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Probability of Detection Study for Visual Inspection of Steel Bridges: Volume 2—Full Project Report

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16. Abstract <p>An inspector's ability to correctly identify surface and internal defects in steel bridge components is critical to protecting public safety. Ensuring that inspectors are properly trained and adequately equipped to detect these defects in locations that are difficult to access and/or in unfavorable environmental conditions must be a high priority. While the Federal Highway Administration and individual state departments of transportation have guidelines for inspector qualifications, trainings, and certifications, there is very little emphasis placed on evaluating or "testing: a given inspector's capability to characterize defects in the field. As a result, there is also very little, if any, data on how well a given inspector actually performs or the variability which can be expected between inspectors.</p> <p>This comprehensive Probability of Detection (POD) study was conducted to establish the ability of an inspector with the current required training to locate and quantify cracks in steel bridge components. This study is believed to be the first statistically-significant study of its kind in the United States.</p>			
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EXECUTIVE SUMMARY

Introduction

An inspector's ability to correctly identify surface and internal defects in steel bridge components is critical to protecting public safety. Ensuring that inspectors are properly trained and adequately equipped to detect these defects in locations that are difficult to access and/or in unfavorable environmental conditions must be a high priority. While the Federal Highway Administration and individual state departments of transportation have guidelines for inspector qualifications, trainings, and certifications, there is very little emphasis placed on evaluating or testing a given inspector's ability to characterize defects in the field. As a result, there is also very little, if any, data on how well a given inspector actually performs or on the variability that can be expected between inspectors.

This comprehensive probability of detection (POD) study was conducted to establish the ability of an inspector with the current required training to locate and quantify cracks in steel bridge components. This study is believed to be the first statistically significant study of its kind in the United States.

Specifically, during this research a POD study focused on visual detection of fatigue cracks in steel bridge girders was performed. Trained and experienced bridge inspectors were asked to conduct routine hands-on inspections of simulated steel bridge components with known defects. The hands-on portion of the inspection course was conducted outdoors and from a man-lift to better simulate field bridge inspections. The focus of the test inspection course was to locate and identify cracks in steel components. The details represented on the test bridge mimic those currently in the bridge inventory. Environmental and personal factors were tracked and compared to detection rates. This study is believed to be the first statistically significant study related to visual inspection of cracks in steel bridge components.

The study has shown that routine visual inspection from the ground and hands-on visual inspection of weathering and painted steel bridge girders were unreliable for finding cracks. In fact, the routine inspection scenario and the hands-on inspection of the weathering steel specimens were discontinued partway through the study due to low detection rates and to allow adequate time for the hands-on inspection of the painted specimens. Based on the results of the POD study, recommendations to improve the reliability of hands-on visual inspection of painted steel bridge girders have been made.

It is important to note that the intention of this study was to evaluate the reliability of visual inspection of steel bridges, not to find fault with individual inspectors. The research set out to determine what cracks are being missed and whether or not the expectations for inspectors are reasonable. If inspectors are expected to find cracks that cannot be reasonably or reliably detected with the current procedures, the system needs to be reevaluated. Additionally, the findings of this study likely represent the upper bound on visual inspection performance. The inspections were performed in isolation, free from many of the distractions and time pressures present during a typical inspection, unobstructed access to the inspection surface was provided, and cracks were present at a higher than average rate.

Findings and Conclusions

Variations in the reporting techniques for both routine and hands-on inspection of steel bridge superstructures were observed. While the documentation styles and level of detail may have been impacted by the study procedures provided or the fact that they were being observed in a test setting, it is clear that there is no consistent standard for identifying what information should and should not be recorded during a visual inspection.

Inspectors did not bring or use the same equipment to conduct hands-on visual inspections. Although no relationship was found between inspection performance and tool use, this is thought to be due to the lack of information collected during the study, and not because inspection tools have no effect on performance.

The routine inspection scenario produced highly varied inspection reports. The inspectors' documentation ranged from detailed cracks with dimensions, to unlabeled tick marks, to general comments on the overall condition of the bridge. Time spent completing the ground scenario ranged from 12 minutes to 82 minutes.

The hands-on inspection scenario for the weathered specimens resulted in an average detection rate of 11%. Of the 198 observations, only 21 hits were identified. Six of the 11 inspectors did not find any cracks.

The average detection rate for all 30 inspectors of all 70 cracks located on the painted specimens was 65%. Detection rates ranged from 31% to 86%. Univariate analysis between detection rates and other factors, like inspection time or the day's weather, revealed slight, but statistically significant, correlations. Detection rate increased with increasing inspection duration, temperature, and training, but it decreased with increasing experience.

For the majority of the inspectors, the likelihood of a crack being detected increased with crack length. However, this was not true for three of the participants.

The average number of false calls for all 30 inspectors on the 147 painted specimens was 90. The number of false calls ranged from 14 to 268. Univariate analysis between the number of false calls and other factors, like inspection time or the day's weather, did not reveal any significant correlations. However, the multivariate analysis revealed that the number of false calls was related to the inspector's employer, the maximum wind speed on the day of the inspection, the use of a tape measure, and completion of the Element Level Bridge Inspection training course. Inspectors who used a tape measure made fewer false calls, while inspectors who were employed by a private inspection/engineering firm experienced higher wind speeds and those who attended the training course tended to make more false calls.

Probability of detection analysis using a log-odds model generated POD values for varying crack lengths. For the total population of cracks for this set of inspectors, a 1-inch-long crack had a 50% chance of being detected and a 5-1/2-inch-long crack had a 90% chance of being detected. The data was too scattered to assign a 95% confidence bound.

A random parameters binary logit model was used to identify variables beyond crack length that affected the probability that a crack would be detected. The analysis showed that crack length, the type of crack, the inspector's years of experience, the inspection duration, and the elapsed time since the first inspection significantly impacted the likelihood of a crack being detected.

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1. INTRODUCTION

1.1 Overview of Problem Being Researched

An inspector's ability to correctly identify surface and internal defects in steel bridge components is critical to protecting public safety. Ensuring that these inspectors are properly trained and adequately prepared to detect these defects in locations that are difficult to access and/or in unfavorable environmental conditions must be a high priority. While the Federal Highway Administration and individual state departments of transportation have guidelines for inspector qualifications, trainings, and certifications, there is very little emphasis placed on evaluating or "testing: a given inspector's capability to characterize defects in the field." As a result, there is also very little, if any, data on how well a given inspector actually performs or the variability which can be expected between inspectors.

Inspectors are tasked with locating and documenting bridge defects so that they can either be monitored more closely for changes or be repaired before becoming critical. Inspectors can employ several non-destructive testing techniques to discover these defects. The most fundamental of these techniques is visual inspection—which requires an inspector to look for visible defects with his/her naked eye. Generally, these inspections are performed at an arm's length away from the surface of the bridge, however, some inspections are performed at a greater distance. Those inspections conducted from a greater distance are often referred to as routine inspections and can be performed from the ground, often using binoculars. Currently the requirements for bridge inspection do not consider certain factors, including the exact tools (i.e., specific type of flashlight) used by an inspector or the inspector's visual acuity.

This comprehensive Probability of Detection (POD) Study was conducted to establish the ability of an inspector with the current required training to locate and quantify fatigue cracks in steel bridge components.

1.2 Overview of Probability of Detection Studies

POD studies are used to determine the probability of detecting a defect in a specified size group under the provided inspection conditions and procedures. The probability of detection metric was developed in the 1960s to quantitatively describe the detection capability of various nondestructive examination (NDE) techniques. Probability of detection is typically expressed as a function of a parameter associated with the given flaw (e.g., length). While the target parameter is assumed to be the most influential factor in determining the probability of detection, it is also a function of many other physical and operational factors including the material, geometry, flaw type, NDE method, testing conditions, and the inspector, his/her certification, education, and experience (Georgiou, 2006).

1.2.1 Controlled and Uncontrolled Factors

The output of a POD study is the quantification of detection as a function of crack size. A probability of detection study seeks to answer the questions: "How large a crack might be missed?" and "How confident are we in the answer provided?" However, because cracks of the same size can result in widely varied probabilities of detection, other factors besides flaw size must be taken into account (Rummel & Matzkanin, 1997). While flaw size is the most influential factor in a POD experiment, other factors contribute to variability. Rummel, Hardy, and Cooper (1989) divided these factors into four categories:

- *Inspection Materials:* Depending on the NDE process, various equipment is needed to perform inspections. To control the impact of equipment on POD results, the equipment for each inspection must be in working order.
- *Inspection Process:* The specimens produced for a POD study must have flaws that are capable of being found by the NDE process that is being evaluated. Using the same types of flaws that are used in reference standards for a particular method of NDE is the most common way to obtain representative specimens.
- *Characteristics of the Target:* In addition to the size of the flaw, other characteristics, including its orientation, location, and shape can influence the likelihood of it being detected.
- *Human Factors:* Inspection personnel is the largest uncontrolled variable affecting inspection reliability. An inspector's training, experience, state-of-mind, and eyesight can all impact the results of a nondestructive evaluation assessment of a structure.

Even with tight control on the variables described above, a highly varied response can be returned for cracks of equal length. Repeated measures on a single crack will yield varied results—the crack will be detected by some inspectors and missed by others. However, testing numerous inspectors on the same set of flawed and unflawed specimens using the same NDE process, provides data that can be generally applied to flaws of the same type and size range that may be encountered in the field (DoD, 2009).

1.2.2 Sample Size

One of the primary reasons that probability of detection studies are not more common, particularly in the steel bridge industry, is due to the fact that it is expensive to produce and maintain realistically sized specimens with representative flaws. Due to the difficulty of manufacturing and expenses related to procuring specimens, there is a tendency to reduce the sample size for a given study. Decreasing the number of specimens that are inspected increases the uncertainty associated with the resulting POD curve (Annis et al., 2013).

For a hit/miss probability of detection study, it is recommended that 60 flaws be present; studies with

fewer than 60 observations are not stable (Annis et al., 2013). It is recommended that the test set contain at least three times as many unflawed inspection sites as flawed sites. The unflawed inspection sites are referred to as “noise.” Each specimen in the test may have more than one noise site (DoD, 2009).

1.2.3 Test Specimens

The test specimens and flaws should be representative in size, orientation, and condition to what would be encountered in the field. The flaws should be placed in locations where they occur on the components in reality and must be able to be detected by the method being evaluated. If a crack cannot be seen visually, it cannot be included in a POD study testing the effectiveness of visual inspection. The surface condition of the specimens can greatly affect detectability and should be consistent with the condition encountered in practice (DoD, 2009).

The flaw lengths on the test specimens should be of lengths that can be found in the field by the method of inspection being evaluated. A uniform distribution of target sizes between the smallest and largest crack size is recommended. For successful convergence, the range of crack sizes should produce coverage between $POD = 3\%$ and $POD = 97\%$. This means the smallest defect in the population would result in a $POD = 3\%$ and the largest defect have $POD = 97\%$, so that the model does not need to extrapolate probabilities for cracks outside the range present in the study (Annis & Gandossi, 2012).

1.2.4 POD Statistical Analysis

In response to the growing popularity of POD studies and a general concern that the data generated from these studies could be easily misinterpreted, the United States Department of Defense (DoD) released *MILK-HDBK-1823A* (DoD, 2009) with guidance for measuring NDE system reliability with POD statistics. This handbook is widely cited throughout the world and is applicable to any NDE method that produces either a quantitative signal, such as ultrasonic testing, or a binary response, such as visual inspection. It presents a uniform approach for assessing the capability of an NDE method by relating the probability of detection (POD) to target size (a). A perfect inspection would be represented by a step function with $POD = 0$ for all defects smaller than the critical defect size and $POD = 1$ for all defects larger than the critical defect size (DoD, 2009). The DoD handbook proposes eight possible underlying mathematical relationships between POD and size that can be fit to the test data and used to predict the results of future inspections.

The author of *MIL-HDBK-1823A* (DoD, 2009) developed accompanying software that utilizes the recommended statistical algorithms to produce the probability of detection versus defect size curves. This software, *mh1823POD*, utilizes the R-programming

language and is freely available to anyone who requests it (Annis, 2016). It provides diagnostic plots of each possible model and allows the user to specify the link function (log-odds, inverse normal, complementary log-log, or log-log) and size relationship (a or $\log(a)$) which best fits the data. The model parameters are automatically estimated by the software using an iteratively reweighted least squares technique that accounts for the non-uniform variance in the error terms. Confidence bounds are computed by varying the parameters away from the values that provide the maximum likelihood in order to generate a family of curves that represent the specified confidence bounds on the maximum likelihood curve. For example, at 95% confidence, the confidence limits are expected to enclose the true POD curve in 95 out of 100 similar inspections. Note that in the case of hit/miss data, confidence bounds are not the same as prediction bounds (Gandossi & Annis, 2010). Since the outcome of a single future inspection will be either a hit (1) or a miss (0), it is meaningless to consider a prediction that may be between 0 and 1. Ultimately, the following values typically used to describe NDE system capability can be extracted from the POD curves:

- a_{50} : defect size that has a 50% probability of detection (50% confidence)
- a_{90} : defect size that has a 90% probability of detection (50% confidence)
- $a_{90/95}$: defect size that has a 90% probability of detection (95% confidence)

1.3 Summary

The POD study was designed to provide a benchmark measure of visual inspection capability for detecting fatigue cracks in steel bridge components using current inspection practices. Probability of detection curves are the current standard for evaluating the detection capability of NDE techniques in numerous industries, including oil and gas, nuclear, and aviation; however, this metric has not previously been applied to the visual inspection of steel bridges. In order to perform a valid POD study, it must include sufficient flawed and unflawed specimens to overcome the inevitable variability in performance, and the specimens and their defects must be realistic and representative of those that would be encountered in the field.

2. PROBABILITY OF DETECTION TEST DESIGN

To gain meaningful data from a probability of detection study, the test must be designed and arranged to have specific characteristics, including a minimum number of defects, proper variation of defect size, and an appropriate ratio of un-cracked to cracked specimens. To best simulate the types of details and cracks that an inspector encounters in the field, a variety of defect types and locations were used on the different types of specimens and arranged in a way that replicated the typical field experience for visual inspection.

The following sections describe the POD test set-up, as well as specifics concerning the specimen design and overall matrix.

2.1 Test Frame

The POD study aimed to assess the accuracy of current visual inspection practices for hands-on inspection of steel bridges. To get an accurate representation of what types and lengths of cracks an inspector is likely to detect, 30 current inspectors were asked to complete a typical hands-on inspection from the bucket of a man-lift using only visual inspection as well as an initial routine inspection of the same structure from the ground. No additional forms of NDE methods, such as magnetic particle (MT) testing, were permitted. A test frame simulating a two-span, three-girder bridge was designed and constructed outdoors at Purdue University's Steel Bridge Research, Inspection, Training and Engineering (S-BRITE) Center. The test specimens, a combination of W36 rolled shapes, welded plate girders, welded cover plates, and riveted plates were suspended from the hot-dip galvanized frame. A photograph of the completed frame and specimens is shown in Figure 2.1.

As shown in Figure 2.1, one span of the test frame was dedicated to unpainted steel, representing weathering steel bridges, while the adjacent span was comprised of painted specimens. It was determined that the difference in surface coating, weathered versus painted, greatly impacted the probability of a crack being detected by visual inspection. The detection rates on the weathered steel span were too low to be evaluated with probabilistic POD analysis and are effectively invalid.

After the first 11 inspectors, the inspections of the weathering steel specimens were discontinued; however, the data from these inspectors are presented herein.

2.1.1 Test Frame Dimensions

The test frame was designed to simulate a highway bridge. The specimens were suspended 26 feet from the ground, requiring the use of a man-lift to conduct the hands-on visual inspections. The total frame length was 80 feet, with each girder having a 40-foot span.

Each of the six girders supported eighteen 23-inch long rolled wide flange or plate girder specimens with varying details. The specifics of detail types included in the matrix are discussed in subsequent sections. The girders were spaced 8 feet 4 inches apart, which fell within the range of typical highway bridge girder spacing.

The girder details, such as transverse stiffeners, longitudinal stiffeners, or gusset plates, were spaced at tighter intervals than would be found on an actual bridge in order to maximize the number and variety of details. These details, which are the typical sites for cracks on steel bridges, were present on each specimen, resulting in detail spacing of two feet. If these details were spaced at 15 to 20 feet, as might be typically found on a highway bridge, the test frame would represent a bridge of approximately 450 feet.

The frame supported 108 W-shape and 75 cover plate type specimens. Only a portion of the specimens were inspected for the POD study. Each inspector performed the test on the same set of specimens in the same order.

Figure 2.1 Test frame and suspended specimens.

2.1.2 Test Frame Features

Several additional features were added to the test frame to further simulate inspection experiences on real bridges. A wooden deck was installed atop the support girders of the frame to replicate the lighting environment produced by a bridge deck in the field and provide access to the upper portion of the frame. Wooden cross-braces were attached at varying locations along the length of the girders. These cross frames served to obstruct the inspector's access to the pieces, as would happen with cross-bracing and lateral bracing on highway bridges. Figure 2.2 shows the wooden deck and cross-bracing.

2.2 Specimen Information

A small selection of specimen types was chosen to represent details widely seen across the state of Indiana. Each W-shape piece was one of five types: a transverse stiffener only, a transverse and longitudinal stiffener, a transverse stiffener and gusset plate with appropriate web gap dimensions, a transverse stiffener and gusset plate with intersecting welds (Hoan detail), or no attached detail. These details were fabricated on W368 × 135 rolled sections or on 3-foot-deep plate girder sections. Each face of the girder was considered a separate specimen and could include different details. The W-shape specimens were 36 inches deep by 23 inches long by 12 inches wide. Two varieties of welded cover plates, square-ended and tapered, were also used in the study. The square-ended cover plates were 24 inches long by 12 inches wide, while the tapered cover plates were 36 inches long and 14 inches wide at the widest end. The cover plates were bolted to the bottom of the bottom flanges of the rolled and plate girder specimens

simulating real cover plate installation in the field. The final type of specimen included was riveted plates. Serving no structural purpose, the rivets were not driven through the plate and bottom flanges of the W-shape specimens to allow flexibility in specimen arrangement for future inspection courses. Rather, the rivets were tack-welded from the back of the riveted plates. In order for the riveted plates to be attached to the bottom of beam specimens or columns, the back of the plate must be flush, hence the rivets were saw-cut down to a shank length where, once riveted, the end of the shank would not protrude from the back of the plate. These riveted specimens were 12 inches wide and 9 feet long.

2.2.1 Specimen Coating

While only data from the painted specimens were used for the probability of detection analysis, some of the inspectors still performed a hands-on inspection on a portion of weathered specimens. This data was also compiled and analyzed. The south span of the test frame supported 54 weathered W-shape specimens, two painted tapered cover plates, and 41 painted square-ended cover plates. The weathered pieces were made of A992 steel that was treated with a brine solution and allowed to develop a rust patina through exposure to the elements for approximately two months before installation on the test frame. A picture of typical weathered specimens can be seen in Figure 2.3.

The north span of the test frame supported 54 painted W-shape specimens, 8 painted riveted cover plates, two painted tapered cover plates, and 14 painted square-ended cover plates. The painted specimens were given two coats of paint in the shop and were then

Figure 2.2 Wood deck and cross-bracing.

Figure 2.3 Weathered specimens.

treated with a brine solution and exposed to the elements. To replicate the coating conditions found on aged, in-service bridges, the paint was randomly scratched with a utility knife in various locations. Additionally, rust-staining was induced through use of brine solution to further mimic the appearance of actual highway bridges. Figure 2.4 shows an example of a painted W36 specimen.

Additionally, eight painted riveted plates were mounted on the vertical columns of the test frame to represent built-up truss members.

2.2.2 Detail Types

A variety of detail types were used to evaluate each inspector's ability to detect cracks. The detail types were consistent with details known to cause cracking in steel bridges and were selected in consultation with the study advisory members to ensure they were representative of Indiana bridges. Further, prior to beginning the actual testing, "beta" testing was performed in which several bridge inspectors and three certified weld inspectors (CWIs) examined all the specimens. They confirmed that the specimens were realistic and representative of in-situ bridge members and the welds were representative of steel members fabricated during the 1960s and 1970s. The following section examines each of the types in greater detail.

2.2.2.1 Transverse stiffener specimens. One type of specimen used during the inspection course was a

W-shape section with a transverse stiffener welded to the center of the web. During the final inspection test course, the inspectors looked at 14 double-sided transverse stiffener (2TS) pieces and five single-sided transverse stiffener (1TS) pieces. The weathering section of the inspection course included one 1TS and one 2TS piece. Figure 2.5 shows a sample of a painted transverse stiffener specimen.

2.2.2.2 Longitudinal stiffener specimens. The next type of specimen had both a longitudinal stiffener and transverse stiffener attached to the web. The longitudinal stiffener was attached at approximately one third of the height of the web. The transverse stiffener was welded to the web in the center of the specimen. The inspection test course included six double-sided (2LS) painted specimens, two one-sided (1LS) painted specimens, and one 2LS specimen on the weathering portion. Figure 2.6 shows a painted longitudinal stiffener specimen with an appropriate, greater than 1/4-inch, web gap.

2.2.2.3 Gusset plate specimens. On the gusset plate specimens, a connection plate was welded to a W36 × 135 specimen with a transverse stiffener. The gusset plate was attached approximately one third of the way up the height of the web. The gusset plate specimens were all single-sided. For the inspection course, inspectors looked at five painted gusset plate specimens. Figure 2.7 shows a gusset plate specimen.

Figure 2.4 Painted specimen.

Figure 2.6 Longitudinal stiffener specimen.

Figure 2.5 Transverse stiffener specimen.

Figure 2.7 Gusset plate specimen.

2.2.2.4 Gusset plate with intersecting welds specimens.

Similar to the previously described specimen type, a gusset plate was attached to a shape with a transverse stiffener at approximately one third of the height of the web. On these specimens, the welds along the transverse stiffener and the gusset plate intersected. This is commonly referred to as a “Hoan” detail made famous by the Hoan Bridge in Milwaukee, Wisconsin. The Hoan was the first bridge to have a constraint induced fracture (CIF), which is now known to be caused by the triaxial constraint of the intersecting welds at the gusset-transverse stiffener intersection that effectively reduces the fracture resistance of the material (Kaufmann et al., 2004). The inspection course contained one painted and one weathered gusset plate specimen with intersecting welds. Figure 2.8 shows a picture of a painted GPIW specimen.

2.2.2.5 Plate girder specimens.

A group of specimens were welded plate girders rather than rolled shapes. These pieces were included to represent the plate girder bridges in Indiana’s bridge inventory. These plate girder pieces had either transverse stiffeners, longitudinal stiffeners, or gusset plate attachments. The inspection course had three painted plate girder specimens and two weathered plate girder specimens. Figure 2.9 shows a picture of a painted plate girder specimen with the transverse stiffener detail.

2.2.2.6 Bearing stiffener specimens.

Specimens with transverse bearing stiffeners, which were fillet welded along the web and both flanges of the rolled shape were included as part of the inspection course. There were two weathered bearing stiffener specimens present for the final inspection course. The painted portion of the course did not include any specimens with bearing stiffeners. Figure 2.10 shows a weathered bearing stiffener specimen.

2.2.2.7 Square-ended cover plate specimens.

The square-ended cover plate specimens were made of two plates welded together, modeling a bottom flange and cover plate termination. These specimens were bolted to the bottom flange of the W-shape specimens suspended from the frame adding to the realism of the inspection by requiring an overhead assessment. The inspection course included 55 painted square-ended cover plates. A picture of this specimen type can be found in Figure 2.11.

2.2.2.8 Tapered cover plate specimens.

The second type of cover plate specimens were made of two plates

fillet welded together. One plate was a 1-foot-wide by 3-foot-long rectangular plate representing the bottom flange that was welded to a tapered cover plate with initial width of 14 inches tapering down to 3 inches over a 15-inch length. Four painted tapered cover plates were inspected by each participant as part of the POD course. A sample tapered cover plate can be seen in Figure 2.12.

2.2.2.9 Riveted cover plates.

The final type of specimen simulated riveted cover plates. Each plate had 54 holes. Rivet heads were tack welded into each hole providing the appearance of a hot riveted built-up member. Because Indiana does not have any weathering steel riveted bridges in their inventory, all the riveted specimens were painted. Eight of these painted specimens were bolted to the bottom of W-shape specimens and eight were bolted to the vertical members of the support frame simulating the inspection position of a vertical member on a riveted built-up truss. Figure 2.13 shows riveted cover plates mounted to the bottom flange of the W-shape specimens (image a) and four of the riveted plated mounted vertically on the test frame columns (image b).

2.3 Number of Defects

2.3.1 Number of Cracks

For hit/miss probability of detection analyses, it is recommended that 60 defects be present in the test (Annis & Gandossi, 2012). For this study, the defects under consideration were cracks on the specimens. A “hit” constitutes the detection of a given crack while a “miss” is simply not detecting the crack. Hit/miss data for the weathered steel specimens was compiled, however, the POD analysis only included the hit/miss data from the painted specimen portion of the inspection course. Seventy (70) possible hits were present on the painted specimens. Three types of cracks were included in this POD study: distortion-induced out-of-plane cracks, load-induced welded cover plate weld toe cracks, and cracks emanating from rivet holes. All the weld toe and distortion-induced cracks in this study were true cracks, introduced through cyclic fatigue loading in a controlled laboratory setting. The cracks emanating from rivet holes were simulated cracks cut into the material using a very fine wire electrical discharge machining (EDM) process. The counts per type of crack for the inspection course can be seen in Table 2.1.

Figure 2.8 Gusset plate with intersecting welds specimen.

2.3.2 Noise Ratio

It is necessary that a POD study include specimens that do not have any flaws, called “noise,” randomly mixed in with the specimens that have defects. At least the same number of control or “noise” sites must be present as flawed sites; and for best practice a noise ratio of 3:1 is recommended (DoD, 2009). For the determination of the noise ratio of this study, each potential crack site, for example along the weld toe of a welded cover plate or area around a riveted hole, was considered. Each of the two faces of a W-shape specimen were counted as a possible crack site. Table 2.2 lists the crack sites and counts of cracked and noise locations for the inspection course.

The total number of crack sites does not equal the total number of hits because several crack sites had more than one crack present. The numbers in this table count each face of a W-shape specimen as a single crack site, however, each face may have more than one potential crack site, for example the area at both the top and bottom of a transverse stiffener, which results in a conservative reporting of noise site locations. It is difficult to count exactly the noise present on the test frame because each specimen has multiple locations for possible cracks.

Figure 2.9 Plate girder specimen.

2.4 Crack Inventory

The size of defects in a POD study should be of similar sizes to the defects they represent in the field. Steel bridge cracks can cover a wide range in the field, from less than 1 inch to a rare full member depth fracture. However, a study of this type had never been conducted for the steel bridge industry and a baseline needed to be established to understand at what length of crack can be reliably detected using visual inspection. Thus, this POD study crack inventory contained cracks ranging from 1/2 inch to 5-3/8 inches. The following section explains the defect size distribution and type utilized in the study.

2.4.1 Size Ranges and Distribution

Probability of detection studies recommend that the number of cracks in each size range be uniformly distributed (Annis & Gandossi, 2012). Four crack size ranges were set between 1/2 inch and 5-1/2 inches. A uniform distribution among the four ranges was targeted, however, due to the nature of growing fatigue cracks, a perfect distribution was not achieved. Table 2.3 shows the crack size ranges and distributions for the cracks present in the POD inspection course.

Figure 2.10 Bearing stiffener specimen.

Figure 2.11 Square-ended cover plate specimen.

Figure 2.12 Tapered cover plate specimen.

(a)

(b)

Figure 2.13 Riveted cover plate specimens mounted (a) horizontally and (b) vertically.

2.4.2 Crack Types

The types of cracks included in the inspector performance testing were out-of-plane cracks, welded cover

TABLE 2.1
Crack Counts by Crack Type

Crack Type	Number
Out-of-plane	28
Welded cover plate weld toe	23
Rivet hole	19
Total hits	70

TABLE 2.2
Crack Sites and Noise Ratios

Crack Site Type	Cracked Sites	Noise Sites	Noise Ratio
Welded cover plate	19	40	2:1
Rivet holes	18	846	48:1
Transverse stiffener	12	28	2.3:1
Longitudinal stiffener	1	12	12:1
Gusset plate	2	4	2:1
W-shape web	2	10	5:1

TABLE 2.3
Crack Size Ranges

Crack Size Range (in.)	Number of Cracks
0.5 < 1.5	24
1.5 < 2.5	12
2.5 < 3.5	14
3.5 < 5.5	20

plate weld toe cracks, and rivet hole cracks. All cracks were assumed to be equally likely to be detected for the primary POD analysis.

2.4.2.1 Out-of-plane distortion cracks. Out-of-plane distortion cracks were created in the laboratory on rolled shapes and plate girder specimens using a process of cyclic fatigue loading. Out-of-plane distortion cracks were introduced on specimens with transverse stiffeners, longitudinal stiffeners, and gusset plates. The 28 out-of-plane distortion cracks ranged in size from 3/4 inch to 5-7/32 inches. Figure 2.14 shows an out-of-plane distortion crack on a painted specimen with a transverse stiffener.

2.4.2.2 Cover plate weld toe cracks. Cracks were induced along the weld toes of the square-ended and tapered welded cover plate specimens through fatigue in a laboratory test set-up. The laboratory set-up was designed to induce the fatigue crack along the transverse weld toe at the termination of the cover plate, where it would occur on an in-service bridge. The 18-weld toe cover plate cracks ranged from 1-7/16 inches to 5-3/8 inches. Figure 2.15 shows a weld toe crack on a square-ended welded cover plate.

2.4.2.3 Rivet hole cracks. Cracks emanating from rivet holes were cut with an EDM wire. The shape, length, and location of each rivet hole crack was specified. The visible length (that which extended beyond the rivet head) of these cracks ranged from 1/2 inch to 1-1/2 inches. Nineteen (19) rivet hole cracks were present on the POD inspection course. Figure 2.16 shows a rivet hole crack.

Figure 2.14 Out-of-plane distortion crack.

Figure 2.15 Cover plate weld toe crack.

Figure 2.16 Rivet hole crack.

2.5 Summary

The test frame was designed to simulate in-situ bridge inspection, requiring inspectors to conduct hands-on work from the basket of a man-lift and work in the outdoor elements. The specimens were designed and

built to mimic common details found on existing steel bridges. A variety of detail types were used. Seventy (70) hits were placed on varying painted specimens ranging from 1/2 inch to 5-3/8 inches long, distributed among four crack size ranges. Three different crack types were included in the POD inspection course.

3. POD TEST PROCEDURES

3.1 Inspection Test Route

The inspection route was held constant for each inspector that participated in the study following the initial two inspectors. The participants first completed the routine inspection of two painted girder lines from the ground. A picture of an inspector conducting his routine inspection from the ground can be seen in Figure 3.1.

Next, the inspector and Purdue personnel put on the appropriate PPE, including safety harness and hard hat, and boarded the man-lift for the hands-on inspection. The Purdue personnel operated the man-lift and navigated through the predetermined course, stopping so that the inspector was within an arm's length of each piece, while also making sure each inspector was comfortable with his or her inspection position. The participant was guided through the preset course that first included the east faces of 8 weathered pieces and then the west faces of those same 8 pieces, for a total of 16 weathered specimens. The time taken to complete this portion of the course was recorded by the Purdue personnel. The inspectors were then taken to the adjacent span to inspect the painted W-shape specimens. This portion of the route began on the east face of the center girder line, continued to the east face an exterior girder line, then concluded with the west faces of the same two girder lines of specimens. After the W-shape specimens were completed, the inspector looked at 8 horizontal riveted plates that were attached to the bottom flanges of the W-shape pieces. Next, the inspector was snaked along the bottom flanges of the

remaining W-shape pieces to inspect the welded cover plates. Lastly, each inspector examined the final 8 vertical riveted plates that were attached to the columns of the frame. Figure 3.2 shows an inspector performing a hands-on inspection of a painted specimen. After the first 11 inspectors, the routine inspection scenario and the hands-on inspection of the weathering steel specimens were discontinued. The inspection route through the painted steel specimens remained unchanged.

3.2 Inspection Test Procedures

Each inspector was given the same information prior to and during his/her participation in the study and assigned a random identification number. This information included an emailed notice to be read prior to participation, written instructions upon arrival on the day of testing, and a confidentiality agreement. During their testing, they were permitted to ask the Purdue personnel any clarifying questions. Each participant was instructed to arrive at Bowen Laboratory at the previously agreed upon time, usually between 7:30 am and 9:00 am. Upon arrival, they were greeted by Purdue personnel and led to a conference room. They were given a two-page instruction document, *Procedures for POD Visual Inspection*, which can be found in Appendix A, outlining the objectives of the study, the two inspection scenarios, a list of assumptions regarding the specimens, and instructions on how to document their findings. Each participant was then asked to sign a confidentiality agreement and complete two vision tests before being taken to the testing site. While on site, the participants were permitted to take breaks

Figure 3.1 Ground scenario inspection.

Figure 3.2 Hands-on inspection scenario.

throughout the day as they would during regular inspection. Lunch was provided to the participants during the performance testing. Due to the cold weather on several of the days of testing, multiple inspectors requested short breaks to warm up in their vehicles, but otherwise, few inspectors requested breaks.

3.2.1 Notice to Inspectors

After each participant was scheduled for testing, Purdue personnel emailed a *Notice to Inspectors* document that can be seen in Appendix A. The letter explained the purpose of the study, the expected time commitment, information regarding lunch, notification that a signed confidentiality agreement would be required, as well as instructions to bring “any tools and personal protective equipment, including safety harness, you would normally use for a visual inspection, both routine and hands-on.” The objective of this study was to measure current bridge visual inspection practices, so an explicit list of tools to bring was not provided. This gave valuable data regarding which tools are actively being utilized by bridge inspectors.

3.2.2 Procedure for POD Visual Inspection

The full document containing the instructions and procedures can be found in Appendix A. The list of assumptions given to the participants can be found below:

1. The specimens are intended to represent 1960s to 1970s welded fabrication and weld quality. While weld quality may not meet modern standards, it is not the focus of the study. You are not required to comment on weld quality.

2. Assume the pieces suspended from the frame are fracture critical members.
3. Treat all gusset plates and vertical stiffeners as if bracing, floor beams, diaphragms, or cross-bracing was attached. For example, many specimens include gusset plates and vertical stiffeners welded to webs. Therefore, you are to assume there are lateral members attached to these components whether they are on the interior or exterior faces of the specimens or nears the top or bottom flange. The bracing members have not been included to facilitate your access.
4. Assume all cover plate terminations are subject to tensile stress ranges.
5. Assume both flanges could be tension flanges.
6. The location of the specimen on the frame should not be used to “infer” the loading or stress state in the specimen. In other words, specimens installed near the ends of the support frame should not be viewed as being near a bearing. All specimens should be viewed as being subjected to the same stress state.
7. Interior and exterior specimens should be treated the same.
8. Both faces of each specimen should be treated the same.
9. Any specimen could have any type of crack or even multiple cracks.

3.2.3 Confidentiality Agreement

After reading the *Procedures for POD Visual Inspection* document, each inspector was presented a confidentiality agreement to read and sign. The confidentiality agreement stated that the participants would not discuss anything related to the POD study and that the inspector’s identification would remain confidential. Each inspector was assigned a random identification code so that their identities would not be discernable.

The full document can be found in Appendix A. All 30 participants willingly signed the agreement.

3.2.4 Vision Testing

Each participant performed two vision tests—the Jaeger test for near vision acuity and the Pelli Robson test for contrast sensitivity. Each inspector was tested using the same test cards and in the same room with consistent lighting. The Jaeger test required the inspector to hold the test card 14 inches from his/her face and read the smallest text he/she could see. The corresponding number of the text size was recorded by Purdue personnel. The Pelli Robson test required the participant to sit in a chair 40 inches from the test board and read the lightest letters he/she was able to discern. The information was again recorded by Purdue personnel. Figure 3.3 shows the test cards for the Jaeger and Pelli Robson vision tests.

3.2.5 Documentation

Each inspector was given a binder labeled with his/her random identification number. The binder included labeled inspection forms for the ground scenario and each specimen included in the hands-on portion of the course. The ground scenario form included a small AutoCAD drawing of each suspended specimen. For the hands-on inspection scenario, a form with a large drawing of each specimen was included (see Figure 3.4). The forms were arranged in the binder in the order that the participant would encounter each specimen during the study. The participant was asked to ensure that the specimen ID on the form matched the specimen ID on the plastic tag magnetized to each specimen before he/she began making notes. The participants were instructed to sketch any cracks found on the corresponding

form, recording the length and location. For any specimen in which no crack was found, the participants were instructed to complete the form noting such. An image of one of the hands-on forms can be seen in Figure 3.3.

3.2.6 Exit Survey

After each participant completed the inspection course, he/she was given the *Exit Survey*, which can be seen in Appendix A. This survey collected information regarding the inspector's background including age, gender, years of experience, and which training courses they attended. The survey asked which tools each inspector brought and used, if there were any tools that he/she wished he/she had available during the test, and whether or not he/she wore glasses or contacts. The survey was updated partway through the study to include additional questions on education level, professional licensure, and overall impression of the inspection scenario and set-up. This data was collected to investigate any trends between these characteristics and success in finding cracks. In addition to the exit survey data, the Purdue personnel tracked the time each participant took to complete each portion of the course, a record of the day's weather, and general firsthand observations of the inspector's activities, such as level of focus, attitude, and inspection strategy. Responses to the survey can be found in Appendix B.

3.3 Summary

Inspection procedures were established to simulate an actual field inspection in a controlled testing environment. Only minor changes to the inspection procedures were made throughout the study to allow for a direct comparison of the results. Initially, the study included

Figure 3.3 Test cards for the Jaeger test (left) and Pelli Robson test (right).

Specimen ID: [REDACTED] Inspector ID: [REDACTED]

BOWEN LABORATORY
PURDUE UNIVERSITY

1042 SOUTH HAVEN ROAD
WEST LAFAYETTE, IN 47906
P: 766-484-2227 F: 766-484-0886

PROJECT: **PROBABILITY OF DETECTION**

SHEET NOTING

REVISION#	DATE	BY

DESIGNED BY: [REDACTED]
 DRAWN BY: [REDACTED]
 CHECKED BY: [REDACTED]
 DATE: [REDACTED]
 PROJECT NO.: [REDACTED] SPR. 2008

SHEET TITLE: [REDACTED]

SHEET NO.: **1 of 1**

Figure 3.4 Hands-on inspection form.

both a routine inspection of the specimens and a hands-on inspection of weathering steel and painted steel specimens. However, the routine inspection and the hands-on inspection of the weathering steel specimens were discontinued after the first 11 participants because these tasks were not providing usable data. During each inspection, data was collected from three sources: (1) the completed inspection binder, (2) proctor observations, and (3) pre- and post-inspection evaluations.

4. INSPECTION RESULTS

Thirty (30) inspectors were tested on the same set of test specimens between November 7, 2014 and December 8, 2016. The data from each inspector were

tabulated and analyzed. Hit/miss data was used to determine the detection rate for each inspector. Additional data, including inspector age and the day's air temperature, were also studied to find correlations with visual inspection success. The hit/miss data from the hands-on painted portion of the inspection course were used in statistical POD analysis and a random parameters binary logit model was used to identify variables beyond crack length that affect the likelihood of detection.

4.1 Inspector Demographics

In order to accurately represent the current bridge inspector population, inspectors from a wide range of backgrounds were invited to participate in the study.

This project included 16 inspectors from state departments of transportation (DOT), 12 inspectors from private engineering and/or inspection firms, and two inspectors from federal agencies. The participating inspectors worked primarily in Illinois and Indiana, with one inspector from California and one inspector from Virginia. Twenty-six (26) of the 30 inspectors had completed the two-week FHWA/NHI *Safety Inspection of In-Service Bridges* training course prior to their participation in the study. The average experience of the participating inspectors was 10.6 years and the inspectors had completed an average of 10.6 hands-on inspections in the 12 months prior to their participation. Twenty-three (23) of the 30 inspectors possessed an engineering license; six were engineering interns (EI), 15 were professional engineers (PE), and two were licensed structural engineers (SE). All 30 inspectors could read the smallest paragraph of text on the test card for the Jaeger vision test and 26 of the inspectors recorded a Log Contrast Sensitivity of 1.95 on the Pelli Robson vision test. Select inspector demographics are compiled in Table 4.1.

4.2 Inspector Response Interpretation

Upon the completion of the course, each inspector submitted his/her binder to Purdue personnel. The binders

were reviewed the same day that the test was completed to ensure accuracy in interpreting the comments and remarks. Even in this controlled testing environment the reporting styles varied from inspector to inspector, and ambiguous notes and comments were interpreted leniently by the reviewers. The Purdue staff who observed the inspector throughout the duration of the test also kept notes tracking the time spent on each portion of the course and recorded general observations regarding the inspector's behavior and attitude.

An answer key binder was created with an AutoCAD drawing of each of the specimens. Each answer key form either stated "NO DEFECT" for the noise specimens or included a dimensioned drawing of the crack in its true location for the cracked specimens. The drawing of each specimen matched the blank forms given to the inspectors in scale and level of detail. The lengths and locations of the cracks were determined and drawn by the Purdue graduate student who initiated the cracks in the specimens in the laboratory. The crack lengths and locations were confirmed with Magnetic Particle (MT) and/or Dye Penetrant (DP) testing and were documented with photographs. An image of two answer key forms can be seen in Figure 4.1.

The binder from each inspector and the answer key binder were compared for each specimen. A spreadsheet that listed each specimen name and crack length,

TABLE 4.1
Inspector Demographics

Inspector ID	Employer	Age (yrs.)	Inspection Experience (yrs.)	Professional Licensure	Number of Hands-on (routine) Inspections	Log Contrast Sensitivity
10EH-10	State	56	30	None	0 (120)	1.95
11CO-02	State	46	11	None	40 (50)	1.95
18GA-03	Private	63	29	PE	4 (20)	1.95
13CA-09	State	58	20	None	6 (200)	1.95
09SD-08	Private	55	28	None	20 (0)	1.95
20MD-19	State	45	20	PE	6 (100)	1.95
04MY-41	Private	40	15	PE	9 (300)	1.95
09ME-03	Private	28	6	PE	5 (5)	1.95
08GS-32	State	30	1.25	EI	5 (35)	1.95
01VM-02	Private	30	6	PE	23 (600)	1.95
12AE-04	State	41	1	PE	1 (40)	1.95
11LB-22	State	55	8	None	4 (145)	1.65
10JW-16	State	40	10	PE	9 (200)	1.95
21RI-01	Private	33	10	PE	5 (112)	1.95
08LK-23	Federal	38	0	PE	0 (0)	1.95
06MA-03	State	56	10	PE	3 (6)	1.8
21GZ-14	Federal	55	30	None	0 (100)	1.95
09VK-18	State	25	2.5	None	8 (25)	1.95
18RT-25	State	53	13	PE	10 (240)	1.95
06JD-15	State	33	8	EI	20 (163)	2.10
06TI-56	State	24	0.75	EI	0 (175)	1.95
27GH-57	Private	29	3	EI	18 (35)	1.95
01DS-23	State	28	4	PE	30 (450)	1.95
24BR-25	State	39	1	PE	25 (45)	1.65
27PC-37	Private	24	1.5	EI	0 (20)	1.95
12LA-04	Private	45	20	PE	25 (700)	1.95
11NH-05	Private	32	10	EI	13 (250)	1.95
10CA-07	State	42	14	PE	20 (70)	1.95
26RO-49	Private	30	5	PE/SE	0 (4)	1.95
25HQ-08	Private	33	1	PE/SE	10 (50)	1.95

Figure 4.1 displays two answer key forms from Brown Laboratory. The left form is for a specimen with a crack length of 4 inches, showing a diagram of a vertical crack and a table for recording data. The right form is for a specimen with no defect, showing a diagram of a vertical crack and a table for recording data. Both forms include a 'PROBABILITY OF DETECTION' section and a 'HIT/CALL' section.

Figure 4.1 Answer key forms.

if applicable, was used to track the hits, misses, false positives and other comments made by the inspector. The information provided by the inspector on each specimen form was interpreted and categorized. Definitions of these categories can be found below:

- **Hit:** A hit was defined as a crack identified as a crack or *possible* crack by the inspector. Possible cracks were awarded credit for a hit because during inspections, typically, an indication marked as a possible crack would be investigated further by the inspection team and then determined whether or not it was a true crack. The instructions stated that each crack found was to be drawn and given a dimension; however, if a crack was indicated on the form and no dimension was given, a hit was still awarded. In the data spreadsheet, a hit received a "1." For each hit, the length of crack noted was recorded.
- **Miss:** A miss was assigned for any crack that was not indicated as a crack or possible crack by the inspector. Each occasion where a crack was not noted by an inspector was entered as a "0" in the data spreadsheet.
- **Possible:** The term possible was used to describe the total number of cracks present on the given selection of specimens.
- **False Positive:** A false positive included any indication by an inspector on the specimen forms indicating he/she found a crack where no crack was present. If an inspector marked a location as a possible crack or wrote that a site needed additional inspection with a different form of non-destructive testing, where there was no crack present, it was considered to be a false positive.
- **Call:** The term "call" was used to denote every occasion the inspector called an indication a crack. The total number of calls is equal to the sum of hits and false positive.
- **Detection Rate:** The detection rate was defined to be the number of hits divided by the number of possible cracks.
- **Hit/Call:** This ratio was selected to show how often an inspector's recording of a crack was actually a crack. A higher (better) hit/call rate indicates that the inspector

had fewer false positives relative to the number of hits than an inspector with a lower (worse) hit/call rate. A higher rate is considered to be more economical because unnecessary NDE resources would be expended less often.

4.3 Ground Inspection Scenario Results

The first 11 participants were instructed to inspect both sides of two girder lines of painted specimens from the ground. They were permitted to walk anywhere beneath the test frame. The bottom flange of the specimens were approximately 25 feet above grade. Each inspector was instructed to perform this portion of the course as they would any routine inspection of a steel highway bridge. They were not provided any inspection tools but permitted to use all tools they brought. Seven of the eleven inspectors used binoculars for the ground scenario. One participant used a flood light and binoculars to conduct the routine inspection from the ground. The time spent on this scenario ranged from 12 minutes to 82 minutes. Three inspectors were instructed to stop the ground scenario before they completed both girders because if allowed to continue, they would not have had sufficient time to complete the hands-on portion of the inspection course. It was more important for the participants to complete the hands-on inspection portion in the daylight. The forms for the incomplete ground scenarios were still reviewed and evaluated for these inspectors.

The 11 ground scenario forms varied in what information was noted and provided by the participants. Due to the variety of the types of comments made on the forms, it was difficult to quantitatively evaluate the ground scenario results. This illustrates the significant

variability of inspection results that are often observed, even in this highly controlled testing environment.

Inspector 06JD-15 spent 78 minutes conducting the routine inspection but was instructed to stop after looking at only one girder line of W-shaped specimens and two girder lines of riveted cover plates due to the slow pace. The participant carefully looked at each specimen and recorded detailed findings for each. In total, five cracks were correctly identified while 23 false positives were recorded. There was a total of 25 cracks on the specimens that this individual inspected, resulting in a 20% detection rate.

Three inspectors marked their forms with only small tick marks. They provided no explanation of what the marks indicated or what the next course of action would be—whether they were seriously concerned and needed to look closer or if they would simply monitor them in the future. One inspector noted five possible cracks on the first seven specimens and then informed the staff that he/she would not conduct an inspection in this manner because it would not produce useful results regarding the condition of the bridge. The inspector stated that he/she would have to get closer to the bridge to provide meaningful inspection information. Three inspectors walked beneath the structure and recorded general comments on the status and condition of the bridge, citing that they would not be looking for cracks from this distance. The general comments were similar to each other stating that the girders had light to moderate corrosion. The results from the ground scenario inspection have been tabulated below in Table 4.2.

Inspectors 13CA-09, 20MD-19, and 24BR-25 provided only general comments about the overall condition of the bridge, so they do not have values for hits and therefore do not have quantifiable detection rates. The response forms were used to determine how many possible cracks each inspector viewed. The number of possible cracks reported in Table 4.2 is the number of hits on the pieces that were viewed by each inspector during the ground scenario test. It should be noted that some of the cracks may not be physically able to be seen from the ground beneath the structure due to obstruction of sight line from the bottom flanges of the

W-shape pieces, so a 100% detection rate was not possible. If the comments and markings applied to both faces of both girder lines and the cover plates, there were 38 cracks present on the specimens. If an inspector did not look at or comment on the riveted cover plates, those 10 cracks were not counted in his/her number of possible cracks to be found. The inspectors listed in the above table with fewer than 28 possible cracks did not complete the full ground inspection scenario.

The most successful inspector, in terms of identifying cracks, found only 20% of the cracks possible. The three inspectors who only made general comments, and Inspector 11LB-22 who stopped after 7 specimens because he/she felt the exercise was not fruitful, spent the least amount of time performing this routine inspection. The results of these four inspectors were not different than the remaining inspectors who spent between two and three times as long conducting the same inspection.

The instructions stated to conduct this portion of the course in the same manner that he/she would conduct routine inspection of non-fracture-critical bridges. However, it is believed that most inspectors spent longer on this inspection because they were being observed and evaluated as part of a research study. When speaking to the inspectors, several mentioned that they would not look for fatigue cracks from the ground. The Purdue staff reminded them to conduct the inspection as they would typically and to provide the same level of detailed information that they would for a routine inspection. Regardless of being read this line, multiple participants still spent time carefully scrutinizing the specimens looking for cracks.

The inspectors who provided only tick marks of the specimens provided very little useful data. It would not be possible for a supervisor or another inspector to look at the bridge inspection form and understand the condition of the bridge. The high variability in the type of information that was reported indicates that the current inspection training and practices do not promote a uniform reporting method. A part of the large variation could also be attributed to misunderstanding or ambiguity in the instructions, or that the inspectors

TABLE 4.2
Ground Scenario Results

Inspector	Hits	Possible Cracks	Time (minutes)	Detection Rate (%)	False Positives	Tools
06JD-15	5	25	78	20	22	Binoculars
10JW-16	0	28	27	0	24	Binoculars
12AE-04	0	28	43	0	8	Binoculars
13CA-09	—	38	17	—	—	None
18RT-25	3	28	36	11	63	None
20MD-19	—	38	14	—	—	None
01DS-23	0	8	56	0	11	Binoculars
24BR-25	—	28	17	—	—	Binoculars
09VK-18	0	28	27	0	70	Binoculars
10EH-10	2	28	82	7	13	Binoculars
11LB-22	0	1	12	0	7	Binoculars and flood light
Total	10	278	—	4	218	

TABLE 4.3
Qualitative Review of Ground Inspection

Inspector	Labeled Cracks?	Commented on Corrosion?
06JD-15	Yes, detailed	No
10JW-16	Only tick marks; no detail	No
12AE-04	Only tick marks; no detail	No
13CA-09	No	Yes
18RT-25	Tick marks, some noted as cracks	Yes
20MD-19	No	Yes
01DS-23	Yes, detailed	Yes
24BR-25	Yes	Yes
09VK-18	Only tick marks; no detail	No
10EH-10	Yes, detailed	Yes
11LB-22	Yes	No

felt as though they were being evaluated and wanted to provide very thorough results, even if they did not reflect their typical practices. A qualitative review of the types of comments and remarks made by each inspector can be found in Table 4.3.

In summary, the ground scenario resulted in highly varied data. The highest crack detection rate was 20% or 5 out of 25 cracks, with 23 false positives. The results indicated that a standard procedure for routine ground inspections was not used by the group of participants. The inspectors' notes ranged from very detailed comments on rust lines and cracks with measurements to only small tick marks with no descriptions of what they represented or how long they were. The binoculars used by the inspectors were not all the same. Specific information on the type and strength of the binoculars was not collected, but when asked about binocular usage, one inspector said it was a personal choice and not a requirement of their employer or the state inspection program. The reliability of inspectors to identify fatigue cracks from the ground is very low.

4.4 Hands-on Inspections of Weathered Specimens Results

After finishing the ground inspection scenario, each participant was asked to put on their safety harness and gather the tools they would use for a hands-on inspection of a fracture-critical bridge. The first 11 participants inspected the same set of weathered specimens at an arm's length from the girders. All 16 of the specimens were W-shape weathered specimens with a total of 18 fatigue cracks. The cracks ranged in length from 1-23/32 inches to 4-3/8 inches. The results from the weathered specimens can be seen below in Table 4.4.

Six of the eleven inspectors did not correctly identify any cracks on the weathered specimens. Five of those six made no marks on their forms, resulting in zero false positives. The time spent inspecting the weathered specimens ranged from 19 minutes to 77 minutes; detection rates ranged between 0% and 39%. Most inspectors had few false calls, however, two inspectors, 18RT-25 and 11LB-22, had 19 and 23 false calls, respectively. These resulted in hit/call rates of 17% and 23%, meaning that

only approximately one in five of their identifications was correct. The false calls could have resulted in additional time and cost to further investigate the indicated areas. The best hit/call rate reported was 100%, which was accompanied with a 6% detection rate. Figure 4.2 shows a plot of each inspector's hit count for the weathered specimens.

Each of the five inspectors, other than Inspector 01DS-23, who found cracks on the weathered specimens used a flashlight during inspection. Two other inspectors, 06JD-15 and 10EH-10, also used flashlights but did not find any cracks. Only one crack was identified on the weathered specimens without the use of a flashlight.

A slight positive trend was observed between the time taken inspecting the weathered specimens and the detection rate. Figure 4.3 shows the detection rate of each inspector versus the time spent conducting the inspection.

Among the inspectors who found cracks, there is a slight increase in detection rate with increasing time spent on inspection. The inspectors, represented by triangles in Figure 4.3, were not engineers; the eight inspectors shown with circles each received engineering degrees. A correlation between detection rate and an engineering degree cannot be made because the mix of inspectors who identified zero cracks included both engineers and technicians.

The relationship between crack length and number of times each crack was detected was examined. Each crack could have been detected a total of 11 times. Figure 4.4 shows the number of times each crack was found according to crack length.

This figure shows that detectability was not entirely dependent on crack length. While the three cracks that were found most frequently were on the larger end of the spectrum, there were three larger cracks present that were never identified by any of the 11 inspectors.

In summary, hands-on visual inspection of weathered steel girders resulted in very low detection rates. The total detection rate for the 11 tested inspectors was 11%. In total, the 11 inspectors had 53 false positives. Among the six inspectors who made crack calls on the specimens, only five had hits. The highest detection rate was 39%. Six inspectors were unable to visually detect

TABLE 4.4
Hands-on Weathered Results

Inspector	Time (minutes)	Hits	False Positives	Detection Rate (%)	Hit/Call (%)
06JD-15	77	0	0	0	—
10JW-16	39	5	1	28	83
12AE-04	24	0	0	0	—
13CA-09	60	0	3	0	0
18RT-25	44	4	19	22	17
20MD-19	51	4	7	22	36
01DS-23	21	1	0	6	100
24BR-25	23	0	0	0	—
09VK-18	19	0	0	0	—
10EH-10	26	0	0	0	—
11LB-22	70	7	23	39	23
Total	—	21	53	11	28

Figure 4.2 Weathered specimens: hits and false positives.

Figure 4.3 Weathered detection rate vs. time.

TABLE 4.5
Detection Rate by Inspector

Inspector ID	Hits	Possible Cracks	Detection Rate (%)	Total Time (minutes)
10EH-10	26	70	37	175
11CO-02	50	70	71	279
18GA-03	33	70	47	309
13CA-09	22	70	31	224
09SD-08	49	70	70	457
20MD-19	45	70	64	236
04MY-41	41	70	59	327
09ME-03	53	70	76	226
08GS-32	47	68	69	269
01VM-02	55	70	79	296
12AE-04	46	70	66	179
11LB-22	47	70	67	224
10JW-16	50	70	71	320
21RI-01	58	70	83	368
08LK-23	59	70	84	279
06MA-03	53	70	76	241
21GZ-14	35	70	50	206
09VK-18	46	70	66	138
18RT-25	42	70	60	202
06JD-15	30	70	43	262
06TI-56	43	68	63	211
27GH-57	49	70	70	217
01DS-23	54	70	77	228
24BR-25	46	70	66	160
27PC-37	33	70	47	116
12LA-04	55	70	79	347
11NH-05	60	70	86	345
10CA-07	42	70	60	192
26RO-49	52	70	74	213
25HQ-08	47	70	67	192

any of the 18 present possible hits. The use of a flash-light improved the likelihood of an inspector correctly finding a crack. Longer inspection times also seemed to produce slightly higher detection rates, although this was not conclusive.

4.5 Hands-on Inspections of Painted Specimens Results

The painted portion of the hands-on inspection included 72 faces of W-shape specimens, sixteen 9-foot long (144 total feet with 864 holes) riveted plate specimens, and 59 painted welded cover plates. The course was set up to meet the requirements for determining probabilities of detection at various crack lengths. The time spent inspecting each portion of the painted course was recorded. The data was analyzed for all of the 70 possible hits together, as well as split up by crack types—out-of-plane distortion, cover plate weld toe, and rivet hole cracks. Two of the horizontally mounted riveted cover plates (RCCP-6 and RCCP-10) were removed before the last two participants completed their inspections. For these inspectors, the total number of possible cracks was 68. The cracks ranged in length from 1/2 inch to 5-3/8 inches. Crack lengths for rivet hole cracks only included the portion of the crack exposed to view and did not include the

segment of the crack hidden under the rivet head. Human and environmental factors were also examined to determine if there were correlations with crack detection.

4.5.1 Total Detection Rates

Thirty (30) inspectors completed the hands-on inspection of the painted specimens. The highest detection rate recorded was 86%, while the lowest was 31%. The average detection rate for all 30 inspectors for these specimens was 65%. Of the 30 participants, the most successful, in terms of identifying cracks, missed 10 cracks on the specimens. The average number of missed cracks for all participants was 24. Table 4.5 shows the number of total hits and detection rate for each inspector.

One of many challenges in conducting a realistic POD study is ongoing maintenance of the specimens. Since the specimens in this study are not regularly exposed to cyclic loading from vehicular traffic, the appearance of the cracks may degrade over time. Rust staining and debris accumulation may gradually obscure some of the cracks, as was seen on the weathering steel specimens. Figure 4.5 shows the detection rate of each inspector versus the number of days since the first inspection. The total length of time between the first

Figure 4.4 Weathered detection counts.

and last inspection was 762 days. Although the visibility of some of the cracks may have changed over time, the overall difficulty of the inspection seems to have remained relatively constant. Large differences in performance were recorded in inspections that occurred on consecutive days, indicating that the variability in results is likely due more to inspector characteristics than changes in the conditions of the specimens. Additionally, following the long gap between the 11th and 12th inspections, the conditions of all the specimens were revalidated by Purdue research staff.

4.5.2 Detection Rates and False Positives

The false positives were tabulated for each inspector. The number of false positives were compared to the number of hits each inspector had. The hit/call rate was calculated for each participant. A low hit per call rate showed that the inspector had a large number of false positives relative to the number of hits. The number of false calls made on the painted specimens during the hands-on inspection ranged from 14 to 268 with a standard deviation of 67. Table 4.6 shows the number of hits, false calls, and hit/call rates for each participant.

The number of hits and number of false positives for each inspector can be seen graphically in Figure 4.6. Higher false positives were not an indicator of higher hit counts. Twenty-two (22) of the 30 inspectors had more false positives than hits leaving the remaining eight inspectors with higher hits than false positives. Inspector 27PC-37 had the highest ratio of false positives to hits, with 6.6 false calls for every one crack that was successfully identified. Inspector 24BR-25 had the lowest ratio of false positives to hits at 0.33 false calls for each hit.

4.5.3 Detection Rates and False Positives by Crack Type

The detection rates and number of false calls by crack type were also examined. The course included 28 out-of-plane distortion cracks, 23 weld toe cracks on cover plates, and 19 cracks at rivet holes. The welded cover plate weld toe cracks had the lowest average detection rate while the average number of false calls was the highest on the W-shape specimens. The detection rate and number of false calls by crack type, as well as for all the cracks, can be seen in Table 4.7.

Figure 4.5 Detection rate versus the elapsed time since the first POD inspection.

TABLE 4.6
False Positives and Hit/Call Rates

Inspector ID	Hits	False Calls	Hit/Call Ratio (%)	Total Time (minutes)
10EH-10	26	156	14	175
11CO-02	50	60	45	279
18GA-03	33	56	37	309
13CA-09	22	14	61	224
09SD-08	49	51	49	457
20MD-19	45	23	66	236
04MY-41	41	85	33	327
09ME-03	53	62	46	226
08GS-32	47	105	31	269
01VM-02	55	31	64	296
12AE-04	46	42	52	179
11LB-22	47	103	31	224
10JW-16	50	174	22	320
21RI-01	58	187	24	368
08LK-23	59	68	46	279
06MA-03	53	195	21	241
21GZ-14	35	18	66	206
09VK-18	46	89	34	138
18RT-25	42	146	22	202
06JD-15	30	47	39	262
06TI-56	43	57	43	211
27GH-57	49	76	39	217
01DS-23	54	37	59	228
24BR-25	46	15	75	160
27PC-37	33	217	13	116
12LA-04	55	162	25	347
11NH-05	60	77	44	345
10CA-07	42	20	68	192
26RO-49	52	67	44	213
25HQ-08	47	268	15	192

Figure 4.6 Painted specimens: hits and false positives.

TABLE 4.7
Average Detection Rate by Crack Type

Crack Type	Detection Rate			Number of False Calls		
	Mean (%)	Standard Deviation (%)	Minimum/Maximum (%)	Mean	Standard Deviation	Minimum/Maximum
All types	65	14	31/86	90	67	14/268
Out-of-plane distortion	62	14	18/82	65	54	5/205
Cover plate weld toe	74	27	4/96	16	14	0/59
Rivet hole	59	17	21/95	9	9	0/34

The average detection rates for each crack type for each inspector were also studied. Twenty-three (23) of the 30 inspectors had their individual highest detection rate for welded cover plate cracks. Four inspectors had their individual highest detection rate for rivet hole cracks, and three inspectors had their individual highest detection rate for out-of-plane distortion cracks. Figure 4.7 shows each individual participant's detection rate by crack type.

Finally, there was a positive correlation between detection rates of the out-of-plane distortion cracks and the cover plate weld toe cracks specimens, meaning that performance on one subset of the inspection could be used to predict performance on another subset. However, there was no correlation between detection rates of the distortion cracks and the rivet hole cracks or between the detection rates of the rivet hole cracks and the weld toe cracks. The relationship between weld toe crack detection rate and out-of-plane distortion induced crack detection rate is shown in Figure 4.8.

4.5.4 Detection Rate and Crack Length

The primary objective of the study was to determine if a relationship between crack detection and crack length existed. The painted specimens contained cracks of varied lengths over approximately a 5-inch range, from 1/2 inch to 5-3/8 inches. The relationship between detection and crack length was studied for all of the cracks as a whole and also separated by crack type. This section considers the change in detection rate with crack length and the probability of detection analysis is presented in Section 4.6.

4.5.4.1 Total detection rate and crack length. Each hit had the potential to be detected 30 times, once by each participant. One crack was detected by all 30 inspectors, while three cracks were not detected by any participants. The largest undetected crack was 3-1/4 inches. This undetected crack was located along the weld toe of a tapered cover plate specimen. The smallest crack, measuring 1/2 inch, was detected by 23 of the

Figure 4.7 Individual detection rates by crack type.

Figure 4.8 Cover plate weld toe crack detection rate vs. out-of-plane distortion crack detection rate.

30 inspectors. This crack was located at a rivet hole. Figure 4.9 shows each crack, sorted by length, and the number of times it was correctly identified by an inspector. Visually, it appears that there was a correlation between crack size and number of detections. Generally, the larger cracks were detected more often than the shorter cracks.

The cracks were grouped into 1/2-inch size ranges, beginning at 1/2 inch to 1 inch, and the detection rate for each size range was computed. The detection rate was determined by summing the number of hits for an individual crack and dividing by the total number of detection attempts made. This was repeated for each crack. The smallest crack size ranges of 1/2 to 1 inch and 1 inch to 1-1/2 inches both had a 46% detection rate, which was the lowest rate, while the largest crack

size range, 5 to 5-1/2 inches, had the highest detection rate, 91%. The detection rates for the crack size ranges in between the extremes varied from 56% to 89%. Figure 4.10 shows the detection rates for each crack size range and considering all crack types. The number of cracks in each size range are shown on the right-hand vertical axis.

4.5.4.2 Out-of-plane crack detection rates and crack length. The out-of-plane distortion crack data was separated from the total data and examined for a relationship between crack length and detection. Figure 4.11 shows the number of times each crack was detected, and Figure 4.12 shows the detection rate for 1-inch crack size ranges. Both plots show an increase in detection for cracks greater than 2 inches.

Figure 4.9 Crack detection counts on painted specimens.

Figure 4.10 Detection rate by crack length.

Figure 4.11 Out-of-plane crack distortion detection counts.

Figure 4.12 Out-of-plane distortion crack detection rates by crack length.

4.5.4.3 Cover plate weld toe crack detection rates and crack length. The cover plate weld toe crack data was also analyzed individually for relationships with crack length. The crack sizes ranges for this type of crack were set to 1-inch increments beginning at 1 inch. Figure 4.13 shows the number of times each crack was detected, and Figure 4.14 shows the detection rate for 1-inch crack size ranges. The detection rates range from 71% to 90% and do not appear to be heavily influenced by crack length.

4.5.4.4 Rivet hole crack detection rates and crack length. The rivet hole crack data was studied separately for a relationship between detection and crack length. Due to the small range of crack sizes within this crack type, the data was split into two size categories: between 1/2 inch and 1 inch and from 1 inch to 1-1/2 inches. The crack lengths reported do not include the length of crack hidden beneath the rivet head. The detection rates are nearly identical for the two crack length ranges; Figure 4.15 shows the number of times each crack was detected; and Figure 4.16 shows the detection rate for 1/2-inch crack size ranges.

4.5.5 Detection Rate and Time

The time each inspector used to complete the inspection course was carefully recorded and documented. The speed at which the participant conducted his/her inspection was compared to his/her detection rate for the total population of cracks, as well as for each crack type individually. The times reported measure the time spent looking at the specimens and do not include any time taken for breaks or lunch.

4.5.5.1 Total detection time. Figure 4.17 shows each inspector's success rate and corresponding time to complete the hands-on inspection for the painted specimens and Figure 4.18 plots the number of false calls versus inspector time. The fastest inspector completed the course in 116 minutes (1 hour and 56 minutes); the slowest inspector spent 457 minutes (7 hours and 37 minutes) completing the course. The average time for the hands-on inspection of the painted specimens was 247 minutes (4 hours and 7 minutes). There was a slight correlation between detection rate and inspection time for the overall painted course. There was no correlation between the number of false calls and inspection time.

4.5.5.2 Out-of-plane distortion crack time. The time each inspector spent looking at the W-shape specimens was recorded and compared to the detection rates for that portion of the course. The shortest time was 1 hour and 11 minutes; the longest was 4 hours and 49 minutes. The average time spent inspecting the painted W-shape specimens was 2 hours and 24 minutes. Figure 4.19 shows the relationship between detection rate and time spent inspecting the out-of-plane distortion cracks on the W-shape, painted specimens. For this type of specimen, the rolled shapes and plate girder pieces, a slight correlation was observed between increasing inspection time and increased detection rates.

4.5.5.3 Cover plate weld toe cracks and time. The cover plate weld toe cracks occurred on the painted cover plates attached to the bottom flanges of the W-shape specimens. The average inspection time for these cover plates was 56 minutes. The shortest recorded time was 22 minutes while the longest recorded

Figure 4.13 Cover plate weld toe crack detection counts.

Figure 4.14 Cover plate weld toe crack detection rates by crack length.

Figure 4.15 Rivet hole crack detection counts.

Figure 4.16 Rivet hole crack detection rates by crack length.

Figure 4.17 Painted detection rate vs. inspection duration.

Figure 4.18 Painted number of false positives vs. inspection duration.

time was 1 hour and 33 minutes. No correlation was observed between increased inspection time and detection rates. This trend can be seen in Figure 4.20.

4.5.5.4 Rivet hole crack time. The time spent inspecting both the horizontal and vertical riveted cover plates was recorded and compared to the detection rates on the riveted specimens. The quickest inspectors finished these specimens in 23 minutes, while the slowest inspector spent 1 hour and 16 minutes completing the inspection of the same specimens. The average time spent looking at the 16 riveted specimens was 47 minutes.

Detection rate was found to increase with increasing inspection time for this type of specimen and crack. Figure 4.21 shows each inspector's detection rate for the riveted members and the corresponding time spent on inspection.

4.5.6 Crack Sizing Results

In addition to recording the location of detected cracks, inspectors were asked to record the length of the cracks on their inspection forms. Some inspectors were more disciplined about providing this measurement

Figure 4.19 Out-of-plane distortion crack detection rate vs. inspection duration.

Figure 4.20 Cover plate weld toe crack detection rate vs. inspection duration.

Figure 4.21 Rivet hole crack detection rate vs. time.

Figure 4.22 Measured crack length versus actual crack length for out-of-plane distortion-induced cracks in the W-shape specimens.

than others. Additionally, inspectors took different approaches to determining these measurements with some carefully measuring each crack, and others visually estimating the length without a measuring scale. Most inspectors used some combination of the two strategies.

Figure 4.22 shows the crack length data for the girder specimens. The actual length of the crack is shown on the horizontal axis and the vertical axis displays the measured value reported by the inspectors. The diagonal 1:1 reference line represents exact agreement between the actual length and the measured length. For the majority of the cracks in the girder specimens, the average of the measured lengths plots below the 1:1 line indicating that the inspectors tended to underestimate the length of the crack. The average absolute error increased with crack size and the percent absolute error remained constant with crack size. Table 4.8 shows the error analysis for the reported length measurement for all the cracks in the W-shape specimens.

Figure 4.23 and Figure 4.24 present the crack length data for the welded cover plate and riveted plate specimens, respectively. In contrast to the girder specimens, the average of the measured lengths of these cracks is generally above the 1:1 line indicating that the inspectors had a tendency to overestimate the length. The average absolute error increased with crack size and the percent absolute error decreased with crack size. Table 4.8 shows the error analysis for the reported length measurement for all the cracks in the welded cover plate and riveted plate specimens.

4.5.7 Human and Environmental Factors

The information provided by the participants on the *Exit Survey* was used to determine if trends existed between inspection performance and various human factors. The environment, namely the day's temperature and wind speed, was also tracked to ascertain if the weather impacted an inspector's likelihood of visually detecting a crack. Each factor was studied individually in terms of detection rate and the number of false positives for the entire crack population and each crack type on the painted specimens. Additionally, multiple variables were considered together to determine if the interaction among them effected detection rate. Descriptive statistics for the independent and dependent variables are shown in Table 4.9

4.5.7.1 Inspector age. The participants ranged in age from 24 to 63, with an average of 40 years. Figure 4.25 shows the detection rate and corresponding age of each inspector for all the cracks and Figure 4.26 plots the detection rate on the welded cover plate specimens against inspector age. A slight negative trend was found between detection rate and inspector age. This trend was even more pronounced with the welded cover plate specimens. Four of the oldest participants had the lowest detection rates on these specimens. In at least three of these cases, the inspectors saw the majority of the cracks, but decided that they were only cracks in the paint, not in the base metal. These decisions were primarily based on previous experience with this detail and they were noted on the inspection forms or discussed with the proctor.

TABLE 4.8
Error Analysis for Crack Length Measurement Results

Statistic	Out-of-Plane Cracks (28 cracks)		Cover Plate Weld Toe Cracks (23 cracks)		Rivet Hole Cracks (19 cracks)	
	Error	Absolute Error	Error	Absolute Error	Error	Absolute Error
Min./max. (in.)	-4.02/8.31		-2.63/8.94		-1/1.5	
Average (in.)	-0.37	0.93	0.51	0.76	0.14	0.24
Std. dev. (in.)	1.27	0.95	1.20	1.06	0.32	0.25
%	-12	30	14	22	16	26

TABLE 4.9
Descriptive Statistics for Dependent and Independent Variables

Variable Description	Min./Max. Values	Mean of Observations	Standard Deviation of Observations
Performance Measures			
Detection rate (all specimens)	0.31/0.86	0.65	0.14
False calls (all specimens)	14/268	90	67
Detection rate (girder specimens)	0.18/0.82	0.62	0.14
False calls (girder specimens)	5/205	65	54
Detection rate (cover plate specimens)	0.43/0.96	0.74	0.27
False calls (cover plate specimens)	0/59	16	14
Detection rate (rivet plate specimens)	0.21/0.95	0.59	0.17
False calls (rivet specimens)	0/34	9	9
Specimen Variables			
Crack length	0.5/5.375	2.42	1.37
Out-of-plane crack (1 if the crack is an out-of-plane crack, 0 otherwise)	—	0.4	1
Cover plate weld toe crack (1 if crack is a weld toe crack, 0 otherwise)	—	0.329	1
Rivet hole crack (1 if crack is at a rivet hole, 0 otherwise)	—	0.271	1
Environmental Variables			
Average temperature on the day of the inspection (°F)	23/73	45.7	16.1
Average wind speed on the day of the inspection (mph)	4/16	8.53	2.52
Maximum wind speed on the day of the inspection (mph)	12/29	18.1	4.53
Flashlight (1 if used, 0 otherwise)	—	0.7	—
Tape measure (1 if used, 0 otherwise)	—	0.6	—
Inspection mirror (1 if used, 0 otherwise)	—	0.07	—
Magnifier (1 if used, 0 otherwise)	—	0.13	—
Individual Variables			
Inspection experience (yrs.)	0/30	10.6	9.33
Age	24/63	40.2	11.7
Inspection duration, all specimens (min.)	116/457	247	75.2
Inspection duration, girder specimens (min.)	71/289	144	57
Inspection duration, cover plate specimens (min.)	22/93	56	17
Inspection duration, rivet plate specimens (min.)	23/86	47	16
No. of routine inspections performed in the last 12 months	0/700	142	174
No. of hands-on inspections performed in last 12 months	0/40	10.6	10.5
No. of training courses attended (out of 8 listed on exit survey)	0/7	2.93	1.66
Professional licensure (1 if licensed PE or SE, 0 otherwise)	—	0.57	—
Employer (1 if employed by a private consultant, 0 otherwise)	—	0.4	—
Gender (1 if male, 0 otherwise)	—	0.9	—
Safety inspection of in-service bridges (1 if inspector has taken the course, 0 otherwise)	—	0.867	—
Fracture Critical Inspection Techniques (1 if inspector has taken the course, 0 otherwise)	—	0.8	—
Introduction to Element Level Bridge Inspection (1 if inspector has taken the course, 0 otherwise)	—	0.267	—
Underwater Bridge Inspection (1 if inspector has taken the course, 0 otherwise)	—	0.2	—

Figure 4.23 Measured crack length versus actual crack length for weld toe cracks in welded cover plate specimens.

Figure 4.24 Measured crack length versus actual crack length for cracks in the riveted plate specimens.

Figure 4.25 Total detection rate vs. inspector age.

Figure 4.26 Cover plate weld toe crack detection rate vs. inspector age.

4.5.7.2 Years of experience. Figure 4.27 shows the total detection rate versus years of inspection experience. The average experience of the participants was 10.6 years, with a minimum of 0 years and a maximum of 30 years. Similar to age, there was a slight negative trend between years of experience and detection rate. In other words, inspectors with more experience demonstrated a lower detection rate. Although common sense suggests that inspection performance should increase with experience, previous research

presents a varied relationship between performance and experience (Demsetz et al., 1996; Leach & Morris, 1998; Moore et al., 2001; See, 2012). Once again, this negative relationship was most pronounced in the welded cover plate specimens as shown in Figure 4.28. Additionally, there is significant variability in performance, even among inspectors with the same length of experience. For instance, two inspectors with 20 years of inspection experience had a 48% difference in detection rate.

Figure 4.27 Total detection rate vs. years of inspection experience.

Figure 4.28 Cover plate weld toe crack detection rate vs. inspection experience.

Covariance between inspection duration and experience was also investigated to determine if more experienced inspectors inspect more quickly or more slowly than less experience inspectors. A positive relationship between inspection experience and inspection duration was observed—more experienced inspectors spent longer on the inspection. The plot of inspection experience against inspection duration can be found in Figure 4.29.

4.5.7.3 Recent previous inspections. Inspectors were asked to provide the number of routine and hands-on bridge inspections that they had completed in the 12 months prior to their participation in the study. The numbers provided by the participants were the inspectors' personal estimates and may not be specific to steel

bridge inspections. The average number of routine inspections was 142 and the average number of hands-on inspections was 10.6. These plots can be seen in Figure 4.30 and Figure 4.31. Looking at the relationships individually between previous inspections and detection rate, there is no clear observed trend.

4.5.7.4 Weather. The temperature and wind speeds were recorded during each day of inspection. Originally, this information was measured by a weather station mounted atop the test structure, however, this device failed partway through the study. The weather data used in this analysis was recorded by the KLAf weather station at the Purdue University Airport. The airport is located immediately adjacent to the test site. On the days

Figure 4.29 Inspection experience vs. inspection duration.

Figure 4.30 Total detection rate vs. number of hands-on inspections.

Figure 4.31 Total detection rate vs. number of routine inspections.

Figure 4.32 Total detection rate vs. air temperature.

Figure 4.33 Inspection duration vs. average air temperature.

of inspection, the average air temperature ranged between 23°F and 73°F, with an average of 46°F. A slight positive correlation was observed between air temperature and inspection success. The plot showing this relationship can be seen in Figure 4.32.

A trend was also looked for between air temperature and inspection time to investigate whether inclement or uncomfortably cold weather caused inspectors to increase their inspection speed. A positive relationship was observed—the inspectors tested on the warmest days spent the longest amount of time completing the course. The plot of inspection time against air temperature can be found in Figure 4.33.

The effect of maximum and average wind speeds was also investigated. Average wind speeds ranged from 4 mph to 16 mph. There is no clear relationship between average wind speed and detection rate as shown in Figure 4.34.

The maximum wind speeds have been plotted against total detection rate in Figure 4.35 and rivet hole crack detection rate in Figure 4.36. Measured maximum wind speeds ranged from 12 mph to 29 mph. There is no clear overall trend between total detection rate and maximum wind speed; however, there is a slight negative relationship between rivet hole crack detection rate and maximum wind speed.

Figure 4.34 Total detection rate vs. average wind speed.

Figure 4.35 Total detection rate vs. maximum wind speed.

Figure 4.36 Rivet hole crack detection rate vs. maximum wind speed.

4.5.7.5 Inspection training. On the exit survey, inspectors were asked to list the inspection training that they had completed. To improve the consistency of the results, the exit survey was revised partway through the study to include a list of eight common training courses and asked the inspector to indicate which ones they had completed. The eight courses listed on the revised exit survey were *Safety Inspection of In-Service Bridges*, *Bridge Inspection Refresher Training*, *Engineering Concepts for Bridge Inspectors*, *Underwater Bridge Inspection*, *Fracture Critical Inspection Techniques for Steel Bridges*, *Inspection and Maintenance of Ancillary Highway Structures*, and *Introduction to Element Level Bridge Inspection* from FHWA/NHI, and *Inspecting Steel Bridges for Fatigue* from Purdue/S-BRITE. The average number of courses was three. None of the inspectors had taken all eight classes and three inspectors had not completed any of the training courses. Considering only the training courses listed on the exit survey, total detection rate increased with increasing attendance at these courses. Similarly, detection of the out-of-plane distortion induced cracks and the cover plate weld toe cracks was also positively correlated with training. The plots showing these relationships can be seen in Figure 4.37, Figure 4.38, and Figure 4.39.

4.5.7.6 Tool use. No significant correlation was found between inspection performance and any single tool that was used. This is likely due to the large variety in tools used during the inspections and the lack of information collected about these tools and their use. The tools brought and used by each inspector are listed in Appendix B: Exit Survey Responses.

Although this study did not find significant correlation between flashlight use and inspection performance, this should not be interpreted to mean that flashlights are not necessary or ambient lighting under a bridge is adequate for visual inspection. Additional information that was not collected during this study, such as the ambient lighting under the bridge during the inspection and the specific specimens on which a flashlight was used, is necessary to determine minimum lighting levels and if flashlights improve the likelihood of detecting a fatigue crack. Absent this information, a flashlight with a minimum light output of 100 lumens and an adjustable focus is recommended for use during all hands-on bridge inspections

4.5.7.7 Multivariate linear regression model. To assess the interaction among the human and environmental factors, separate multivariate linear regression analyses were used to predict detection rate and the number of false positives. These analyses were completed in NLOGIT 6 by Econometric Software, Inc.

The model predicting detection rate provided similar results to the univariate analysis with detection rate best described by a function considering inspection duration, inspection experience, and training. The results

from this analysis are shown in Table 4.10. Once again, the relationships between detection rate and duration and training were positive, while the relationship between detection rate and experience was negative. The exclusion of temperature from this model suggest that the relationship between performance and temperature found in the univariate analysis may be an indirect relationship through duration. In other words, favorable inspection conditions encouraged inspectors to spend more time performing the inspection and the increased time resulted in improved performance. The improvement in the R^2 statistic indicates that the multivariate linear regression model explains the data better than any of the univariate models.

As noted previously, no single variable showed more than a very slight relationship with the number of false calls. However, the multivariate regression analysis was able to find a relationship between some of the human and environmental variables and the number of false calls made by an inspector. The results from this analysis are shown in Table 4.11. In this study, inspectors that worked for a private consultant, had completed the FHWA/NHI *Introduction to Element Level Bridge Inspection* course, and were exposed to higher maximum wind speeds made more false calls. Conversely, inspectors that used a tape measure made fewer false calls.

The negative relationship between the number of false positives and the Element Level Bridge Inspection training course is somewhat unexpected and warrants additional scrutiny. It may be an artifact of the study because the inspections began only a month after element level inspection became mandatory for all bridges on the National Highway System, and so only eight of the 30 inspectors had received the training. Alternatively, it could be that the inspection approach utilized in an element level inspection is more detailed and precise, leading inspectors to include every indication on their sketch.

The negative relationship between the number of false calls and the use of a tape measure also deserves further investigation since the tape measure is obviously not a tool expected to improve visual acuity or the discriminability of flaws. Instead, this variable might actually be measuring an inspector's tendency to view the specimen from a short distance and willingness to touch the inspection surface. These inspection techniques have been found to improve inspection performance in previous studies (Drury & Watson, 2002; Spencer, 1996). It is not known if using a tape measure forces an inspector to touch the inspection surface, or if inspectors that have predisposition to do this are also more likely to use a measuring tape.

4.6 Probability of Detection Analysis of Painted Specimen Cracks

The hit/miss data was analyzed using *R*, a statistical computing and graphics software, along with a

Figure 4.37 Total detection rate vs. number of training courses.

Figure 4.38 Out-of-plane distortion crack detection rate vs. number of training courses.

Figure 4.39 Cover plate weld toe crack detection rate vs. number of training courses.

TABLE 4.10
Results from the Multivariate Linear Regression Model Estimating Detection Rate

Variable Description	Estimated Parameter	Standard Error	t-statistic	P(> t)
Constant	0.423	0.058	7.24	0.0000
Inspection duration (min.)	0.001	2.4E-4	4.45	0.0002
Inspection experience (yrs.)	-0.009	0.002	-5.07	0.0000
Number of trainings	0.023	0.010	2.31	0.0291

Number of observations = 30
 $R^2 = 0.639$
Adjusted $R^2 = 0.598$

TABLE 4.11
Results from the Multivariate Regression Model Estimating Number of False Calls

Variable Description	Estimated Parameter	Standard Error	t-statistic	P(> t)
Constant	-16.2	48.2	-0.34	0.740
Employed by private engineering/inspection firm	77.2	22.5	3.44	0.002
Used a tape measure	-65.4	22.1	-2.96	0.007
Max. wind speed (mph)	5.50	2.31	2.38	0.025
Attended element level bridge inspection training course	57.4	22.7	2.53	0.018

Number of observations = 30
 $R^2 = 0.460$
Adjusted $R^2 = 0.373$

software package provided by the Department of Defense to supplement Military Handbook 1823a, Nondestructive Evaluation (NDE) System Reliability Assessment (2009). After inputting the data, the best fitting model was selected. For these data series, a logit model was used. The data for all 30 inspectors were included in the analyses. Three additional subsets of data were independently analyzed: out-of-plane distortion cracks, cover plate weld toe cracks, and rivet hole cracks. For each case, the a_{50} , a_{90} and $a_{90/95}$ crack lengths were computed for each inspector and for the population of inspectors. However, the data collected in the study does not converge well, too many small cracks were found, too many larger cracks were missed, and the inspectors demonstrated highly varied detection rates, and it was not possible to determine crack length with a 90% likelihood of being detected with a 95% confidence bound. Care should be taken when applying the results from this population of inspectors to a future inspection. The average POD curve disguises the strengths and weaknesses of each individual inspector and may not be able to predict the performance of a future inspector, who could be a “good” or a “bad” inspector.

4.6.1 Methodological Approach

In order to represent binary response data (hit/miss) as a linear function of the defect size, a link function is

introduced to transform the binary data (0 or 1) to probability data (between 0 and 1). In this way, size can be related to the probability of a hit or the probability of a miss. The most widely used link function is the logistic function, also known as a log-odds or logit function, and the model takes the form (Gandossi & Annis, 2010):

$$\log\left(\frac{POD(a)}{1-POD(a)}\right) = \beta_0 + \beta_1 \alpha \quad (\text{Eq. 4.1})$$

Solving for $POD(a)$ provides:

$$POD(a) = \frac{\exp(\beta_0 + \beta_1 \alpha)}{1 + \exp(\beta_0 + \beta_1 \alpha)} \quad (\text{Eq. 4.2})$$

where $\alpha = \log(a)$ or $\alpha = a$. Because β_0 and β_1 have no obvious physical meaning, the equation is reparametrized in terms of the location parameter, μ , and scale parameter, σ , as φ :

$$POD(a) = f(a, \theta) = \varphi_{link}^{-1}\left(\frac{x - \mu}{\sigma}\right) \quad (\text{Eq. 4.3})$$

Where

$$\varphi_{link}\left(\frac{x - \mu}{\sigma}\right) = \log\left(\frac{POD(a)}{1 - POD(1)}\right) \quad (\text{Eq. 4.4})$$

Figure 4.40 Total data set POD vs. crack length.

Now:

$$f_1(x|\beta_0, \beta_1) = \log\left(\frac{POD(a)}{1 - POD(a)}\right) = f_2(a|z) \quad (\text{Eq. 4.5})$$

where:

$$z = \left(\frac{x - \mu}{\sigma}\right)$$

Because

$$f_1(x|\beta_0, \beta_1) = f_2(a|z)$$

Then

$$\beta_0 + \beta_1 x = \frac{x - \mu}{\sigma}$$

And therefore:

$$\sigma = \frac{1}{\beta_1}$$

$$\mu = -\beta_0 \sigma$$

μ is the size at which $POD = 0.5$ and σ is the inverse of the generalized linear model regression slope.

4.6.2 All Cracks POD Analysis Results

In total, 2,100 observations were made during the course of this study. The POD vs. Crack Size plot for the complete data set can be seen in Figure 4.40. The hits are plotted at $POD = 1$ and the misses are plotted at $POD = 0$. The statistical model computed a curve to show the probability of detection for any crack length in the range of crack sizes present in the study. For this study, a 1-inch crack had a 50% probability of being detected. This set of inspectors, which is considered to be representative of the current population of bridge inspectors, resulted in an a_{90} length of 5-1/2 inches, meaning for 90% of inspectors to identify a crack, it would have to be at least 5-1/2 inches long. Figure 4.41 shows the individual POD versus a curve for each inspector. Inspectors 13CA-09, 06JD-15, and 18GA-03 show a negative relationship between probability of detection and crack length, meaning they were more likely to find shorter cracks than longer cracks. (It should be noted that the research team does not believe the inspectors are better equipped to find shorter cracks, but instead some outside factors or happenstance contributed to them detecting shorter cracks or missing longer cracks.) After removing the results from these

inspectors whose detection did not conform to the assumptions of the POD model (i.e., POD increasing with increasing crack length), the probability of detection curve was regenerated. For the 27 remaining inspectors and all the specimens, the a_{50} crack length remains 1", but the a_{90} crack size is reduced to 4-1/2".

The probability of detection at 1-inch increments was calculated for each inspector. Table 4.12 shows the average probability of detection at each length increment along with the minimum and maximum probabilities of detection for the 27 inspectors whose probability of detection increases with increasing crack size.

4.6.3 Out-of-Plane Cracks POD Analysis Results

The hit/miss record for each inspector's observations on the out-of-plane distortion cracks were analyzed independently and plotted. The 840 observations were analyzed for this data subset. For this sample, the a_{50} and a_{90} crack lengths were 2 inches and 4 inches, respectively. Figure 4.42 shows the POD vs. Crack Length curve for the data from all 30 inspectors together. Figure 4.43 shows the individual POD vs. a curve for each of the 30 inspectors. For the out-of-plane distortion cracks, all of the inspectors demonstrated an increasing probability of detecting cracks of increasing length.

4.6.4 Cover Plate Weld Toe Cracks Probability of Detection Analysis Results

The 23-cover plate weld toe cracks were analyzed to determine the probability of detection as a function of crack length for the given population of inspectors. Figure 4.44 shows the POD curve from all 30 inspectors. This curve takes into account the hits and misses of 30 observations on 23 cover plate weld toe cracks. According to this model, even the smallest weld toe crack, 1-7/16 inches long, has a 50% probability of being detected, but for a 90% chance of being detected, the crack would need to be over 10 inches long. The range of crack lengths included in the welded cover plate specimens is likely not wide enough to capture the true POD curve. As discussed previously, for successful convergence in a POD study, the crack sizes should range from $POD = 3\%$ to $POD = 97\%$. These results are considered invalid but presented for completeness.

The plot showing each individual inspector's POD curve can be seen in Figure 4.45. Ten of the inspectors detected 22 out of the 23 possible cover plate weld toe cracks and therefore have a high probability of detection for all lengths of cracks of this type. Inspectors 13CA-09, 18RT-25, 04MY-41, and 25HQ-08 showed a negative relationship between probability of detection and crack length, meaning they were more likely

to find shorter cracks than longer cracks. This was likely due to flawed decision making rather than failure to locate the crack. Based on previous experience, some of the inspectors believed the weld toe cracks to be cracks in the paint, not fatigue cracks in the base metal. In these cases, personal biases or expectations have more influence on performance than defect size.

4.6.5 Rivet Hole Cracks Probability of Detection Analysis Results

The final subset of data independently analyzed using the POD model was the hit/miss data collected from the 19 rivet hole cracks. The overall POD versus crack length curve for the tested group of inspections can be seen in Figure 4.46. According to this model, even the smallest rivet hole crack, 1/2-inch long, has a 50% probability of being detected, but for a 90% chance of being detected, the crack would need to be much longer, with the model predicting a crack over 84 inches long. Similar to the cover plate weld toe cracks, the range of crack lengths was not wide enough to capture the full POD curve. Within the 1-inch range provided, the probability of detection is nearly constant at approximately $POD = 0.6$. The plot showing the individual inspector curves can be seen in Figure 4.47. Seventeen of the inspectors had a negative relationship between probability of detection and crack length for the riveted hole cracks.

4.6.6 POD Analysis Summary

While the data could not be used to determine probabilities of detection for various crack sizes within a 95% confidence bound, the data could still be analyzed to generate POD curves for this specific grouping of inspectors. The a_{50} and a_{90} values for the total test and for each crack type have been tabulated in Table 4.13.

4.7 Random Parameters Binary Logit Model

The variability in the POD curves suggests that factors beyond crack length affect the probability of detecting an individual crack. A random parameters binary logit model was developed to predict the probability of detection for each crack based on the hit/miss results for each inspector, the crack characteristics, and the human and environmental factors. The following sections describe the methodological approach and present the results of the statistical analysis.

4.7.1 Methodological Approach

The intent of this analysis is to develop a model to predict the likelihood that an individual crack will be detected. Each observation is recorded as either

TABLE 4.12
Probability of Detection by Crack Length (all specimens)

Crack Size (in.)	Average POD (%)	Std. Dev. POD (%)	Minimum POD (%)	Maximum POD (%)
1/2	40	13	14	63
1	49	13	21	73
2	66	14	31	87
3	79	14	43	95
4	87	13	54	99
5-3/8	92	10	58	100

Figure 4.41 Total data set individual POD vs. crack length curves.

Figure 4.42 Out-of-plane distortion cracks POD vs. crack length.

Figure 4.43 Out-of-plane distortion cracks individual POD vs. crack length.

Figure 4.44 Cover plate weld toe cracks POD vs. crack length.

Figure 4.45 Cover plate weld toe cracks individual POD vs. crack length.

Figure 4.46 Rivet hole cracks POD vs. crack length.

Figure 4.47 Rivet hole cracks individual POD vs. crack length.

TABLE 4.13
Summary of a_{50} and a_{90} Crack Lengths

Crack Type	a_{50} (in.)	a_{90} (in.)
All cracks	1	5-1/2
Out-of-plane distortion cracks	2	4
Cover plate weld toe cracks ^a	0	10
Rivet hole cracks ^a	0	8-1/2

^aPOD curves considered invalid due to limited range of crack lengths considered.

a hit (1) or miss (0). Because two discrete outcomes are considered, a binary logit model is appropriate (Washington et al., 2011). These models are derived by defining a linear utility function, U_{in} , that describes the outcome i for observation n such that

$$U_{in} = \beta_i X_{in} + \varepsilon_{in} \quad (\text{Eq. 4.7})$$

where β is a vector of estimable coefficients for discrete outcome i , X_{in} is a vector of observable characteristics that determine the discrete outcome for observation n , and ε is a random disturbance term. For this single choice situation, the probability that observation n is a hit can be written as

$$P(\text{hit}) = \text{Prob}(U_{\text{hit},n} > U_{\text{miss},n}) \quad (\text{Eq. 4.8})$$

Substituting Equation 4.7 into Equation 4.8 and rearranging, the probability of a hit becomes

$$P_n(\text{hit}) = \text{Prob}(\varepsilon_{\text{hit},n} - \varepsilon_{\text{miss},n} < \beta_{\text{hit}} X_{\text{hit},n} - \beta_{\text{miss}} X_{\text{miss},n}) \quad (\text{Eq. 4.9})$$

And

$$P_n(\text{hit}) = F(\beta_{\text{hit}} X_{\text{hit},n} - \beta_{\text{miss}} X_{\text{miss},n}) \quad (\text{Eq. 4.10})$$

where $F(\bullet)$ is the cumulative density function of the difference of the disturbance terms. Setting the utility function describing a miss to zero and assuming the disturbance terms are extreme value Type I distributed, the difference will have a logistic distribution and the binary logit model results:

$$P_n(\text{hit}) = \frac{\text{EXP}(\beta_{\text{hit}} X_{\text{hit},n})}{1 + \text{EXP}(\beta_{\text{hit}} X_{\text{hit},n})} \quad (\text{Eq. 4.11})$$

However, a couple complications with this set of observations require minor adjustments to the probability formulation shown in Equation 4.11. The first complication is due to the nature of the data collected in this study. In this study, 30 inspectors provided 70 observations (one observation for each crack) on the presence or absence of a crack. Since each inspector generated multiple observations, it is inevitable that these observations will share unobserved effects, thus

violating the assumption of serial independence of the disturbance terms. The unobserved effects will cause the standard errors of the coefficients to be underestimated, thereby inflating the t -statistics. This will increase the likelihood of mistakenly rejecting a true null hypothesis (Washington et al., 2011). This complication can be addressed with a random effects model which includes an individual specific disturbance term, μ_k , in addition to the overall disturbance term. Modifying Equation 4.7, the linear function describing the utility function for outcome i becomes

$$U_{kt}^i = \beta^i X_{kt}^i + \varepsilon_{kt}^i + \mu_k \quad (\text{Eq. 4.12})$$

where the subscript n has been replaced with the inspector number, k ($k = 1, \dots, 30$) and the crack number, t ($t = 1, \dots, 70$). All other terms are as previously defined. Accounting for random effects, the probability that crack t is correctly located by inspector k can be written as

$$P_{kt}(\text{hit}) = \frac{\text{EXP}(\beta^{\text{hit}} X_{kt}^{\text{hit}} + \mu_k)}{1 + \text{EXP}(\beta^{\text{hit}} X_{kt}^{\text{hit}} + \mu_k)} \quad (\text{Eq. 4.13})$$

The second complication arises from the complexity of visual inspection. As discussed previously, visual inspection is a complex and imperfect process involving a variety of human factors. Since many of these human factors cannot be quantified and explicitly captured in statistical models, results generated from these models may be biased or erroneous. Random parameter models were developed to consider these unaccounted-for factors (typically referred to as unobserved heterogeneity). While random effects consider unobserved effects within an individual inspector's set of observations, random parameters account for the unobserved factors across the observations which might influence the likelihood of detection (Mannering et al., 2016). In this model, random parameters allow the influence of certain explanatory variables to vary across the sample of inspectors. For example, while a standard binary logit model can account for the effect of experience on detection, only a random parameters model would consider the influence of underlying inspector characteristics, such as patience, confidence, or bias. These variables are not included in the model but could affect the relationship between experience and probability of detection. Statistically, this possibility is accounted for with the introduction of a mixing distribution into the probability equation such that the probability that crack t is correctly located by inspector k is

$$P_{kt}(\text{hit}) = \int \frac{\text{EXP}(\beta^{\text{hit}} X_{kt}^{\text{hit}} + \mu_k)}{1 + \text{EXP}(\beta^{\text{hit}} X_{kt}^{\text{hit}} + \mu_k)} f(\beta|\varphi) d\beta \quad (\text{Eq. 4.14})$$

where $f(\beta|\varphi)$ is the density function of β with φ referring to a vector of the mean and variance of that density function. In this mixed logit model, β can now

account for inspector specific variations of the effect of X on crack detection probability with the density function, $f(\beta|\varphi)$, used to determine β . Typically, a normal distribution is assumed for the density function, although other distributions are feasible. Due to the complexity of estimating a different parameter for each observation, a simulation based maximum likelihood approach is used. The log likelihood function is written as

$$LL = \sum_{k=1}^{30} \sum_{t=1}^{70} \sum_{i=1}^2 \delta_{itk} \ln[P_{kt}(i)] \quad (\text{Eq. 4.15})$$

where δ_{itk} is equal to one if the observed outcome for inspector k and crack t is i and zero otherwise, and all other variables are as previously defined. As recommended by Washington, Karlaftis, and Mannering (2011), a Halton sequence with 200 draws was used. In this way, values of β are drawn from $f(\beta|\varphi)$, the probabilities are computed, and estimated parameters are selected to maximize the likelihood function. Model estimation was completed in NLOGIT 6 by Econometric Software, Inc.

4.7.2 Analysis Results

Many combinations of factors were analyzed to determine which traits significantly impacted likelihood of detection. For this population of inspectors, the probability of detection for each crack is best described by a function considering crack length, crack type, inspector experience, inspection duration, and the elapsed time since the first inspection. Crack length and experience were found to vary across the inspector population, as indicated by the significance of their standard deviations. Specimen type, wind speed, inspection duration, and time since the first inspection were considered fixed across the population.

This model includes both random effects due to the repeated observations from a single inspector and random parameters to account for the variability in the influence of the independent variables across the observations. Random parameters were included for estimated parameters with a standard deviation that was significantly different from zero. Random effects were accounted for by allowing the constant term to vary across the observations. Since this study consists of panel data (repeated observations from the same observer), random effects were included even though the standard deviation of the constant term was not significantly different from zero. The likelihood ratio test was used to confirm that both random effects and random parameters should be included in the final model. The results from this model are shown in Table 4.14.

The model produced marginal effects to show how each parameter affects the POD. The marginal effect gives the change in probability of detection for a unit change in the independent variable. The marginal effects for the relevant parameters can be seen in Table 4.15. A larger marginal effect indicates a greater influence on

TABLE 4.14
Results from the Binary Logit Model Estimating the Probability of Detection for Each Crack

Variable	Estimated Parameter (std. dev.)	Standard Error Estimate (std. dev.)	t-statistic (std. dev.)
Constant	-0.902 (0.029)	0.170 (0.059)	-5.32 (0.50)
Crack length (in.)	0.645 (0.371)	0.054 (0.029)	11.93 (12.91)
Out-of-plane crack (1 if out-of-plane crack, 0 otherwise)	-0.782	0.085	-9.22
Cover plate weld toe crack (1 if weld toe crack, 0 otherwise)	-0.775	0.111	-7.02
Experience (yrs.)	-0.009 (0.021)	0.005 (0.004)	-1.89 (4.90)
Inspection duration (min.)	0.004	0.001	6.09
No. of days since first inspection	-0.0006	0.0002	-4.22

Number of observations = 2,096
Log-likelihood of constant = -1309.6
Log-likelihood at convergence = -1136
Adjusted ρ^2 = 0.125

TABLE 4.15
Marginal Effects

Variable Description	Avg. Marginal Effect (std. dev.)
Crack length (in.)	0.156 (0.087)
Out-of-plane crack (1 if out-of-plane crack, 0 otherwise)	-0.159 (0.024)
Cover plate weld toe crack (1 if weld toe crack, 0 otherwise)	-0.153 (0.031)
Inspection duration	6.41E-4 (2.73E-4)
Years of inspection experience	-0.002 (0.002)
Elapsed time since first inspection (days)	-1.11E-4 (4.72E-5)

the likelihood of detecting the crack while a smaller marginal effect indicates a lesser influence. For the dummy variables, marginal effects are computed as the difference in the estimated probabilities when the variable is changed from zero to one, while all the other variables are set equal to their means. For continuous variables, the marginal effects are computed from the partial derivative of the probability equation. In both cases, the reported marginal effect represents the average over all the observations.

In addition to the relationships between performance and environmental conditions and inspector attributes, this model provides insight into how the characteristics of the crack may influence the probability of detection. On average, a 1-inch increase in crack length resulted in a 15.6% increase in probability of detection. For 96% of the observations, an increase in crack length resulted in a higher probability of detection for that crack. For the remaining 4% of the observations, the probability of detection decreased with increasing crack length. A similar trend was reflected in the probability of detection curves discussed in Section 4.6. In these cases, the failure to detect the crack may have been caused by an error in the decision task, as opposed to the search task, as was observed on the welded cover plate specimens.

Cracks were more likely to be located during inspections that lasted longer. This variable was fixed across the population and a one-minute increase in inspection time increases the likelihood of detecting a crack, regardless of length, by 0.06%.

Supporting the previous finding of a positive correlation between detection rate on the girder specimens and the welded cover plate specimens, the binary logit model indicated that cracks in both the W-shape specimens and the welded cover plate specimens were approximately 16% less likely to be detected as compared to cracks in the riveted plate specimens.

Individual cracks were more likely to be found during the earlier inspections and less likely to be found during the later inspections. This variable is fixed across the population, and the likelihood of detecting a specific crack decreased approximately 8% from the first inspection on Day 1 of the study to the last inspection on Day 762. This is not unexpected as specimen maintenance is a well-documented challenge to POD studies (DoD, 2009). This trend was not present in the regression analyses indicating that for an individual inspector, performance is more heavily influenced by human factors than by crack characteristics. As shown in Figure 4.5, on seven occasions there was more than a 10% difference in detection rates between inspections that happened on consecutive days. Conversely, there was a 454-day gap between the 11th and 12th inspectors, but the difference in detection rates was only 9%. The effect of human factors on detection rate significantly outweighs the influence from the change in the crack appearance, and so it remains valid to directly compare the results from all 30 inspectors over the 2+ year study.

Similar to the regression models, the binary logit model also revealed a negative relationship between probability

of detection and inspection experience. However, this model was able to capture the variation in influence across the sample of inspectors. For 67% of the observations, the probability of detecting a crack decreased with experience while, for the remaining 33% of the observations, the likelihood of finding a crack increased with experience. On average, a one-year in experience reduces the probability of detecting the crack by 0.2%.

4.8 Summary

- The routine inspection scenario produced highly varied inspection reports. The inspectors' documentation ranged from detailed cracks with dimensions, to unlabeled tick marks, to general comments on the overall condition of the bridge. Time spent completing the ground scenario ranged from 12 minutes to 82 minutes.
- The hands-on inspection scenario for the weathered specimens resulted in an average detection rate of 11%. Of the 198 observations, only 21 hits were identified. Six (6) of the 11 inspectors did not find any cracks.
- The average detection rate for all 30 inspectors of all 70 cracks located on painted specimens was 65%. Detection rates ranged from 31% to 86%. Univariate analysis between detection rates and other factors, like inspection time or the day's weather, revealed slight, but statistically significant, correlations. Detection rate increased with increasing inspection duration, temperature, and training, but decreased with increasing experience.
- The average number of false calls for all 30 inspectors on the 147 painted specimens was 90. The number of false calls ranged from 14 to 268. Univariate analysis between the number of false calls and other factors, like inspection time or the day's weather, did not reveal any significant correlations. However, the multivariate analysis revealed that the number of false calls was related to the inspector's employer, the maximum wind speed on the day of the inspection, the use of a tape measure, and completion of the Element Level Bridge Inspection training course. Inspectors that used a tape measure made fewer false calls while inspectors that were employed by a private inspection/engineering firm, experienced higher wind speeds, and attended the element level inspection course tended to make more false calls.
- For the majority of the inspectors, the likelihood of a crack being detected increased with crack length. However, this was not true for three of the inspectors.
- Probability of detection analysis using a log-odds model generated POD values for varying crack lengths. For the total population of cracks for this set of inspectors, a 1-inch-long crack had a 50% chance of being detected and a 5-1/2-inch-long crack had a 90% chance of being detected. The data was too scattered to assign a 95% confidence bound.
- A random parameters binary logit model was used to identify variables beyond crack length that affected the probability that a crack would be detected. The analysis showed that crack length, the type of crack, the inspector's years of experience, the inspection duration, and the elapsed time since the first inspection impacted the likelihood of a crack being detected.

- It is likely that the findings of this study represent the upper bound on visual inspection performance. The inspections were performed in isolation, free from many of the distractions and time pressures present during a typical inspection, unobstructed access to the inspection surface was provided, and cracks were present at a higher than average rate. Additionally, although inspectors were encouraged to perform their inspection as they would a typical fracture critical inspection, it is likely that they were motivated to excel by the presence of the proctor.

5. INSPECTOR TRAINING

Based on the results from this study, it is clear that the current standards for visual inspection of steel bridges produce highly variable results. One possible explanation is insufficient training or lack of consistency in training. Focusing on the detection of fatigue cracks in steel bridges, currently available training courses and material seem to provide a strong background in where and how fatigue cracking may occur. All relevant training discusses the mechanics of bridge behavior, including identification of tension and compression regions, description of in-plane and out-of-plane loading, and recognition of fatigue prone details. And yet, in reviewing the inspection results, it is clear that many inspectors, regardless of training and experience, may not fully understand how and where fatigue cracking occurs. Although inspectors were regularly reminded to do their best to differentiate between fatigue cracks and other crack-like surface defects, some may have adopted an unrealistically conservative inspection strategy to limit their misses. Even still, several inspectors identified what they believed to be cracks in highly unlikely locations or orientations. For instance, many inspectors identified cracks in the plain web section of the girder specimens or parallel to the primary stress in the riveted plates. These types of errors imply that inspectors either do not have a proper understanding of the mechanics of fatigue cracking or are unable to apply the theories learned in the classroom in the field. While the excessive numbers of false calls may be partially a construct of the inspection scenario, it does reveal a high level of uncertainty among some of the inspectors, and during actual bridge inspections, this uncertainty may produce the opposite result—fewer false calls and more missed cracks.

5.1 Observational Skills Training

To address the disconnect between training and execution, a new half-day training course focused on the cognitive skills used during visual inspection was developed. Since there is not a practical way to apply a standardized step-by-step procedure to visual inspection, the objective of this training course is to improve the application of technical knowledge in the field by teaching inspectors "how to inspect" rather than "where

TABLE 5.1
Description of Perception and Recognition Unit

Objective	Convey how perception and recognition work and how these processes can enrich or inhibit inspection tasks
Topics	<ol style="list-style-type: none"> 1. Definitions of perception and recognition 2. Rules of perception (simplicity, closure, figure-ground) 3. Illusions 4. Recognition theories (template matching, prototype matching, recognition by component)
Exercises	<ol style="list-style-type: none"> 1. Hidden figures (identify a critical target among a distracting background)
Sample Slides

to inspect” or “what to inspect.” The course first subdivides the inspection activity into four distinct tasks (prepare, search, decide, and document) and then identifies the observation skills used in each task (perception and recognition, attention, memory, mental imaging and mental models, and judgement and decision making). These are the skills that enable an inspector to observe and interpret environmental information, compare it to previous experiences and knowledge stored in long-term memory, and use that analysis as the basis for a decision. This course covers both the theory and application of these skills and offers techniques for improvement. Additional details for the training module on each observation skill are provided below. The information is delivered through a combination of lecture, class discussion, and individual exercises. Similar to a course developed for the International Atomic Energy Agency (Toquam et al., 1995), this training course is tailored to bridge inspection,

although the observation skills are common to all visual inspection activities.

5.1.1 Perception and Recognition

Perception and recognition skills allow an inspector to identify and understand familiar structural features or operating conditions (Toquam et al., 1995). Perception is the entry point for making observations; if perceptions are flawed, the response will also be flawed. Both perceptions and recognition may be influenced by personal expectations or experiences. Specific details of the Perception and Recognition unit are provided in Table 5.1.

5.1.2 Attention

Attention skills enable an inspector to fully inspect all potentially important regions of the inspection

TABLE 5.2
Description of Attention Unit

Objective	Convey how attention works and how it can be limited, especially during stressful or demanding situations
Topics	<ol style="list-style-type: none"> 1. Definition of attention 2. Types of attention (focused, selective, and divided)
Exercises	<ol style="list-style-type: none"> 1. Attention to detail (identify the differences between two pictures) 2. The “gorilla” experiment (video demonstrating how the brain selectively attends to certain stimuli and completely misses other stimuli)
Sample Slides

surface, not just the most central or most obvious (Toquam & Morris, 1994). Attention skills are responsible for distinguishing between environmental inputs that deserve attention and those that do not. Expectations, habituation, and stress can influence attention (Toquam et al., 1995). Sensory inputs warranting attention during a bridge inspection may be visual, auditory, or tactile. Specific details of the Attention unit are provided in Table 5.2.

5.1.3 Memory

Memory is the process by which information is stored for later use (Toquam et al., 1995). Memory skills allow an inspector to recall information about the structure, remember to do specific things during the inspection, recognize critical structural features and governing operating conditions, accurately record measurements, quantity estimates and observations, and remember to follow up on action items. Memory is also necessary for developing a knowledge base about a specific structure or type of structure. Specific details of the Memory unit are provided in Table 5.3.

5.1.4 Mental Images

Mental imaging is the perception of “remembered” information absent immediate sensory input (Toquam et al., 1995). Mental images can be used for remembering and organizing visual information, solving spatial problems, and interpreting observations. Mental images can also be manipulated, transformed, or rotated to reveal the required information. Specific details of the Mental Images unit are provided in Table 5.4.

5.1.5 Mental Models

Mental models are built on mental images but include cause and effect relationships in addition to spatial relationships (Toquam et al., 1995). They are used to understand the purpose and form of the structure, explain its function, and predict future changes. Mental models can be updated based on observed behavior in the field and refined with input from other inspectors or engineers. Specific details of the Mental Models unit are provided in Table 5.5.

5.1.6 Judgment and Decision Making

Judgement and decision-making skills allow an inspector to apply logic and reasoning to observations to form conclusions about the condition of the structure (Toquam & Morris, 1994). In this training course, a judgement is defined as a quick evaluation made based on a single cue and a decision is defined as a final evaluation made based on a large number of cues from many different sources. Specific details of the Judgement and Decision-Making unit are provided in Table 5.6.

5.2 Inspection Tools and Techniques Training

In speaking with inspectors during the study, it was clear that inspectors had very little exposure to actual fatigue cracks. A number of inspectors remarked that they found more cracks during this single day inspection than during their entire career, often spanning multiple decades. Consequently, a new training module was developed for inclusion in the *Inspecting Steel Bridges for Fatigue* course offered at Purdue University’s

TABLE 5.3
Description of Memory Unit

Objective	Convey how memory works and its limitations; convey the importance of memory aids
Topics	<ol style="list-style-type: none"> 1. Definition of memory 2. Stages of memory (sensory register, short term memory, long-term memory) 3. Types of attention (focused, selective, and divided)
Exercises	<ol style="list-style-type: none"> 1. Dual n-back (short term memory exercise that requires the user to process both auditory and visual information and retain new information without replacing older information)

Sample Slides

MEMORY

Memory is the process by which we store observations for later use.

- Determine what you need to remember to do your job
- Develop a strategy to ensure those needs are met
- Memory Stages
 - Sensory register
 - Short-term memory
 - Long-term memory

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MEMORY TRAINING EXERCISE

Remember the location and length of the 3rd to last crack.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Ok, so where was the 3rd to last crack and what was its length?

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TABLE 5.4
Description of Mental Images Unit

Objective	Convey what mental images are and how they can be used to organize, manipulate, and interpret spatial information during a bridge inspection
Topics	1. Definition of mental images 2. Examples of mental images (pinned bearing vs. roller bearing)
Exercises	1. Mental rotation (rotate 3D shapes until they match)
Sample Slides	

MENTAL IMAGING

Mental imaging is the picture of "remembered" information we keep in our mind after the experience

- Mental images of structures can be useful for
 - Recalling visual information
 - Solving problems involving spatial relationships
 - Interpreting observations
- Image can be manipulated, transformed, rotated, etc.
- As necessary, supplement your mental sketch with an actual sketch

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MENTAL IMAGING - BEARINGS

Rotation only,
No translation

Rotation and
Translation

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TABLE 5.5
Description of Mental Models Unit

Objective	Convey what mental models are, how they are related to mental images, and how they can be used to answer “what if” questions
Topics	1. Definition of mental models
Exercises	1. Applying mental models (connection plate detail, cover plate detail)
Sample Slides

TABLE 5.6
Description of Judgement and Decision-making Unit

Objective	Convey how judgements and decisions are formed and how to avoid making common errors or miscalculations
Topics	1. Definition of judgement and decision making 2. Problem solving techniques
Exercises	1. Heuristics (representativeness, availability, confirmation bias)
Sample Slides	

JUDGEMENT

Judgement occurs many times throughout the inspection process based on a single, brief observation

- Possible judgements are:
 - Not relevant
 - Incomplete (more information needed)
 - Ready for final decision
- Without resources, judgments are made based on experiences, expectations, and motivations which may be biased
- Heuristics can help or hinder judgements

Problem solving approach that relies on practical methods, such as rules-of-thumb or trial-and-error

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DECISION MAKING

- Decision making is used to make final conclusions based on all available information
 - Outcome expected to have significant impact(s)
 - Resource intensive (inspector time, knowledge, skill, etc.)
 - Influenced by perceived level of risk
- Requires the development and testing of multiple hypotheses
 - Avoid confirmation bias
- Important to accurately reflect level of confidence in the decision
 - Seek feedback

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Figure 5.1 Select slides from training on the tools and techniques of performing a visual inspection.

S-BRITE Center. This module includes a brief introduction to the physical tools and techniques of visual inspection. Additionally, inspectors had the opportunity to apply the training during a mock visual inspection of full-size bridge specimens with actual fatigue cracks. Four sample slides from this training module are included in Figure 5.1.

5.3 Summary

The large variability in inspection performance indicates that the current training program produces inspectors with differing inspection abilities. Although the content of the existing courses appears to be adequate, it seems that some inspectors are struggling to apply the lessons learned in the classroom in the field. A new training course and a new training module were developed to address this deficiency. These trainings focus on the physical and mental factors of visual inspection and aim to teach inspectors “how to inspect” rather than “where to inspect.”

6. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

During this research, a POD study focused on visual detection of fatigue cracks in steel bridge girders was

performed. This study is believed to be the first statistically based study of its kind in the United States. The study has shown that routine visual inspection from the ground and hands-on visual inspection of weathering and painted steel bridge girders were unreliable for finding cracks. Based on the results of the POD study, recommendations to improve the reliability of hands-on visual inspection on painted steel bridge girders have been made and can be found in Section 6.2 of this report.

Again, it should be noted that the intention of this study was to evaluate the reliability of visual inspection on steel bridges, not to find fault with individual inspectors. The research set out to answer the questions “What cracks are being missed?” and “Are our expectations for inspectors reasonable?” If inspectors are being expected to find cracks that cannot reasonably or reliably be found with the current procedures, the system should be reevaluated. For example, because the average inspector from this study found 65% of the cracks, it may not be economical to send out a team of inspectors bi-annually to look for cracks that they cannot reasonably detect. Risk-based inspection intervals would save agencies time and money, and very likely produce more reliable inspection findings.

6.1 Conclusions

Performance testing 30 bridge inspectors using visual inspection led to the following key conclusions:

- Variations in the reporting techniques for both routine and hands-on inspection of steel bridge superstructures were observed. While the documentation styles and level of detail may have been impacted by the study procedures provided or the fact that they were being observed in a test setting, it is clear that there is no governing standard for identifying what information should and should not be recorded during a visual inspection. Some inspectors provided detailed notes about the defect, likely causes, and recommended follow up efforts, while others simply drew a single line without any notes.
- Inspectors did not bring or use the same equipment to conduct hands-on visual inspections. For example, some inspectors regularly used flashlights and wire brushes, while others used nothing but their unassisted eyes.
- Routine inspections from the ground could not reliably find fatigue cracks. The participants averaged a 4% detection rate during the ground scenario test. Inspectors varied significantly in what they chose to report and how they selected to record their findings. These results suggest that requesting that the inspectors look for or comment on anything more specific than general bridge condition or obvious failures during routine inspections is not a good use of time or resources.
- Current practices for hands-on visual inspection of weathered steel bridge girders were not reliable for finding fatigue cracks. The participants averaged an 11% detection rate during the performance testing on weathered steel specimens. Six of the 11 tested inspectors had a 0% detection rate.
- Hands-on visual inspection for cracks on painted steel girders was moderately reliable, but highly variable. The inspectors averaged a 65% detection rate during the performance testing. The highest detection rate was 86%, while the lowest was 31%.
- The average number of false calls for all 30 inspectors on the 147 painted specimens was 90. The number of false calls ranged from 14 to 268.
- This study showed increased years of experience had a negative correlation with detection. Increasing temperature, inspection time, and training increased detection rate during the testing.
- No single variable showed a correlation with the number of false positives. The multivariate analysis revealed that inspectors that used a tape measure made fewer false calls while inspectors that were employed by a private inspection/engineering firm, experienced higher wind speeds, and attended the element level inspection course tended to make more false calls.
- For the majority of the inspectors, the likelihood of visually detecting cracks on painted steel girders increased with increasing crack length. For the total population of cracks for this set of inspectors, a 1-inch-long crack had a 50% chance of being detected and a 5-1/2-inch-long crack had a 90% chance of being detected. The data was too scattered to assign a 95% confidence bound.
- In addition to crack length, the analysis showed that the type of crack, the inspector's experience, the inspection duration, and the elapsed time since the first inspection

significantly impacted the likelihood of a crack being detected.

- Inspectors did not bring or use the same equipment to conduct hands-on visual inspections. For example, some inspectors regularly used flash lights and wire brushes, while others used nothing but their unassisted eyes.

6.2 Recommendations and Future Research

Recommendations for improving the reliability of visual inspection on steel bridges have been grouped into three categories: equipment, procedures, and training.

6.2.1 Equipment

It is recommended that a standard set of equipment be provided to each inspector to ensure consistency among inspectors. Items for the standard tool set should include, but are not limited to a light-emitting diode (LED) or halogen flashlight with light output of at least 100 lumens and adjustable focus, wire brush, scraper, hammer, 5 × power and lighted 10 × power magnifying glasses, telescoping inspection mirror, easy to use measuring device, and 1/4-inch square rod for measuring web gaps. Requiring each inspector to bring and use the provided standard set of tools could better equip them for detecting defects and encourage them to follow proper inspection procedures. Inspectors should be provided with basic training outlining the proper use for each tool.

6.2.2 Inspection Procedures

Providing detailed procedures for hands-on visual inspection of steel bridges may improve the method's reliability. The procedures should clearly state a process for inspecting different types of details, including using the prescribed tools to closely inspect areas prone to defects. The procedures should use the same terminology and descriptions that are used in the training courses. Requiring that the correct tools be used to closely inspect details prone to fatigue cracks may increase the likelihood of cracks being found. It is also recommended that an equipment checklist be provided for each inspection. The inspectors should indicate on the checklist that each tool was available and in working order for the inspection.

Additional procedural recommendations are offered based on visual inspection research, although their effectiveness for hands-on bridge inspections was not explicitly evaluated in this study:

- *Encourage active observation.* Although visual cues are the main source of information about the condition of the structure, previous research has found that inspectors can improve the inspection performance by touching the surface, listening for rattles or squeaks, and smelling leaks or overheating parts. Even while using only the eyes, inspectors should frequently adjust their viewing angle and distance from the inspection surface and use basic tools to increase the discriminability of flaws (Drury & Watson, 2002; Spencer, 1996). Based on the results of this

study, requiring inspectors to use a tape measure may be one way to ensure that they are actively engaged with the inspection surface.

- *Hold regular calibration meetings and refresher training.* Calibration meetings and refresher training can help maintain a uniform understanding and application of inspection standards. This will help improve consistency in decision making and reduce the variability in inspection results. These trainings should be specific to INDOT and attended by all inspectors performing inspections under INDOT's supervision.
- *Provide regular feedback.* Supervisors should provide regular feedback to inspectors to improve the accuracy and consistency of visual inspections. Although it is difficult to provide performance feedback since the true accuracy of an inspector's findings are not known, cognitive feedback has also been found to be effective in improving inspection performance (Gramopadhye et al., 1997). Cognitive feedback may focus on an inspector's strategy, expectations, or assumptions. For instance, this type of feedback could correct an inspector's misconception about the relative cost of a missed crack and a false call. Without feedback, the same errors in judgment and decision making will be unknowingly repeated in the future.
- *Rotate inspectors.* Even with similar experience or training, these results show that inspectors have differing abilities to detect cracks. In fact, only one crack was detected by all 30 inspectors and only three cracks were not detected by any of the inspectors. This supports the practice of inspector rotation as a quality control measure intended to reduce the likelihood that defects are repeatedly missed (Agrawal & Washer, 2013).
- *Allow adequate time to complete each inspection and encourage inspectors to use the allotted time.* Two of the most widely studied trends in visual inspection tasks are the "speed-accuracy tradeoff" and the "vigilance decrement." The "speed accuracy tradeoff" implies that as inspection speed increases, inspection accuracy decreases. This trend was observed in this study and adequate time should be allowed for the inspection so that inspectors do not have to rush. The vigilance decrement is a well-documented behavioral effect whereby performance accuracy decreases with increasing time on a vigilance task. The most common recommendation for combatting the vigilance decrement is allowing for more frequent breaks. These do not need to be non-working breaks; simply alternating tasks may be adequate. The literature recommends switching tasks or taking a break every 20 to 30 minutes to maintain the necessary level of attention and focus (See, 2012). In this study, there was no noticeable improvement in the performance of inspectors that took a break during the inspection task and those that did not. One possible explanation is that the break schedule was controlled by the inspector throughout the inspection rather than being predetermined. Inspectors may have already been suffering the ill effects of prolonged vigilance before they took a break.

6.2.3 Training

Visual inspection research frequently cites inspector training as the most cost effective and efficient strategy for improving inspection performance (See, 2012). Past

studies have shown that training courses should address the physical, procedural, and cognitive aspects of the inspection task. Proven training systems employ a modular approach, include immediate feedback during training, encourage active participation and engagement from attendees, allow for self-discovery, clearly define acceptability standards, discuss common errors, and address a wide variety of possible defects (See, 2012). The training discussed in Chapter 5 was developed in accordance with these recommendations.

Due to the large variability in results and the relatively weak predictive power of any of the variables expected to correlate with performance, it is recommended that performance testing be implemented. After completing the required classroom based and hands-on training courses, the inspectors should be required to pass a practical inspection test.

6.2.3.1 Performance testing. Four models of performance criteria have been outlined below for the practical inspection test. Due to the limited amount of available data, and the high variability of the data from this study, it is not yet possible to establish set requirements. The data collected from this inspector population was subjected to the proposed criteria and the outcomes are presented for discussion.

One option is to establish a flat detection rate for passing. For example, the inspectors would each be required to find 70% of the total cracks present on the course. This option is simple and easy to determine if an inspector meets the criteria. However, the flat rate does not consider any differences between crack sizes. There is no weighting to place more importance on finding more critical cracks. Further, the question that really should be asked is how many cracks it is acceptable to miss. Table 6.1 summarizes the inspection performance of the passing inspectors for a range of required detection rates.

A second option is to use a graduated scale for detection rates. For instance, to pass the practical exam, an inspector must find 50% of cracks shorter than 1 inch, 65% of cracks with lengths between 1 and 3 inches, and 80% of cracks greater than 3 inches long. This method stresses and presumes that inspectors should be better able to find longer cracks. Again, criticality of the actual crack is not directly included in the test. For example, a 1-inch crack in a butt weld in a tension flange of a fracture critical girder is more critical than a 3-inch out-of-plane distortion crack in a web of girder in a multi-beam bridge. Table 6.2 summarizes the inspection performance of the passing inspectors for a range of required detection rates.

A third option is to set passing criteria based on crack types. Setting the criteria based on the type of crack, and how detrimental the particular crack type is for the structure, promotes a more reasonable approach to bridge inspection. For example, load induced cracks emanating from butt welds grow perpendicular to the stress, and can quickly lead to member fracture. For

TABLE 6.1
Summary of Results for Inspector Qualification Based on the Unweighted Detection Rate (all results are for the passing inspectors)

Required Score to Pass (%)	Pass Rate (%) (no. of inspectors)	Avg. No. of Missed Cracks	Avg. No. of False Calls	Max. No. False Calls	Largest Crack Missed
50 (35 hits)	83 (25)	21	89	268	5-3/8"
60 (42 hits)	77 (23)	20	92	268	5-7/32"
70 (49 hits)	43 (13)	16	96	195	4-29/32"
80 (56 hits)	10 (3)	11	111	187	3-1/4"

TABLE 6.2
Summary of Results for Inspector Qualification Based on the Weighted Detection Rate (all results are for the passing inspectors)

Required Score to Pass (%) (<1", 1"-3", >3")	Pass Rate (%) (no. of inspectors)	Avg. No. of Missed Cracks	Avg. No. of False Calls	Max. No. False Calls	Largest Crack Missed
40, 60, 80	33 (10)	16	100	195	4-29/32"
50, 65, 80	20 (6)	13	120	195	3-3/8"
55, 70, 80	13 (4)	12	124	187	3-3/8"
65, 75, 80	7 (2)	11	73	77	3-1/4"

TABLE 6.3
Summary of Results for Inspector Qualification Based on the Crack Type Detection Rate (all results are for the passing inspectors)

Required Score to Pass (%) (distortion induced, load induced)	Pass Rate (%) (no. of inspectors)	Avg. No. of Missed Cracks	Avg. No. of False Calls	Max. No. False Calls	Largest Crack Missed
40, 60	33 (10)	17	76	187	4-29/32"
50, 70	13 (4)	12	92	187	3-1/2"
60, 80	7 (2)	11	132	187	3-1/4"

this crack type, the criteria for finding cracks less than 1-inch-long may be set to be 70% of the possible cracks. For distortion induced cracks that typically grow more slowly and pose less risk, a lower acceptable rate, possibly 50%, may be acceptable. Table 6.3 summarizes the inspection performance of the passing inspectors for a range of required detection rates.

A fourth option is to evaluate inspector performance based on both detection rate and the number of false calls. Large numbers of false positives result in higher costs (longer inspection times and additional equipment being used to further investigate the suspected, but "unreal" cracks) and can negatively affect a bridge inspection program. Inspectors could be rated based on both their detection rate and the number of false calls, with a minimum rating necessary for passing. The rating could be calculated using Equation 6.1 where n is the relative severity of a miss to a false call (Shaw, 2002). For example, a minimum rating of 75% could be required with a missed crack considered three times more severe than a false call. Table 6.4 summarizes the inspection performance of the passing inspectors for a range of required inspector ratings.

$$\text{Rating} = \frac{1}{2} \times \left(1 + \frac{\text{detected flaws}}{\text{total flaws}} - \frac{\text{false indications}}{n \times (\text{total indications})} \right) \quad (\text{Eq. 6.1})$$

6.3 Future Work

The following section outlines recommended future work to build upon the results of the present research. This study improved understanding of the capabilities of current visual inspection procedures, but much still remains to be examined.

- Based on the findings of this study, the influence of the following variables warrants further investigation. These variables should be tested using a subset of the 30 previously tested inspectors as well as a group of new inspectors. Results from these inspections should be compared to the results presented herein to determine if the changes caused any improvement.
 1. *Equipment use.* During this study, the majority of inspectors used only a flashlight and a tape measure. The effectiveness of lesser used tools, such as inspection mirrors, head lamps, and magnifiers, should be investigated. Procedures for utilizing the tools for visual inspection should be provided prior to the inspection. This training will not be specific to the probability of detection inspection but should instead address basic visual inspection techniques and best practices.
 2. *False positives.* During this study, many inspectors made an unexpectedly large number of false calls.

TABLE 6.4

Summary of Results for Inspector Qualification Based on Detection Rate and the Number of False Calls (all results are for the passing inspectors)

Required Rating to Pass (%)	Pass Rate (%) (no. of inspectors)	Avg. No. of Missed Cracks	Avg. No. of False Calls	Max. No. False Calls	Largest Crack Missed
75 (n = 3)	40 (12)	17	70	187	4-29/32"
80 (n = 3)	7 (4)	13	53	77	3-1/2"
75 (n = 4)	60 (18)	19	81	195	4-29/32"
80 (n = 4)	23 (7)	14	76	187	3-1/2"

The reason(s) for this is unknown but may be attributable to the inspection scenario. More worryingly, the false positives may indicate a general uncertainty regarding the cause and appearance of fatigue cracks. In order to better understand the meaning of the false positives, a small subset of inspectors will be explicitly evaluated based on both their hit percentage and the number of false calls made.

3. *Nighttime inspection.* In order to limit traffic disruption, many bridge inspections are performed at night. In order to realistically simulate the inspection environment for these inspections, a small subset of inspectors will complete the inspection course at night.

4. *Warm temperature inspection.* All of the inspections were performed in moderate to cold temperatures (between 23°F and 73°F). In order to obtain a full understanding of the effect of temperature on inspection performance, a small subset of inspectors will be asked to complete the inspection during warm weather.

- In order to correlate inspection results on the POD test frame with the inspection results from an actual bridge specimen, a small subset of inspectors who have already completed the course should be invited back for a follow up inspection actual bridge specimens with identified fatigue cracks at the S-BRITE Center.
- Deliver the new observational skills training course to inspectors. This is intended to be a half-day standalone course offered through the S-BRITE Center. Feedback will be solicited from course attendees and attendees will be invited to participate in the probability of detection study to evaluate the effectiveness of the training.
- It is recommended that additional specimens with different types of defects, such as butt weld cracks, should be added to the test frame. The course should also be expanded to include additional defects such as section loss from corrosion and missing bolts.

The recommended additions to the course and study would provide more insight into how different factors affect visual detection on steel bridge inspection as well as provide more confidence in the determined reliability of visual detection.

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APPENDICES

Appendix A. Test Procedure Documents

Appendix B. Exit Survey Responses

Appendix C. Sample Inspection Forms

APPENDIX A. TEST PROCEDURE DOCUMENTS

Notice to Inspectors (Version 1)

Probability of Detection Study Participant:

Thank you for agreeing to participate in Purdue University's Probability of Detection Study. The goal of this study is to assess the current effectiveness of visual inspection on steel bridges and to develop improved training and procedures for the visual inspection of steel bridges if the needs are identified through the research.

The study consists of two inspection scenarios:

Scenario #1 – Routine Inspection of a simulated two-span steel bridge from the ground with full walking access around and beneath the structure.

Scenario #2 – Hands-on inspection using a man-lift.

The course is estimated to require 6 hours to complete.

On the day of your participation, please bring any tools and personal protective equipment, including safety harness, you would normally use for a visual inspection, both routine and hands-on. Check the weather and dress appropriately, as all activities for this study are held outdoors. Lunch will be provided.

It is critical to the study that all procedures and findings are kept confidential. **To participate in this study, a signed confidentiality agreement is required.** You will be asked to sign the confidentiality agreement upon your arrival at the study site. If information regarding the study set-up or results are shared among inspectors, the results will become invalid. Likewise, your identity will remain confidential. The results from your specific participation will only be shared with INDOT as needed.

If you have any questions, please contact:

Dr. Robert J Connor
rconnor@purdue.edu

Jason Lloyd, PE
lloyd@purdue.edu

Thank you for your willingness to participate in this study. We look forward to working with you.

Dr. Robert J. Connor

Jason B. Lloyd, PE

Luke R. Snyder

Julie Whitehead

Notice to Inspectors (Version 2)

Probability of Detection Study Participant:

Thank you for agreeing to participate in Purdue University's Probability of Detection Study. The goal of this study is to assess the current effectiveness of visual inspection on steel bridges and to develop improved training and procedures for the visual inspection of steel bridges if the needs are identified through the research.

The study consists of the following inspection scenario:

Hands-on inspection of a simulated two-span steel bridge using a man-lift.

The course is estimated to require 6 hours to complete.

On the day of your participation, please bring any tools and personal protective equipment, including safety harness, you would normally use for a hands-on visual inspection. Check the weather and dress appropriately, as all activities for this study are held outdoors. Lunch will be provided.

It is critical to the study that all procedures and findings are kept confidential. **To participate in this study, a signed confidentiality agreement is required.** You will be asked to sign the confidentiality agreement upon your arrival at the study site. If information regarding the study set-up or results are shared among inspectors, the results will become invalid. Likewise, your identity will remain confidential. The results from your specific participation will only be shared with INDOT as needed.

If you have any questions, please contact:

Dr. Robert J Connor
rconnor@purdue.edu

Jason Lloyd, PE
lloyd@purdue.edu

Thank you for your willingness to participate in this study. We look forward to working with you.

Dr. Robert J. Connor

Jason B. Lloyd, PE

Leslie E. Campbell, PE

Confidentiality Agreement

CONFIDENTIALITY AGREEMENT

Purdue University S-BRITE Center: Probability of Detection Study

Purdue University S-BRITE Center: Probability of Detection Study

Principal Investigator/ S-BRITE Center Director: Dr. Robert J Connor

S-BRITE Center Research Engineer: Jason B. Lloyd, PE

Graduate Students: Luke R. Snyder, Julie Whitehead

As a participant in this research study I understand that I may have access to confidential information regarding the test procedures, study layout and test specimens. By signing this statement, I am indicating my understanding of my responsibilities to maintain confidentiality and agree to the following:

- I understand that details about study procedure and test specimens are completely confidential.
- I agree not to discuss, divulge, publish, or otherwise make known to unauthorized persons, including any other INDOT inspectors or colleagues, or to the public any information obtained in the course of this research study without written permission from the S-BRITE Director.
- I understand that sharing any information with other participants in the study invalidates the results and hinders INDOT from improving bridge inspection procedures and inspection quality. I agree not to divulge or otherwise make known to unauthorized persons any of this information, unless specifically authorized to do so by approved protocol or by the local principal investigator acting in response to applicable law or court order, or public health or clinical need.
- I agree to notify the principal investigator immediately should I become aware of an actual breach of confidentiality or a situation which could potentially result in a breach, whether this be on my part or on the part of another person.

Signature

Date

Printed name

Signature of Purdue Official

Date

Printed name

Visual Inspection Procedures (Version 1)

Probability of Detection Study

Performance Testing Procedure

Visual Inspection Testing

Purdue University S-BRITE Center

2014

This document describes the guidance and procedures for inspectors participating in the Purdue University S-BRITE Probability of Detection Study. This procedure is for Visual Inspection only.

Proctor Instructions - VI:

Read these instructions to the inspector prior to the test.

You are about to participate in a probability of detection study for visual inspection of steel bridges. It is critical to the study that all procedures and findings are kept **CONFIDENTIAL**. Before participating in this study, a signed confidentiality agreement is required. Likewise, your identity will remain confidential, unless requested by INDOT. The results from your specific participation will not be shared or be published. If you do not wish to sign the confidentiality agreement, you may excuse yourself at this time.

The objectives of this portion of study are as follows:

1. Establish the effectiveness of current visual inspection techniques for identifying cracks while inspecting steel bridges;
2. Establish the probability of detection based on current inspection practices;
3. Establish methods for improving probability of detection of cracks in steel bridges.

You are permitted to use any tools and equipment that you typically utilize during a visual inspection. Lunch will be provided during your full day of inspection. You should conduct this inspection in the same manner and with the same care as normally implemented in the field. During your inspection, breaks are allowed for fatigue or other reasons as you need. If you normally take a break during a certain time period, you should take that break during the study. Please notify the Proctor when you wish to take your break.

Inspection Scenarios:

There are two inspection scenarios in which you will participate. Scenario 1 shall be completed from the ground. You may walk around and beneath the structure as if you were inspecting a highway bridge from below. There will be no lift or ladder access permitted. Report your findings on the forms for Scenario 1. You may use any tools you normally use for such an inspection.

Scenario 2 will be a hands-on inspection that is to be performed in a fashion consistent with a typical "fracture critical" inspection. The inspection is only focused on the visual detection of cracks. The Proctor will operate the manlift and guide you through the course in the correct order.

A manlift will be used to provide access for Scenario 2. You will be inspecting a portion of the 108 specimens suspended from the support fixture. Each specimen has two faces with a corresponding inspection form. These forms are contained in the binder provided. Most specimens also include a portion of a cover plate. Your binder includes a corresponding inspection form for each cover plate. A completed form is required for each specimen face and cover plate inspected.

Probability of Detection Study

Performance Testing Procedure

Visual Inspection Testing

Purdue University S-BRITE Center

2014

Assumptions Regarding Specimens

1. The specimens are intended to represent 1960's to 1970's welded fabrication and weld quality. While weld quality may not meet modern standards, it is not the focus of the study. You are not required to comment on weld quality.
2. Assume the pieces suspended from the frame are fracture critical members.
3. Treat all gusset plates and vertical stiffeners as if bracing, floorbeams, diaphragms, or cross-bracing was attached. For example, many specimens include gusset plates and vertical stiffeners welded to webs. Therefore, you are to assume there are lateral members attached to these components whether they are on the interior or exterior faces of the specimens or near the top or bottom flange. The bracing members have not been included to facilitate your access.
4. Assume all cover plate terminations are subject to tensile stress ranges.
5. You should assume both flanges could be tension flanges.
6. The location of the specimen on the frame should not be used to "infer" the loading or stress state in the specimen. In other words, specimens installed near the ends of the support frame should not be viewed as being near a bearing. All specimens should be viewed as being subjected to the same stress state.
7. Interior and exterior specimens should be treated the same.
8. Both faces of each specimen should be treated the same.
9. Any specimen could have any type of crack or even multiple cracks.

Inspection Notes

If you detect a crack, please sketch it on the form and record its length and location. If no crack is found, the inspection form must still be completed indicating such. The order of specimen inspection will follow the order of the inspection forms in your binder. As stated, the Proctor will operate the manlift and guide you through the course in the correct order. Ensure that the Specimen ID on the form matches the ID on the specimen. At the end of your inspection, please submit the completed inspection booklet to the Proctor. Upon completion of the entire inspection course, please complete the Inspector Exit Form, which will be given to you by the Proctor.

Thank you for your participation and cooperation. Feel free to ask the Proctor any questions related to the study procedures at any time during this test.

Visual Inspection Procedures (Version 2)

Probability of Detection Study

Performance Testing Procedure
Visual Inspection Testing
Purdue University S-BRITE Center
2016

This document describes the guidance and procedures for inspectors participating in the Purdue University S-BRITE Probability of Detection Study. This procedure is for Visual Inspection only.

Proctor Instructions - VI:

Read these instructions to the inspector prior to the test.

You are about to participate in a probability of detection study for visual inspection of steel bridges. It is critical to the study that all procedures and findings are kept **CONFIDENTIAL**. Before participating in this study, a signed confidentiality agreement is required. Likewise, your identity will remain confidential, unless requested by INDOT. The results from your specific participation will not be shared or be published. If you do not wish to sign the confidentiality agreement, you may excuse yourself at this time.

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1. Establish the effectiveness of current visual inspection techniques for identifying cracks while inspecting steel bridges;
2. Establish the probability of detection based on current inspection practices;
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Inspection Scenarios:

This will be a hands-on inspection and is to be performed in a fashion consistent with a typical "fracture critical" inspection. You may use any tools you normally use for such an inspection. The inspection is only focused on the visual detection of cracks. The Proctor will operate the manlift and guide you through the course in the correct order.

You will be inspecting a portion of the 108 specimens suspended from the support fixture. Each specimen has two faces with a corresponding inspection form. These forms are contained in the binder provided. Most specimens also include a portion of a cover plate. Your binder includes a corresponding inspection form for each cover plate. A completed form is required for each specimen face and cover plate inspected.

Probability of Detection Study

Performance Testing Procedure

Visual Inspection Testing

Purdue University S-BRITE Center

2016

Assumptions Regarding Specimens

1. The specimens are intended to represent 1960's to 1970's welded fabrication and weld quality. While weld quality may not meet modern standards, it is not the focus of the study. You are not required to comment on weld quality.
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3. Treat all gusset plates and vertical stiffeners as if bracing, floorbeams, diaphragms, or cross-bracing was attached. For example, many specimens include gusset plates and vertical stiffeners welded to webs. Therefore, you are to assume there are lateral members attached to these components whether they are on the interior or exterior faces of the specimens or near the top or bottom flange. The bracing members have not been included to facilitate your access.
4. Assume all cover plate terminations are subject to tensile stress ranges.
5. You should assume both flanges could be tension flanges.
6. The location of the specimen on the frame should not be used to "infer" the loading or stress state in the specimen. In other words, specimens installed near the ends of the support frame should not be viewed as being near a bearing. All specimens should be viewed as being subjected to the same stress state.
7. Interior and exterior specimens should be treated the same.
8. Both faces of each specimen should be treated the same.
9. Any specimen could have any type of crack or even multiple cracks.

Inspection Notes

If you detect a crack, please sketch it on the form and record its length and location. If no crack is found, the inspection form must still be completed indicating such. The order of specimen inspection will follow the order of the inspection forms in your binder. As stated, the Proctor will operate the manlift and guide you through the course in the correct order. Ensure that the Specimen ID on the form matches the ID on the specimen. At the end of your inspection, please submit the completed inspection booklet to the Proctor. Upon completion of the entire inspection course, please complete the Inspector Exit Form, which will be given to you by the Proctor.

Thank you for your participation and cooperation. Feel free to ask the Proctor any questions related to the study procedures at any time during this test.

Exit Survey (Version 1)

Probability of Detection Study

Inspector Information

Please complete the following form. All information collected is used for research purposes only.

Inspector ID: _____

Inspection Date: _____

Employer: _____

Years of Inspection Experience: _____

Age: _____

Gender: _____

- 1) Please list all tools you brought to complete this inspection.

- 2) Please list which tools you used during the inspection course.

- 3) Are there any additional tools you wish you would have had available?

- 4) Do you wear corrective lenses (glasses or contacts)?

If yes, did you wear them during the inspection?
- 5) How many hands-on inspections have you completed in the last 12 months?

- 6) Approximately how many routine inspections have you completed in the last 12 months?

- 7) Please list the inspection training you have completed and when it was completed.

- 8) Are you a certified welder or weld inspector?
Yes, I'm a CWI Yes, I'm a certified welder No Other (please specify)

- 9) Has anyone discussed anything related to this study prior to your participation?

Exit Survey (Version 2)

Probability of Detection Study Inspector Information

Please complete the following form. All information collected is used for research purposes only.

Inspector ID: _____ Inspection Date: _____
Employer: _____ Years of Inspection Experience: _____
Age: _____ Gender: _____
Height: _____

- 1) Please list all tools you brought to complete this inspection.
- 2) Please list which tools you used during the inspection course.
- 3) Are there any additional tools you wish you would have had available?
- 4) Do you wear corrective lenses (glasses or contacts)? If yes, did you wear them during the inspection?
- 5) How many hands-on inspections have you completed in the last 12 months? How many of these inspections were performed on steel bridges?
- 6) Approximately how many routine inspections have you completed in the last 12 months? How many of these inspections were performed on steel bridges?
- 7) Please indicate which inspection training courses you have completed and the date of completion (estimates are acceptable for the dates):
 - Safety Inspection of In-Service Bridges (FHWA/NHI): _____
 - Bridge Inspection Refresher Training (FHWA/NHI): _____
 - Engineering Concepts for Bridge Inspectors (FHWA/NHI): _____
 - Underwater Bridge Inspection (FHWA/NHI): _____
 - Fracture Critical Inspection Techniques for Steel Bridges (FHWA/NHI): _____
 - Inspection and Maintenance of Ancillary Highway Structures (FHWA/NHI): _____
 - Introduction to Element Level Bridge Inspection (FHWA): _____
 - Inspecting Steel Bridges for Fatigue (Purdue/S-BRITE): _____
 - Others: _____

Probability of Detection Study
Inspector Information

8) Are you a certified welder or weld inspector?

Yes, I'm a CWI Yes, I'm a certified welder No Other (please specify)

9) Are you a registered professional engineer?

10) Approximately what percentage of your work time (on a per week basis) is spent performing bridge inspections?

11) What is the highest educational level that you have completed?

- _____ High School degree or equivalent
- _____ Trade School Degree
- _____ Associate's Degree
- _____ Bachelor's Degree in CIVIL ENGINEERING? Or OTHER? (circle one)
- _____ Master's Degree in CIVIL ENGINEERING? Or OTHER? (circle one)
- _____ PhD in CIVIL ENGINEERING? Or OTHER? (circle one)

12) How rushed did you feel during the inspection?

Not Rushed Moderately Rushed Very Rushed

13) How accessible were the bridge specimens?

Inaccessible Mostly Accessible Very Accessible

14) Did the presences of the observer affect your inspection practice?

Not affected Somewhat affected Very affected

Probability of Detection Study
Inspector Information

15) How did your effort level during this task compare to your effort level during a typical bridge inspection?

More effort Similar effort Less effort

16) How did your focus level during this inspection compare to your focus level during a typical bridge inspection?

More focused Similar focus Less focused

17) Overall, how did you feel (physically) during the inspection today?

Poor Below Average Average Above Average Great

18) Has anyone discussed anything related to this study prior to your participation?

APPENDIX B. EXIT SURVEY RESPONSES

Table B.1 Inspector Characteristics

Inspector ID	Gender	Age (yrs.)	Inspection Experience (yrs.)	Employer	Professional Licensure	No. of Hands-on (Routine) Inspections in the Previous 12 Months	Education Level	Jaeger Test Score	Pelli-Robson Test Score
10EH-10	Male	56	30	State	None	0 (120)	Unknown	J1	1.95
11CO-02	Male	46	11	State	None	40 (50)	Bachelor's Degree	J1	1.95
18GA-03	Female	63	29	Private	PE	4 (20)	Unknown	J1	1.95
13CA-09	Male	58	20	State	None	6 (200)	Unknown	J1	1.95
09SD-08	Male	55	28	Private	None	20 (0)	Associate Degree	J1	1.95
20MD-19	Male	45	20	State	PE	6 (100)	Unknown	J1	1.95
04MY-41	Male	40	15	Private	PE	9 (300)	Bachelor's Degree	J1	1.95
09ME-03	Male	28	6	Private	PE	5 (5)	Unknown	J1	1.95
08GS-32	Male	30	1.25	State	EI	5 (35)	Bachelor's Degree	J1	1.95
01VM-02	Male	30	6	Private	PE	23 (600)	Bachelor's Degree	J1	1.95
12AE-04	Male	41	1	State	PE	1 (40)	Unknown	J1	1.95
11LB-22	Male	55	8	State	None	4 (145)	Unknown	J1	1.65
10JW-16	Male	40	10	State	PE	9 (200)	Unknown	J1	1.95
21RI-01	Male	33	10	Private	PE	5 (112)	Unknown	J1	1.95
08LK-23	Male	38	0	Federal	PE	0 (0)	PhD	J1	1.95
06MA-03	Male	56	10	State	PE	3 (6)	Master's Degree	J1	1.8
21GZ-14	Male	55	30	Federal	None	0 (100)	Bachelor's Degree	J1	1.95
09VK-18	Female	25	2.5	State	None	8 (25)	Unknown	J1	1.95
18RT-25	Male	53	13	State	PE	10 (240)	Unknown	J1	1.95
06JD-15	Male	33	8	State	EI	20 (163)	Unknown	J1	2.10
06TI-56	Female	24	0.75	State	EI	0 (175)	Bachelor's Degree	J1	1.95
27GH-57	Male	29	3	Private	EI	18 (35)	Bachelor's Degree	J1	1.95

Inspector ID	Gender	Age (yrs.)	Inspection Experience (yrs.)	Employer	Professional Licensure	No. of Hands-on (Routine) Inspections in the Previous 12 Months	Education Level	Jaeger Test Score	Pelli-Robson Test Score
01DS-23	Male	28	4	State	PE	30 (450)	Unknown	J1	1.95
24BR-25	Male	39	1	State	PE	25 (45)	Unknown	J1	1.65
27PC-37	Male	24	1.5	Private	EI	0 (20)	Bachelor's Degree	J1	1.95
12LA-04	Male	45	20	Private	PE	25 (700)	Bachelor's Degree	J1	1.95
11NH-05	Male	32	10	Private	EI	13 (250)	Unknown	J1	1.95
10CA-07	Male	42	14	State	PE	20 (70)	Bachelor's Degree	J1	1.95
26RO-49	Male	30	5	Private	PE/SE	0 (4)	Master's Degree	J1	1.95
25HQ-08	Male	33	1	Private	PE/SE	10 (50)	Master's Degree	J1	1.95

Table B.2 Tools Brought and Used for Hands-On Inspection

Inspector ID	Tools Brought	Tools Used for Hands-On	Additional Tools Wanted
10EH-10	Flashlight Tape measure Crack card Scraper Gloves Toolpouch	Flashlight Scraper Gloves	None
11CO-02	Flashlight Magnifying glass (app on phone) Grinder Telescoping mirror Wire brush/Steel brush Multi-tool	Flashlight Magnifying glass (app on phone) Wire brush/Steel brush	None
18GA-03	Flashlight Tape measure	Flashlight Tape measure	None
13CA-09	Tape measure Magnifying glass Wire brush/Steel brush Cold weather gear	Tape Measure Magnifying glass Wire brush/Steel brush Cold weather gear	None
09SD-08	Flashlight Tape measure Ruler Headlamp (did not work) Brush/Broom	Flashlight Tape measure Ruler Brush/Broom	Dremel with flapper wheel MT/PT
20MD-19	Flashlight Ruler Crack card Hammer Scraper Brush Rag Gloves	Flashlight Rag Gloves	None
04MY-41	Flashlight Tape measure Thickness gauge Scraper Wire brush/Steel brush Screw driver Pocket knife Camera	Flashlight Tape measure	Dye penetrant
09ME-03	Tape measure Hammer Brush/Broom Misc. hand tools Gloves	Tape measure Brush/Broom	None
08GS-32	Flashlight Tape measure	Flashlight Tape measure	None

Inspector ID	Tools Brought	Tools Used for Hands-On	Additional Tools Wanted
01VM-02	Flashlight Tape measure Crack card Calipers Brush/Broom	Flashlight Tape measure	None
12AE-04	Tape measure Wire brush/Steel brush Rag	Tape measure Wire brush/Steel brush Rag	Paint remover
11LB-22	Flashlight Magnifying glass Hammer Scraper Wire brush/Steel brush Hard hat 1/4" bar stock	Flashlight Magnifying glass	None
10JW-16	Flashlight Tape measure Magnifying glass Carpenter rule Wire brush/Steel brush Rag	Flashlight Tape measure Carpenter rule Wire brush/Steel brush Rag	Paint remover Grinder
21RI-07	Flashlight Tape measure Folding ruler Magnifying glass Binoculars Telescoping mirror Hammer Scraper Calipers Brush/broom Wire brush/Steel brush Chalk Gloves	Tape Measure Folding ruler Telescoping mirror Calipers Broom/Brush	None
08LK-23	Flashlight Tape measure Magnifying glass Telescoping mirror Screw driver Putty knife Wire brush/Steel brush Brush/Broom	Flashlight Tape measure Wire brush	Very small wire brush Small tape measure
06MA-03	Flashlight Hammer	None	None
21GZ-14	Flashlight Tape measure Binoculars Scraper Ladder	Flashlight	None
09VK-18	Flashlight Wire brush/Steel brush Rag	Wire brush/Steel brush	None

Inspector ID	Tools Brought	Tools Used for Hands-On	Additional Tools Wanted
18RT-25	Flashlight Gloves Cold weather gear Gloves	Flashlight Gloves Cold weather gear	None
06JD-15	Flashlight Tape measure Crack card Wire brush/Steel brush Brush/Broom	Flashlight Wire brush	Magnifying glass
06TI-56	Tape measure Crack card	Crack card	None
27GH-57	Flashlight Headlamp Tape measure	Flashlight Headlamp Tape measure	None
01DS-23	Flashlight Tape measure Wire brush/Steel brush Brush/Broom Ladder	Tape measure	None
24BR-25	Flashlight Scraper Wire brush/Steel brush Brush/Broom Wire brush	Flashlight Brush/Broom	Magnifying glass
27PC-37	Flashlight Headlamp Ruler	Headlamp Ruler	None
12LA-04	Flashlight Folding ruler Magnifying glass Lighted mirror Scalpel Wire brush/Steel brush Multi-tool Gloves Camera	Flashlight Folding ruler Magnifying glass Scalpel Wire brush/Steel brush Multi-tool Gloves	Drill with wire brush
11NH-05	Headlamp Folding ruler Telescoping mirror Calipers	Headlamp Folding ruler Telescoping mirror	Eddy current
10CA-07	Flashlight Ruler Hammer Scraper Grinder Wire Brush/Steel brush Dye Penetrant	Flashlight Ruler	None
26RO-49	Flashlight Tape measure Folding ruler	Flashlight Folding ruler	None

Inspector ID	Tools Brought	Tools Used for Hands-On	Additional Tools Wanted
25HQ-08	Flashlight Measuring tools Crack card Brush/Broom	Crack card Brush/Broom	None

Table B.3 Completed Bridge Inspector Training

Inspector ID	Inspection Training (from the 8 courses listed on the exit survey)
10EH-10	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection
11CO-02	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection Inspecting Steel Bridges for Fatigue
18GA-03	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
13CA-09	Safety Inspection of In-Service Bridges
09SD-08	
20MD-19	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
04MY-41	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection Inspecting Steel Bridges for Fatigue
09ME-03	Safety Inspection of In-Service Bridges Underwater Bridge Inspection Inspection and Maintenance of Ancillary Highway Structures Fracture Critical Inspection Techniques for Steel Bridges
08GS-32	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
01VM-02	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
12AE-04	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges
11LB-22	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges
10JW-16	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
21RI-01	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection Inspecting Steel Bridges for Fatigue
08LK-23	Engineering Concepts for Bridge Inspectors Inspection and Maintenance of Ancillary Highway Structures Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection

Inspector ID	Inspection Training (from the 8 courses listed on the exit survey)
06MA-03	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Engineering Concepts for Bridge Inspectors Underwater Bridge Inspection Inspection and Maintenance of Ancillary Highway Structures Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection
21GZ-14	
09VK-18	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges
18RT-25	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Fracture Critical Inspection Techniques for Steel Bridges
06JD-15	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges
06TI-56	Safety Inspection of In-Service Bridges
27GH-57	Safety Inspection of In-Service Bridges
01DS-23	Safety Inspection of In-Service Bridges Underwater Bridge Inspection Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
24BR-25	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
27PC-37	
12LA-04	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Underwater Bridge Inspection Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection
11NH-05	Safety Inspection of In-Service Bridges Underwater Bridge Inspection Fracture Critical Inspection Techniques for Steel Bridges
10CA-07	Safety Inspection of In-Service Bridges Bridge Inspection Refresher Training Underwater Bridge Inspection Fracture Critical Inspection Techniques for Steel Bridges Introduction to Element Level Bridge Inspection
26RO-49	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue
25HQ-08	Safety Inspection of In-Service Bridges Fracture Critical Inspection Techniques for Steel Bridges Inspecting Steel Bridges for Fatigue

APPENDIX C. SAMPLE INSPECTION FORMS

Sample Inspection Forms

Specimen ID: XXXXXXXXXX		Inspector ID: _____

<div style="display: flex; justify-content: space-between;"> <div style="width: 30%;"> <p>BOWEN LABORATORY PURDUE UNIVERSITY</p> <p>1040 SOUTH RIVER ROAD WEST LAFAYETTE, IN 47906 P: 765-494-2227 F: 765-494-0886</p> </div> <div style="width: 35%;"> <p>PROJECT: PROBABILITY OF DETECTION</p> <p>SHEET NOTES: _____</p> </div> <div style="width: 30%;"> <p>REVISIONS:</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%;">NO.</th> <th style="width: 40%;">DATE</th> <th style="width: 50%;">BY</th> </tr> </thead> <tbody> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td></tr> </tbody> </table> <p>DESIGNED BY: _____</p> <p>DRAWN BY: _____</p> <p>CHECKED BY: _____</p> <p>DATE: _____</p> <p>PROJECT NO.: SPR 3820</p> </div> <div style="width: 5%;"> <p>SHEET TITLE:</p> <p> </p> </div> </div>				NO.	DATE	BY															
NO.	DATE	BY																			
SHEET NO.: _____			1 of 1																		

Specimen ID: [REDACTED]

Inspector ID:

1040 SOUTH RIVER ROAD
WEST LAFAYETTE, IN 47906
P: 765-494-2227 F: 765-494-9888

PROJECT:

PROBABILITY OF
DETECTION

SHEET NOTES:

REVISIONS:

NO.	DATE	BY

DESIGNED BY:

DRAWN BY:

CHECKED BY:

DATE:

PROJECT NO.: SPR 3820

SHEET TITLE:

SHEET NO.: 1 of 1

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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