting—An actual rusting surface may be a hybrid of the types of rust distribution depicted in the visual examples. In this case, report the total percentage of rust to classify the surface (9–H through 1–H).

TABLE 3.3
ASTM Corrosion Performance Rating (SSPC, 1993)

Corrosion Rating	Assessment Description	Areas to be Repainted (%)
10	No rust or <0.01% rust	0
9	<0.03% rust	0
8	Few isolated spots, <0.1% rust	0
7	<0.3% rust	0
6	Extensive rust spots, <1% rust	8
5	<3% rust	18
4	<10% rust	40
3	Approximately 1/6 of surface rusted	60
2	Approximately 1/3 of surface rusted	100
1	Approximately 1/2 of surface rusted	100
0	Approximately 100% of surface rusted	100

3.1.7 Environmental Data

Environmental data were obtained from the National Oceanic and Atmospheric Administration (NOAA). These data were specific to individual counties in the state of Indiana. The data collected include average annual temperature, average annual precipitation, number of freeze-thaw cycles, and freeze index.

3.1.8 User Cost

Due to the absence of specific steel bridge painting activity data, user cost data related to steel bridge painting were obtained through adoption of user cost models developed in the literature. In the present study in relation to steel bridge painting, relevant user cost on traffic delays, and loss of productivity due to steel bridge painting activity were considered.

3.2 Deterioration Models for Painted Steel Bridges

3.2.1 Statistical Variables

In order to model the deterioration of paint on steel bridges, a number of variables were considered initially. These variables include paint age, paint condition rating, district location of steel bridge, highway functional class (NHS/Non-NHS), average annual daily traffic, average annual daily truck traffic, type of paint (lead-based or zinc-based), average annual temperature in a county, average annual precipitation in a county, wet days in a county, warm days, and number of freeze thaw cycles. Paint condition rating was the dependent variable, and the remaining variables were considered as the independent variables. Discrete paint condition ratings range from 0 (worst condition) to 10 (best condition). Many of the variables were observed to insignificantly influence paint conditions, however only three independent variables came out to be statistically significant at the 5% significance level. Thus, these variables (steel bridge painted age, NHS/Non-NHS, and average annual temperature in a county) were used in the final model.

3.2.2 Statistical Analysis

In the past, a number of statistical techniques were used to model the deterioration of steel bridge paint condition ratings, as discussed in Chapter 2. The two main techniques employed for such analysis were regression and the stochastic Markov decision process. Although each technique has its merits and demerits, the regression approach was observed in the present study to capture the expected deterioration pattern of steel bridge paint conditions better than the stochastic Markov decision process. Also, a comparison analysis of these two techniques conducted on steel bridge paint conditions found the results from the regression approach to be better (Zayed et al., 2002). In addition, INDOT's current bridge management system uses a regression approach. Finally, the present study observed, using nine years of steel bridge paint condition rating data, little to no variation in paint condition rating across the selected bridges. Thus, capturing the deterioration of paint condition using a stochastic approach was not feasible. Nonetheless, the study conducted a preliminary analysis using some stochastic techniques, including binary probit and random-effects binary probit models, and found the results to be counterintuitive. Therefore, the present study selected and used the regression approach to analyze the deterioration of steel bridge paint conditions.

The statistical approach used was in the form of a log linear model shown in Equation 3.1.

$$Y = \gamma + \beta_i LN(X_i) + \varepsilon_i, \qquad (3.1)$$

where Y = dependent variable; γ=constant term; X_i vector of independent variables; β_i=estimated parameters; and ε_i=disturbance term.

From the preliminary analysis, the deterioration pattern for painted steel bridges on NHS highways was found to be different for painted steel bridges on Non-NHS highways. In order to test whether to create only one model that captures both highway functional classes or to separate the models into NHS and non-NHS, a log likelihood ratio test was conducted using the test statistic:

$$X^2 = -2[LL(\beta_{LC}) - LL(\beta_{HC})], \qquad (3.2)$$

where $LL(\beta_{LC})$ is the log likelihood at convergence value for the model with the lower convergence value, and $LL(\beta_{HC})$ is the log likelihood at convergence value for the model with the higher convergence value (Greene, 2012; Washington, Karlaftis, & Mannering, 2011). The statistic X^2 is χ^2 distributed and the difference in the numbers of estimated parameters between the models is the degrees of freedom. Using the test statistics, two separate models were recommended. The present study developed separate model for NHS painted steel highway bridges and non-NHS bridges, as shown in Table 3.4.

In Table 3.4, PCR = paint condition rating of steel highway bridge; $PAGE$ = painted age, that is, the years the paint coating system has been on the bridge; $TEMP$= the average annual temperature of the county in which the bridge is located; and γ,β_1,β_2= estimated parameters.

As shown in Table 3.4, an increase in the painted age of the steel bridge decreases the painted condition rating. This result is intuitive. The trend was the same for bridges on the NHS and non-NHS.

The county's average annual temperature values significantly affect the rate of change in condition rating of the paint system on a steel highway bridge. All other things being equal, a bridge located in a county with higher average annual temperature value would deteriorate more slowly than the same bridge in a county with a lower average annual temperature value. The sign of the estimated parameters was the same for NHS highways and non-NHS highways. In the present study, average annual temperatures range from 47 °F to 57 °F.

The factors *bridges over water* and *bridges over roads* were considered in the initial analysis, but they were not found to be statistically significant.

3.2.3 Painting Effectiveness Computation

The effectiveness of a paint treatment was computed using the concept of area under the deterioration curve, as discussed in Chapter 2. For the present study,

TABLE 3.4
Steel Bridge Paint Condition Deterioration Models

Description	Model		Coefficient	t-statistics	Adjusted R^2
NHS	$PCR = \gamma + \beta_1 LN(PAGE) + \beta_2 LN(TEMP)$	γ	–23.195	–8.44	0.406
		β_1	–1.216	–23.38	
		β_2	7.852	11.83	
Non-NHS		γ	–25.108	–6.24	0.411
		β_1	–1.082	–16.39	
		β_2	8.224	8.42	

the effectiveness of a paint treatment was carried out using calculus as indicated in Equation 2.5.

3.3 Cost Models for Painted Steel Bridges

3.3.1 Agency Cost Variables and Model

In order to develop a cost model to capture the relationship between the cost of painting a steel highway bridge, a number of variables were considered. The variables included painted area of the steel bridge, highway functional class (NHS/Non-NHS), the deck area, length and width of bridge, average annual daily traffic, and average annual truck traffic. All the independent variables were tested at different statistical significance levels for possible relationship with the dependent variable, but only paint age and highway functional class (NHS/Non-NHS) were found to be statistically significant at the 5% significance level and were included in the final model. The dependent variables considered initially included agency paint cost and agency paint unit cost. Both variables were evaluated against the independent variables, however, agency paint unit cost was observed to produce the better results. It captures the economies of scale in relation to the size of the different painting projects. The final agency unit paint cost model is presented in Table 3.5.

In Table 3.5, PUC = unit cost to paint steel highway bridges; PA = painted area, that is, the bridge surface area painted; NHS = 1 if the steel bridge is located on an NHS (national highway system) road, otherwise zero; and γ, β_1, β_2 = estimated parameters.

The bridge surface area painted significantly influences the cost of painting a bridge. An increase in the surface area decreases the agency unit cost to paint a steel bridge. This result indicates economies of scale, which would not be adequately captured if the total agency cost was used as a dependent variable.

The highway functional class (NHS/Non-NHS) statistically affects the agency unit cost for painting steel bridges. An increase in the number of steel bridges on the NHS would decrease the unit agency cost to paint these bridges.

Life-cycle painting cost analysis was carried out to estimate the total agency cost over the life cycle of a painted steel bridge. In order to compute the life-cycle cost of painted steel bridges, the various treatment types available for painting a steel highway bridge should be evaluated. Conceptually, the life-cycle agency cost analysis of painting steel bridges should be carried out as illustrated in Figure 3.1. The figure indicates that after new painting is applied for a new bridge, spot repair/paint is carried out followed by an overcoat and then a spot repair/paint before the bridge is replaced.

However, in the present study, the costs of two other treatment types (spot paint and overcoat) were not available, because INDOT does not use these treatment types on steel bridges. INDOT only carries out new painting, and waits for the coating system to deteriorate to a predefined condition threshold of about 5, before a complete recoating is carried out. Thus, the agency life-cycle paint cost for an existing steel bridge considers new painting and complete recoating, as illustrated in Figure 3.2. In the present study, the life-cycle agency cost for steel bridge painting was carried out using the profile in Figure 3.2.

3.3.2 User Costs

Economic efficiency analysis in the present study would require the inclusion of user-related costs caused by steel highway bridge painting. However, the challenge is the determination of the relative weights for user and agency costs. Although some studies counted user costs on an equal basis with agency costs, there is a possibility of a trade-off between agency expenses and user cost (FHWA, 2002). Accordingly, some studies

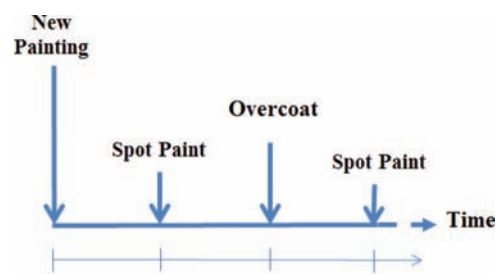


Figure 3.1 Conceptual steel bridge painting profile.

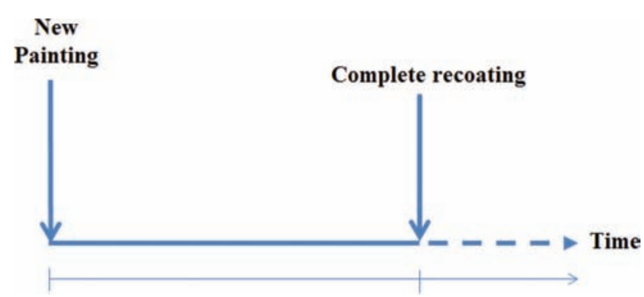


Figure 3.2 State of practice: steel bridge painting profile.

TABLE 3.5
Agency Unit Paint Cost Model

Model		Coefficient	t-statistics	Adjusted R^2
$PUC = \gamma + \beta_1 LN(PA) + \beta_2(NHS)$	γ	24.525	5.60	0.287
	β_1	–1.621	–3.72	
	β_2	–1.273	–2.17	

have argued that only a percentage of user costs ought to be added to agency costs in project evaluation and in the decision-making process. There seems to be no consensus on the issue. In the present study, the equal weight option is one of several options considered in the next chapter.

In order to estimate the user cost related to traffic delay due to a steel bridge painting activity, the present study developed a model to estimate the expected duration, D, of a painting project. The model is, $D = 65.952LN(X) + 154.2$, where X is the contract cost in millions. Based on the estimated work zone duration, the work zone user travel delay cost can be estimated, based on the total traffic volume, surface bridge area painted, the value of time and the percentage of vehicles delayed during the painting period.

For the present study, a case study was created in which average daily traffic volume was 16,911 vehicles per day over a typical steel highway bridge. It was assumed that 10% of the traffic would be delayed, value of time was \$7.25 per hour, and bridge surface area was 22,376 ft^2, resulting in a user cost of \$14.46/ft^2 (in 2015\$). This value will be considered in the next chapter when evaluating the total cost associated with steel bridge painting.

4. DECISION TREE FOR STEEL BRIDGE PAINTING

This chapter computes and evaluates the cost-effectiveness values for possible trigger values for steel highway bridge painting. The cost and effectiveness computations derived in the previous chapter facilitated the cost-effectiveness computations in this chapter. In addition, a decision tree for when to paint a steel highway bridge is proposed and discussed, to help INDOT evaluate possible changes to its current practice.

4.1 Cost-Effectiveness of Steel Bridge Paint Treatments

A paint treatment type is considered cost effective when the benefits derived from the treatment outweigh the costs associated with the treatment. As discussed in previous chapters, the costs associated with steel bridge painting for the present study may include agency costs and user costs. However, it is difficult to determine the proper relative weights for agency and user costs. In some past studies, the focus of evaluating the cost-effectiveness of a treatment was limited to agency cost. In other studies, user costs were considered using sensitivity analysis, where agency cost and user cost were given varied weights. In the present study, sensitivity analysis was used to assess the relative weights of agency and user cost values associated with steel bridge painting.

4.1.1 State of Practice: Life-Cycle Agency Cost Analysis

To facilitate the computation of the cost-effectiveness values for different treatments, a life-cycle cost analysis for each strategy needs to be established. For the present study, INDOT's current strategy of completely recoating a steel bridge approximately every 25 years during the bridge's life was evaluated, to establish its cost-effectiveness. For the purpose of the present study, the life of a steel highway bridge was considered to range from 65 years to 85 years, with an average of 75 years, based on previous studies in Indiana. Thus, using INDOT's current practice of recoating every 25 years, it means that a steel bridge with a 75-year life will receive complete recoating two times before the bridge is replaced, as presented in Figure 4.1. If this practice is expected to continue, costs can be compared using equivalent uniform annual cost.

Based on the frequency of complete recoating in the life of a steel bridge (Figure 4.1), and using a discount rate of 4% (BEA, 2016), the present worth cost is computed as:

$$PW_{CP} = NP + \frac{CR_1}{(1+i)^{25}} + \frac{CR_2}{(1+i)^{50}} \qquad (4.1)$$

where PW_{CP}= present worth cost from the current practice in Indiana, NP = cost of new painting of a steel bridge; i = average annual interest rate; and CR_i= cost of complete recoating in year i.

On the basis of INDOT's historical steel bridge painting data, the average unit cost for painting new steel bridges was \$7.79 (in 2015\$) per square foot area painted, with a standard deviation of \$0.39. Also, the average cost for complete recoating steel bridges was \$6.29 (in 2015\$), with a standard deviation of \$0.38. Using this information, and considering agency cost only, the present worth cost of the current practice for painting steel highway bridges in Indiana can be computed as:

$$PW_{CP} = 7.79 + \frac{6.29}{(1+0.04)^{25}} + \frac{6.29}{(1+0.04)^{50}} = \$11.03/ft^2$$

The present worth agency cost can be annualized as:

$$EUAC_{CP} = 11.03\left(\frac{0.04 \times (1+0.04)^{75}}{(1+0.04)^{75} - 1}\right) = \$0.47/ft^2$$

The user cost was estimated to be \$14.46/ft^2 in the last paragraph of Chapter 3. If this user cost is included

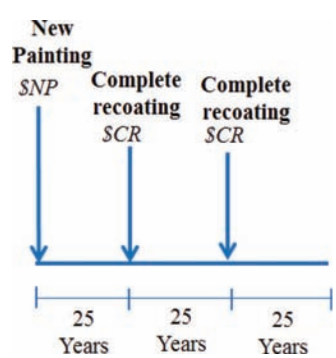


Figure 4.1 Life-cycle cost analysis: Indiana's steel bridge painting practice.

in the present worth of the user cost associated with bridge painting, then the present worth is computed as:

$$PW_{UC} = 14.46 + \frac{14.46}{(1+0.04)^{25}} + \frac{14.46}{(1+0.04)^{50}} = \$21.92/ft^2$$

The present worth user cost can be annualized as:

$$EUAC_{UC} = 21.92 + \left(\frac{0.04 \times (1+0.04)^{75}}{(1+0.04)^{75} - 1}\right) = \$0.93/ft^2$$

After the cost numbers are computed, the effectiveness numbers can be computed to establish the cost-effectiveness of the current practice. Using the deterioration model developed and discussed in Chapter 3 of this report, the effectiveness value was computed as:

$$Eff = \int_0^{TL} (\gamma + \beta_1 LN(PAGE) + \hat{a}_2 LN(TEMP))dpage \quad (4.2)$$

The variables are the same as explained in Chapter 3. The limits are from zero to TL, where TL is the treatment life or service life for the treatment. The treatment life for a painting or coating system varies from 12 to 50 years, with an average of 25 years, based on the model output at condition 4. Using this information, the complete recoating treatment effectiveness is computed as:

$$Eff = \int_0^{25} (-23.195 - 1.216LN(PAGE) + 7.852LN(52))dPAGE \quad (4.3)$$

Solving Equation 4.3 yields a total effectiveness value of 128.3 condition-years gained, from Year zero to Year 25. In order to establish the annual effectiveness value, 128.3 was divided by the service life of the treatment (25 years). The annual effectiveness value is $\left(\frac{128.3}{25}\right) = 5.132$, resulting in an agency cost-effectiveness value of $\left(\frac{5.132}{0.47}\right) = 10.919$. If only user cost is considered, the cost-effectiveness will be $\left(\frac{5.132}{0.93}\right) = 5.518$. Combining agency and user costs into a total cost analysis will result in a cost-effectiveness value of $\left(\frac{5.132}{0.5 \times 0.47 + 0.5 \times 0.93}\right) = 7.331$. Thus, the cost-effectiveness of the current painting practice in Indiana is 7.331. This value was computed assuming the relative weights of agency cost to user cost are one-to-one (that is, 50% of the weight is assigned to agency cost and 50% assigned to user cost). However, if the weight ratio changes, the cost-effectiveness value will be different. Sensitivity analyses with four relative weights of agency cost to user cost are presented in Table 4.1. A graphical illustration, with varying relative weights of agency cost to user cost ratios, is presented in Figure 4.2. From the table and the figure, it can be observed that, if the weight of agency cost is 0.8 and the weight of user cost is 0.2, the cost-effectiveness will be 9.132.

TABLE 4.1
Effect of User Cost of Steel Painting Cost-Effectiveness

Agency Cost Weight	User Cost Weight	Cost-Effectiveness
0	1	5.518
0.5	0.5	7.331
0.80	0.2	9.132
0.84	0.16	9.441
1	0	10.919

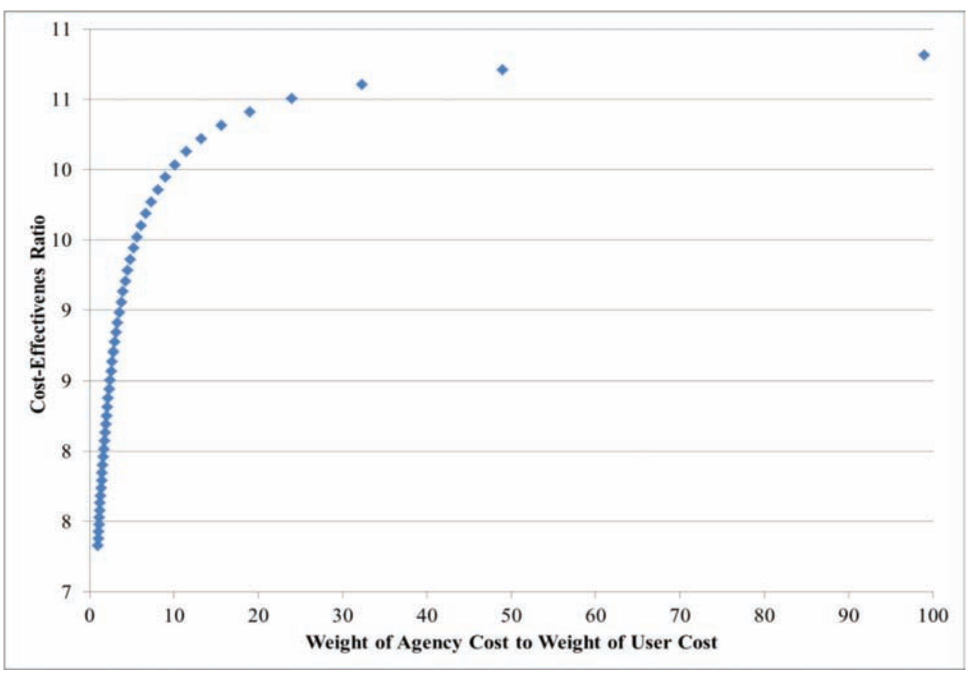


Figure 4.2 Painting cost-effectiveness versus ratio of weight of agency cost to weight of user cost.

In order to evaluate the potential of either applying complete recoating at conditions 3 or 5, the same computational procedure discussed for condition trigger value 4 was applied, with some assumptions. For trigger values 3 and 5, 15% and 8% of the traffic volume was assumed to be delayed compared 10% for trigger value 4. This assumption was included because, from practice, a lower paint condition would require a longer time for painting compared to a relatively better paint condition. Thus, the present study assumed that condition trigger value 3 would require more painting duration compared to condition trigger value 5. The cost-effectiveness results are presented in Table 4.2. The results in Table 4.2 assume that the weight for user cost is the same as the weight for agency cost. In the table, it can be observed that paint condition trigger 4 is the most cost-effective for the current practice.

4.2 Proposed Painting Treatments Strategy

The present study considered alternatives to current INDOT's treatment strategy to facilitate longevity of steel highway bridges. An alternative strategy was derived from the guidelines in ASTM and SSPC standards as discussed earlier in Chapter 2.

In order to develop this strategy, three treatment types were assumed to be possible in the life of a steel highway bridge. These treatment types are new painting, spot repair or painting, and overcoat. A spot repair takes place when the rusted areas on a steel highway bridge are removed from the surface, and a new paint is applied to those specific areas or surfaces. Overcoating is carried out on a steel highway bridge when all defective areas are removed and the entire steel bridge surface receives a new paint. This new paint ought to be compatible with the existing paint system.

To evaluate possible strategies, these treatment types (new painting, spot repair/painting, and overcoating) will be considered in the life-cycle analysis of a steel highway bridge, as illustrated in Figure 4.3. In the figure, spot repair or painting is considered in the 20th year, overcoating in the 40th year, and spot repair in the 60th year. The bridge is replaced in the 75th year.

In order to evaluate this strategy, and compare the results with INDOT's current practice, cost values are needed. The costs associated with spot repair/painting and overcoating from previous studies are presented in Table 4.3. In the table, for example, new steel bridge average painting cost was \$7.79 (in 2015\$) per square foot area painted.

Using the treatment types in Figure 4.3, with a 4% discount rate and cost values in Table 4.3, the present worth agency cost based on the proposed strategy is:

$$PW_{PPSAC} = 7.79 + \frac{3.69}{(1+0.04)^{20}} + \frac{4.43}{(1+0.04)^{40}} + \frac{3.69}{(1+0.04)^{60}} = \$10.75/ft^2$$

The present worth of agency cost can be annualized as:

$$EUAC_{PPSAC} = 10.75\left(\frac{0.04\times(1+0.04)^{75}}{(1+0.04)^{75}-1}\right) = \$0.45/ft^2$$

To compute user cost for the proposed painting strategy, the present study assumes that spot repair takes a shorter painting time than complete recoating, because the paint condition requiring spot repair is in a better condition; thus, spot repair is expected to have insignificant bridge user delay (i.e., assumed as no bridge user delay) compared to complete recoating. For overcoat, it was assumed that the travel time delay caused to bridge users would be about 50% that of complete recoating, based on past experiences from other states. The present worth user cost associated with bridge painting for the proposed painting strategy is:

$$PW_{PPSUC} = 14.46\left(\frac{0.5\times 14.46}{(1+0.04)^{40}}\right) = \$15.97/ft^2$$

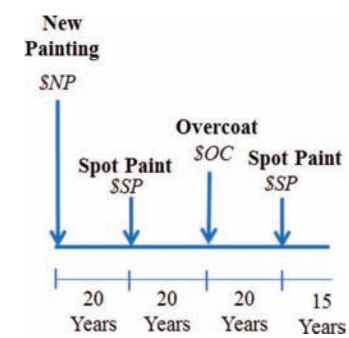


Figure 4.3 Proposed steel bridge painting activity profile.

TABLE 4.2
A Comparison of Paint Condition Trigger Values for Current Practice

Paint Condition Trigger	Annualized Effectiveness	Traffic Volume delayed (%)	User Cost ($\$/ft^2$)	Agency Cost ($\$/ft^2$)	Total Cost ($\$/ft^2$)	Cost-Effectiveness
3	4.306	15	1.03	0.36	1.39	6.196*
4	5.132	10	0.93	0.47	1.40	7.331
5	6.108	8	1.25	0.74	1.99	6.139**

*Cost-effectiveness value for trigger value 3 $= \left(\frac{4.306}{0.5\times1.03+0.5\times0.36}\right) = 6.196$

**Cost-effectiveness value for trigger value 5 $= \left(\frac{6.108}{0.5\times1.25+0.5\times0.74}\right) = 6.139$

The present worth of user cost is annualized as:

$$EUAC_{PPSUC\infty} = 15.97\left(\frac{0.04\times(1+0.04)^{75}}{(1+0.04)^{75}-1}\right) = \$0.67/ft^2$$

Based on the computations presented above, the total annualized cost (agency and user) for the proposed painting strategy is \$0.45 + \$0.67 = \$1.12/ft^2, which is lower than \$0.47 + \$0.93 = \$1.40/ft^2 for the current practice. Based on only the cost components, the proposed strategy in Figure 4.3 will yield the lower annualized cost.

The effectiveness of each treatment type can be developed based on historical data. However, in the absence of these data, the paint deterioration models developed and presented in Chapter 3 were used to compute the effectiveness. This approach assumes that paint deterioration on steel highway bridges is similar, regardless of the treatment type. This assumption may not be accurate, because the use of a complete recoating deterioration model as a surrogate for spot repair and overcoating may not reflect the actual pattern of deterioration. However, in the absence of any deterioration model from spot repair and overcoating treatments, the present study used the models derived from complete recoating to estimate the effectiveness of both spot repair and overcoating. The effectiveness values for using the proposed strategy are presented in Table 4.4.

The cost-effectiveness value of the proposed strategy is 9.805, and this value is higher than the cost-effectiveness value of the current practice (7.331, see Tables 4.1 and 4.2). Based on the results, it would be appropriate for INDOT to either continue applying complete recoating at trigger value 4 (see Table 4.2), or include spot repair and overcoating in the management of steel highway bridges. The latter strategy is considered a better option than the former based on the cost-effectiveness results, and the next section discusses how INDOT can incorporate the latter strategy into the proposed decision tree for painting steel highway bridges.

4.2.1 Painting Decision Tree

In order to consider spot repair and overcoating in the decision-making process of steel bridge painting, a steel painting decision tree is proposed in Figure 4.4. The tree is based on the results computed earlier and the guidelines from the ASTM/SSPC (Table 4.5).

TABLE 4.3
Cost per Paint Treatment Type

Description	Cost (2015\$/ft^2)	Source/Remarks
Steel bridge painting when bridge is newly constructed	7.79	INDOT
Spot repair/painting	3.69	Derived from Zayed et al., 2002.
Overcoating	4.43	Derived from Zayed et al., 2002. Overcoating coat is about 1.2 times the coat of spot painting

TABLE 4.4
Cost-Effectiveness of Proposed Painting Strategy

Annualized Effectiveness	User Cost (\$/ft^2)	Agency Cost (\$/ft^2)	Total Cost (\$/ft^2)	Cost-Effectiveness
5.491	0.67	0.45	1.12	9.805

TABLE 4.5
Condition Triggers for Steel Bridge Painting (derived from ASTM, 2009)

Condition State	Condition Rating/ Trigger	Description	Areas to Be Repainted (%)	Surface Status
1	10	No rust or <0.01% rust	0	Almost no corrosion
	9	<0.03% rust	0	Almost no corrosion
2	8	Few isolated spots, <0.1% rust	0	Almost no corrosion
	7	<0.3% rust	0	Slight corrosion
3	6	Extensive rust spots, <1% rust	8	Slight corrosion
	5	<3% rust	18	Obvious corrosion
4	4	<10% rust	40	Entirely corroded
	3	Approximately 1/6 of surface rusted	60	Entirely corroded
5	2	Approximately 1/3 of surface rusted	100	Entirely corroded
	1	Approximately 1/2 of surface rusted	100	Entirely corroded
	0	Approximately 100% of surface rusted	100	Entirely corroded

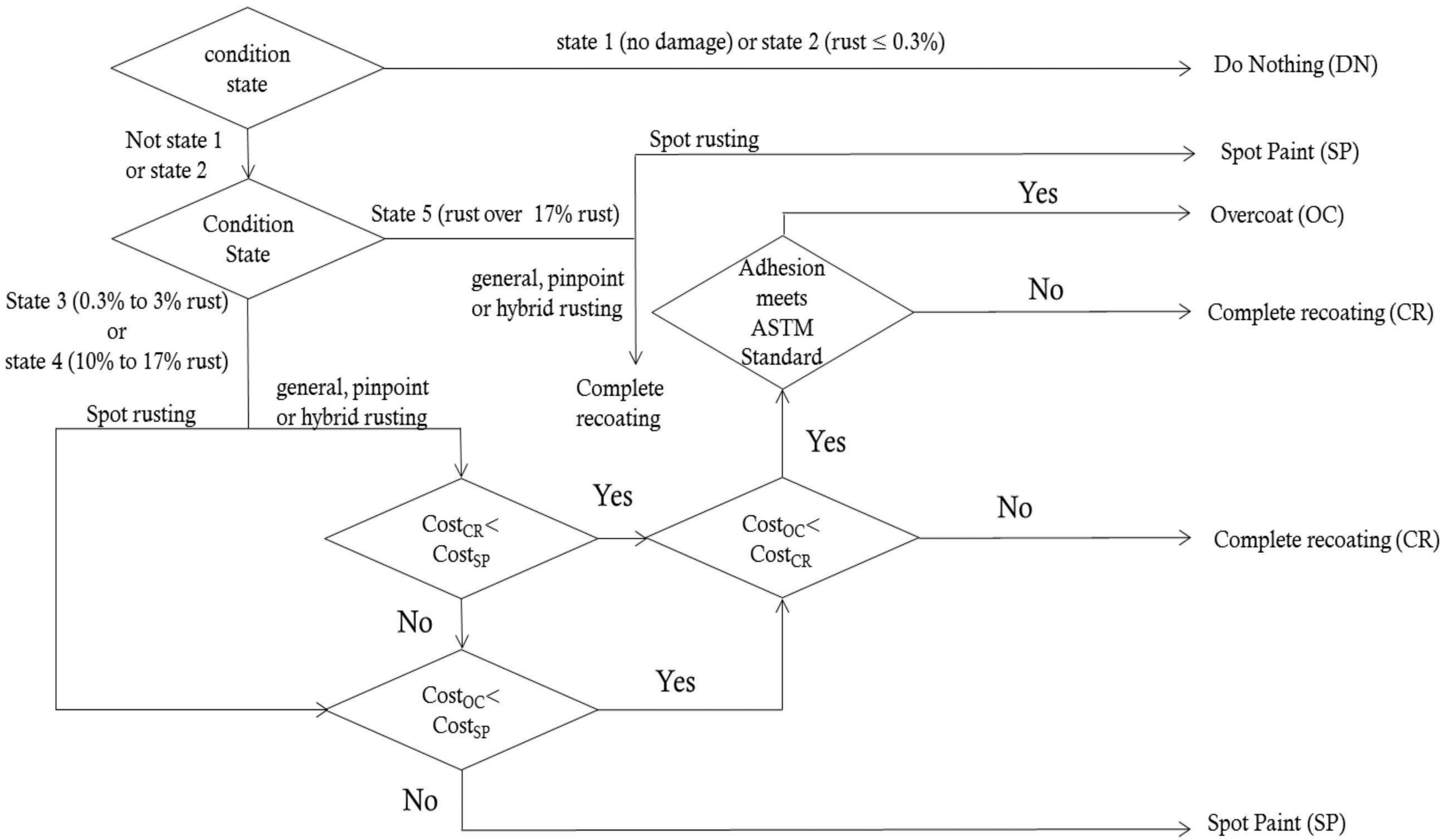


Figure 4.4 Painting decision tree.

The decision to select a specific painting treatment type for a painting distress can be determined from Figure 4.4. If a steel bridge has condition *rating* 2, 1 or 0 (which is the same as condition *state* 5 in Table 4.5), either it has extensive spots of corrosion on the surface or the surface is entirely corroded. The decision can either be spot repair, if the corrosion is located at varied spots, or complete recoating, if the entire surface is corroded. The decision tree would serve as a broad framework to guide INDOT in the determination as to when to apply a particular paint treatment type. If the steel bridge has condition rating 10 or 9 (corresponding to condition state 1) or condition rating 8 or 7 (corresponding to condition state 2), that bridge does not require any treatment type, and it is indicated in Figure 4.4 as "do nothing."

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The present study was carried out to establish a cost-effective way of painting steel highway bridges. Using data collected from INDOT and other agencies, deterioration models were developed for painted steel highway bridges on NHS and NNHS routes. The models were used to compute the effectiveness expected from the current INDOT practice for painting steel highway bridges.

In addition, an agency painting cost model was developed based on cost-related data from INDOT. In order to include user-related costs, scenario analyses were conducted based on varying hypothetical relative weights of agency cost to user cost.

After evaluating INDOT's current practice, a painting decision tree was developed. The tree can serve as a framework that would enable INDOT to consider other maintenance treatment types, namely spot repair/painting and overcoating. Based on the results, it would be appropriate for INDOT to either continue applying complete recoating at trigger value 4, or include spot repair and overcoating in the management of steel highway bridges based on the proposed painting strategy. The proposed decision framework would allow INDOT to be more cost-effective in deciding when and how to paint a steel highway bridge.

5.2 Recommendation and Future Research

Based on the results from the present study, the adoption of the developed decision tree would facilitate and enable INDOT to be more cost-effective in relation to steel bridge painting. Due to data unavailability on spot repair and overcoat treatment types, the present study made some assumptions about treatment costs and subsequent paint performance. If INDOT begins to use spot repair and overcoating, cost and performance data should be collected to permit a check on the cost-effectiveness of such treatments.

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APPENDIX: EVALUATING DEGREE OF RUSTING ON PAINTED STEEL SURFACE (ASTM, 2012)

Rust Distribution

Spot Rusting

Spot rusting occurs when the bulk of the rusting is concentrated in a few localized areas of the painted surface. The reference photographs in Figures A.1, A.2, and A.3 depicting this type of rusting are labeled 9-S through 1-S.

General Rusting

General rusting occurs when various size rust spots are randomly distributed across the surface. The reference photographs in Figures A.1, A.2, and A.3 depicting this type of rusting are labeled 9-G through 1-G.

Pinpoint Rusting

Pinpoint rusting occurs when the rust is distributed across the surface as very small individual specks of rust. The reference photographs in Figures A.1, A.2, and A.3 depicting this type of rusting are labeled 9-P through 1-P.

Other Rusting

An actual rusting surface may be a hybrid combination of the types of rust distribution depicted in the reference photographs. In this case, combinations of the photographs and rust grades may be needed to classify the surface.

Procedures

Select Area

Select the area which is to be evaluated for degree of rusting. This area may be as small as a test panel or as large as the hull of a ship. For complex structures, each member may be evaluated as a whole, or different sections may be evaluated separately (e.g., top of flange, web of a beam, or edges).

Determine Rust Distribution

Determine the rust distribution (spot, general, or pinpoint) that most closely matches the selected area. Compare the selected area with the corresponding color photograph or black and white image. Determine the percentage of rust on the surface by visual comparison with the reference photographs, by electronic scanning techniques, or other methods agreed upon by the contracting parties.

Determine Rust Grade

The rust grade is determined by the percentage of visible rust on the surface as defined in Figures A.1, A.2, and A.3. If rust buildup is evident under the coating, as in a rust blister or as rust undercutting, then that rusted area shall be included in the determination of the rust grade.

- A rust blister is defined as a spot on a painted surface where the coating is intact but raised from the surface by the expansion of rust. The rust is not visible, but lies beneath the coating. A rust blister is not the same as a fluid-filled blister, which is typically caused by osmotic pressure or solvent entrapment. The volume of rust (if present) in a fluid-filled blister is a small percentage of the volume of the blister, whereas rust occupies most of the volume of a rust blister. A fluid-filled blister may collapse, but a rust blister will not collapse. Fluid-filled blisters should not be included in the determination of the rust grade.
- If rust blisters are present, the rust grade shall be determined considering the rust blisters as visible rust. This rating must be recorded in such a manner that it is clear to the contracting parties that rust blisters were present and that they were considered as visible rust when assigning a rust grade.
- Rust undercutting at a damaged area, at a broken blister, or at a place where the painted surface meets a rusted area, shall be considered as visible rust in the determination of the rust grade. A dull putty knife may be used to remove loose coating, thereby exposing the rusted areas.

Other Considerations

Care must be exercised when determining the percentage of rust on the surface.

- Some finishes are stained by rust. This staining shall not be considered as rust.
- Accumulated dirt or other material may make accurate determination of the degree of rusting difficult. This dirt shall not be considered as rust.
- Certain types of dirt that contain iron or iron compounds may cause surface discoloration that should not be mistaken for corrosion.
- In evaluating surfaces, consideration shall be given to the color of the finish coating. A light surface that contrasts with the rust may appear to have a lower rust grade than a similarly rusted surface with a color that blends with the rust.

Reporting

Report the area or item evaluated, the type or types of rust distribution, the presence of rust blisters (if applicable), and the rust grade.

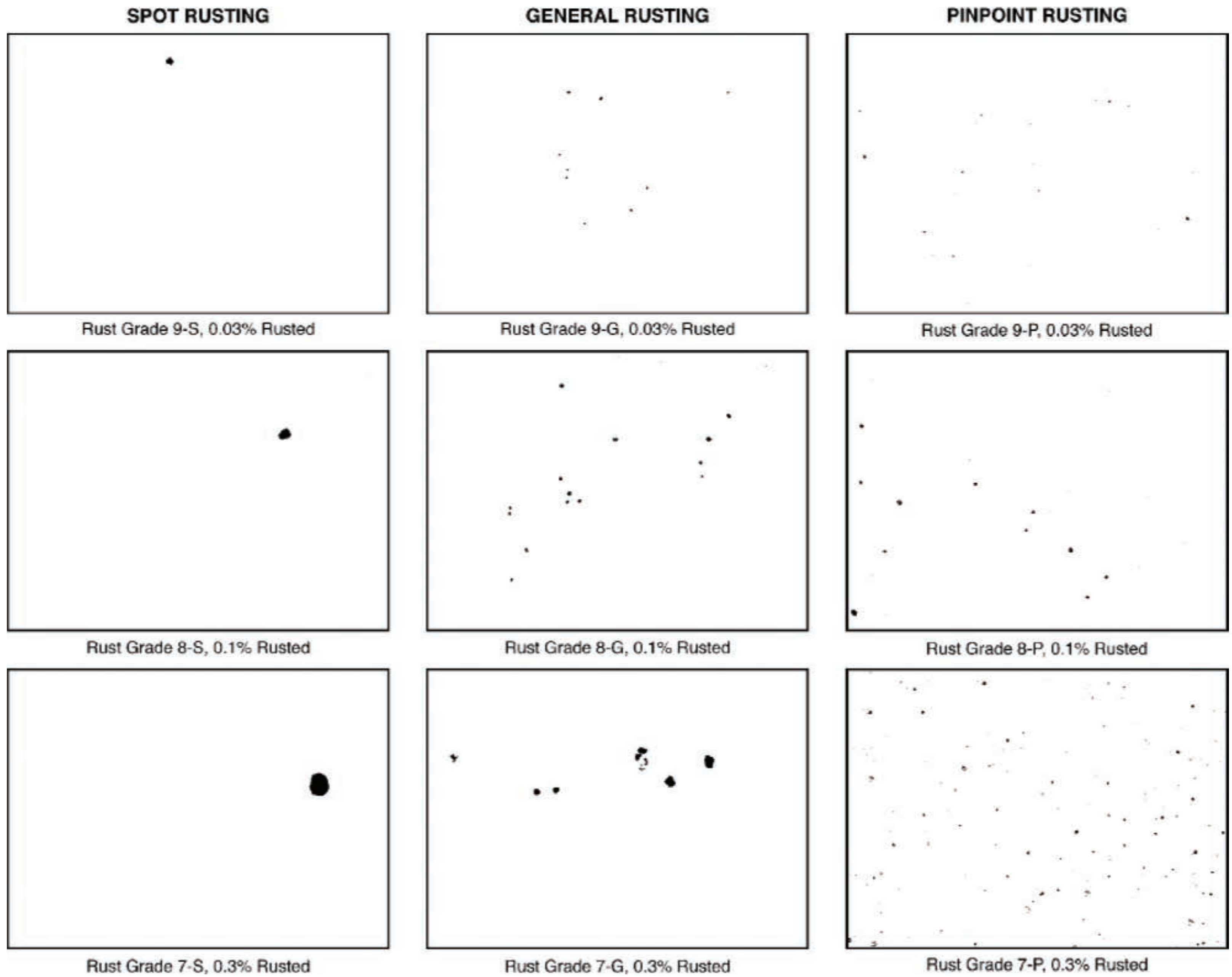

Figure A.1 Rust grades: 7, 8, and 9.

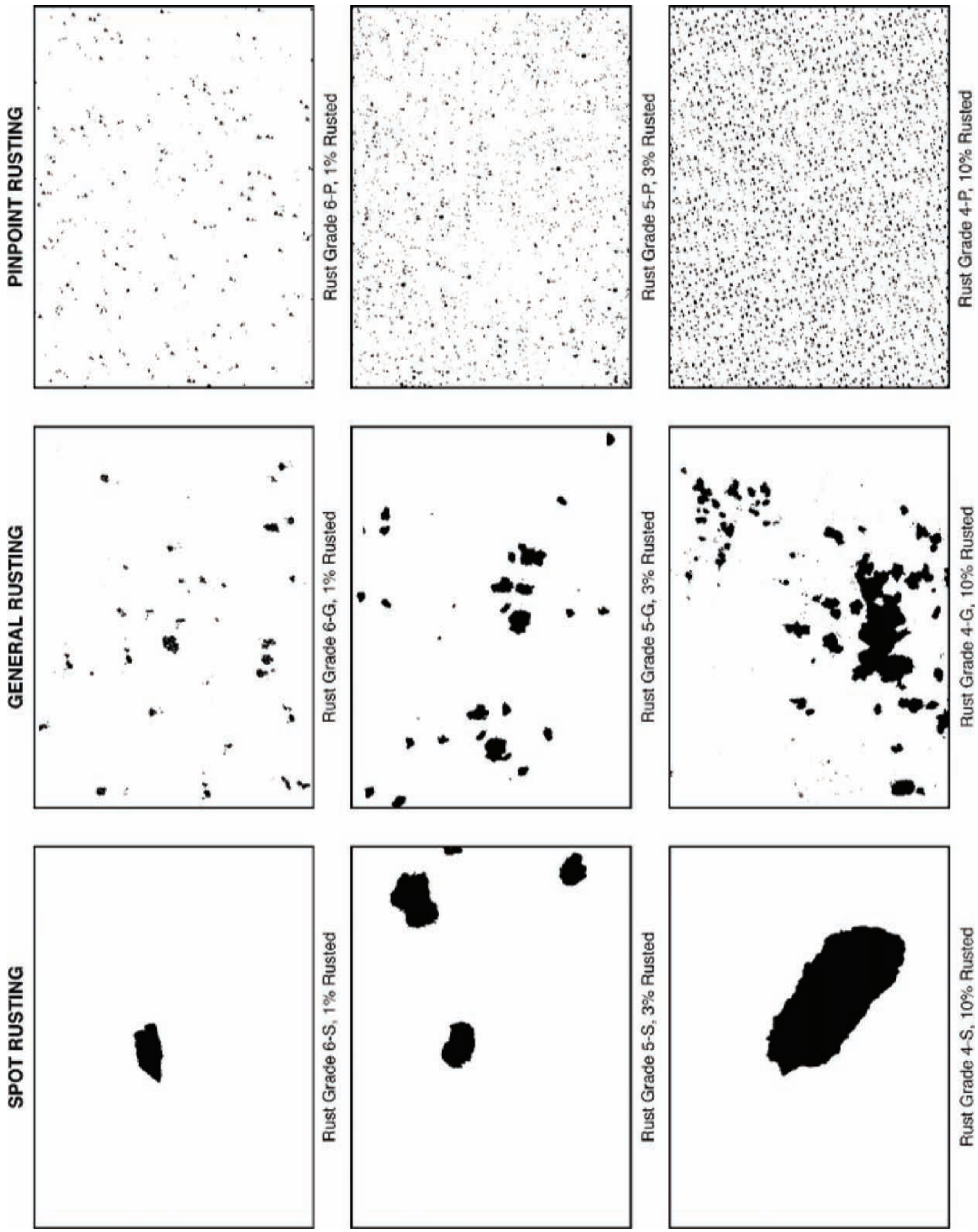

Figure A.2 Rust grades: 4, 5, and 6.

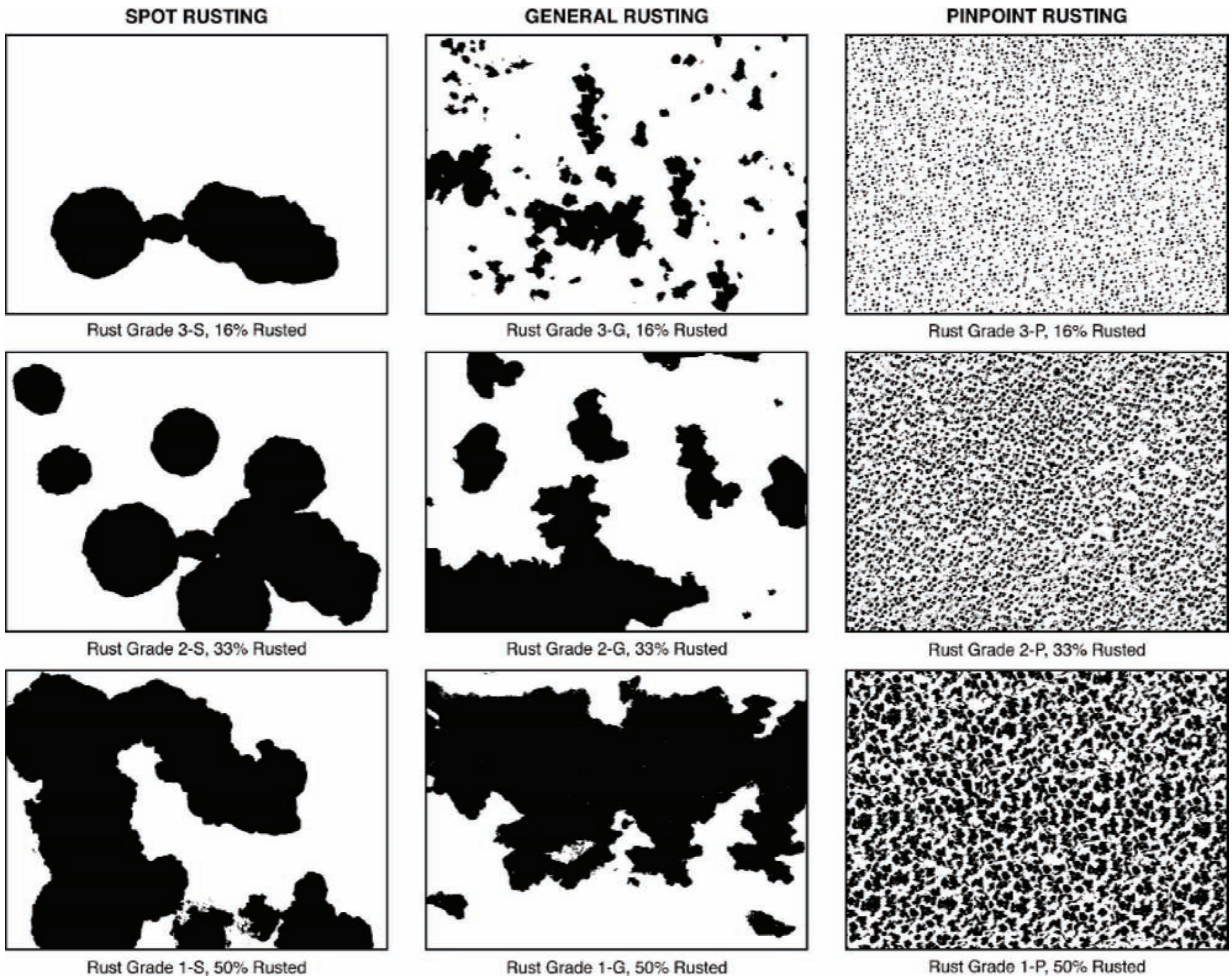

Figure A.3 Rust grades: 1, 2, and 3.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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