JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
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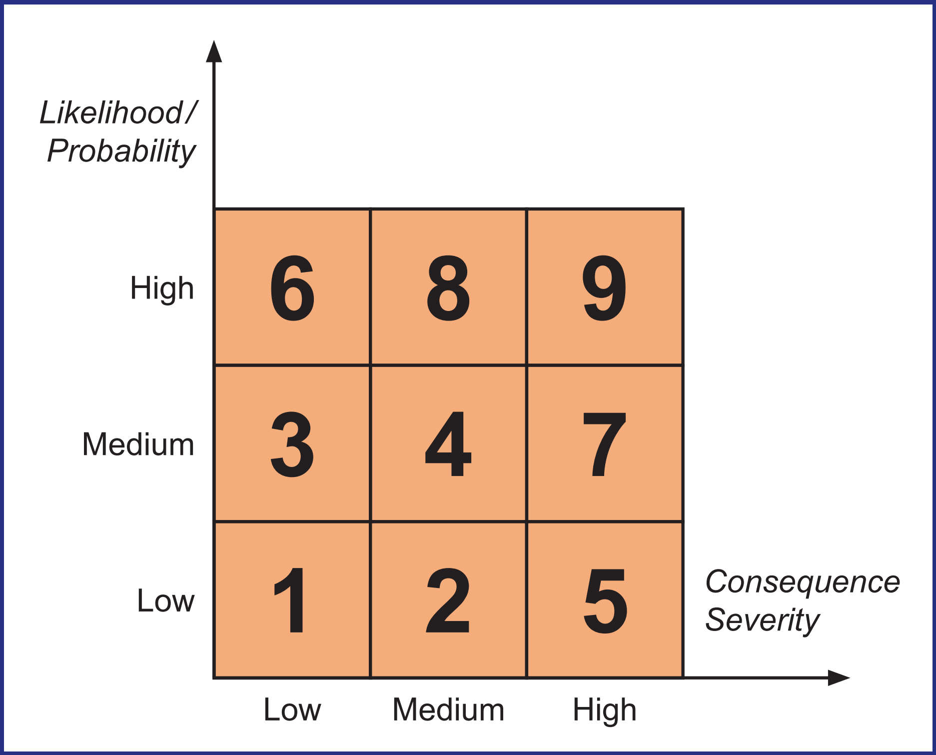
Risk-Based Construction Inspection



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16. Abstract

Construction inspection is a critical component in the quality assurance (QA) program to ensure the quality and long-term performance of pavements. Over the years, INDOT has been developing and modifying its standard specification to set requirements for construction inspection and material testing. With the retirement of experienced employees, INDOT is challenged with the lack of knowledge to effectively inspect the critical elements of construction results/deliverables such as pavement, soil embankment, and bridge (decks). There is a critical need for INDOT to allocate limited resources to the riskiest areas and equip construction inspectors with necessary knowledge to conduct inspection, ensure the quality of construction results, and minimize risks to INDOT.

This study developed a risk-based inspection guide that has addressed the aforementioned problems of shortage in staffing and loss and lack of knowledge by providing answers in aspects of what, when, how, and how often to inspect. A comprehensive list of testing and inspection activities were extracted from INDOT's material testing manual, INDOT's standard specification, and the QA implementation at the Ohio River Bridge (ORB) project. This list was narrowed down to a core set of items based on survey responses and interviews with INDOT domain experts. Testing and inspection activities in the core set were aligned with the construction process. The risk associated with each inspection activity was assessed by considering both the probability of failure and consequence severity of failure in four dimensions: cost, time, quality, and safety. A composite risk index was developed as a single measure for the overall risk. All inspection activities were prioritized based on the composite index. For implementation, a linking mechanism was developed to link inspection activity, pay item, and check items (extracted from specification). This linking mechanism aligns with the business process of construction inspection at INDOT: starting with a pay item, field inspectors retrieve the associated check items and their inspection priority (based on risk), inspection frequency, and inspection criteria. A digital, ontology- and risk-based inspection system was proposed and its conceptual model was delivered to INDOT for its incorporation in the field application of construction documentation, a component of the e-Construction initiatives at INDOT. It will be tested on Project R-30397 through a pilot study.

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EXECUTIVE SUMMARY

RISK-BASED CONSTRUCTION INSPECTION

Introduction

Construction inspection is critical to ensuring the quality and long-term performance of infrastructure. With the retirement of experienced employees and people leaving for the private sector, the Indiana Department of Transportation (INDOT) is challenged by the lack of knowledge to effectively inspect the critical elements of construction results/deliverables such as pavement, soil embankment, and bridge decks. Therefore, there is a critical need to develop a risk-based strategy for INDOT to focus on the riskiest areas and equip construction inspectors with the necessary knowledge to conduct inspections, ensure the quality of construction results, and minimize risks to INDOT.

This study developed a risk-based inspection guide that has addressed the aforementioned problems of staff shortages and the loss and lack of knowledge by providing answers to what, when, how, and how often to inspect. A comprehensive list of 333 testing and inspection activities was created from reviews of the material testing manual, the standard specification, and the QA implementation at the Ohio River Bridge (ORB) project. This list was compared to that of neighboring states (Illinois, Kentucky, Michigan, Wisconsin, Minnesota, and Ohio) and to national guidance documents and subsequently narrowed down to a core set of 126 items based on survey responses and interviews with INDOT domain experts and industrial partners. Testing and inspection activities in the core set were aligned with the construction process. The risk associated with each inspection activity was assessed by considering both the probability of failure and consequence severity of failure in four dimensions: cost, time, quality, and safety. A composite risk index was devised as a single measure for the overall risk. All inspection activities were prioritized based on the composite index, resulting in a total of 90 critical items that were identified as the riskiest areas. For implementation, a linking mechanism was developed to link inspection activity, pay item, and check items (extracted from specification). This linking mechanism aligns with the business process of construction inspection at INDOT: starting with a pay item, field inspectors retrieve the associated check items and their inspection priority (based on risk), inspection frequency, and inspection criteria. A digital, ontology-, and risk-based inspection system was proposed and its conceptual model was delivered to INDOT for its incorporation into the field application of construction documentation—a component of the e-Construction initiative at INDOT. The inspection system is being tested on Project R-30397 as a pilot study and is expected to reduce the workload of field inspectors.

Findings

The main findings are as follows:

- INDOT's materials testing manual explicitly regulates the sample size, sampling process, testing methods, and acceptance criteria for all materials. INDOT's standard specifications cover both materials and construction requirements but do not provide explicit information on the frequency and methods of construction inspection. Many of the acceptance criteria are qualitative rather than quantitative, which requires interpretation by construction inspectors. Consequently, the implementation varies among districts, projects, and individual inspectors.
- There is high similarity among the seven states regarding material testing and construction inspection requirements. The implementation of performance-related specification (PRS) has not changed materials and inspection requirements.
- Using the risk assessment framework developed in this study, a total of 90 critical inspection items in earthwork, PCCP, HMA pavement, and bridge decks were identified to be the riskiest areas. Each is aligned with the construction process with recommended inspection frequency and priority based on the risk.
- The ontology-based approach is effective in retaining and managing inspection knowledge and data.
- The specification sections and subsections can be used to connect risk-prioritized inspection activities, check items, and pay items so that dynamic inspection forms can be generated in real time on an as-needed basis, which aligns well with the business process being pursued at INDOT.
- Manual extraction of check items from specifications is time-consuming and error-prone. Inconsistencies among different sections have been noticed. The suggestion is to leverage natural language processing tools to automate this process.

Implementation

A prototype of a risk-based and knowledge-based digital inspection system was developed. The system adopted an ontological approach to store and manage both inspection knowledge and data (i.e., inspection results). The linking mechanism among pay items, check items, and inspection activities enables the integration of construction inspection in the project delivery and construction documentation process. A dynamic checklist for any given pay item can be generated in real time on an as-needed basis. Using the generated checklist, the inspector performs a guided inspection, and the results are documented and saved in the database for future reference. The prototype is being tested on a pilot project and is expected to reduce the workload of field inspectors.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Construction inspection is a critical component in the quality assurance (QA) program to ensure the quality of construction end products. Over the years, state transportation agencies have developed standard specifications and construction operation manuals to guide construction inspectors. Such documents specify what to inspect, how to inspect, and the criteria. Construction inspectors use the specification and the construction operation manual to inspect as the construction progresses and compare the inspection results to the criteria to decide whether to accept the work. It is very important to conduct construction inspection in a timely and effective manner, to ensure the quality of construction and minimize the risk to the state transportation agencies.

1.2 Problem Statement

Indiana Department of Transportation (INDOT) is challenged with the lack of knowledge to effectively inspect the critical elements of construction results/deliverables such as pavement, soil embankment, and bridge (decks). This challenge is attributed to three factors, detailed as follows.

1. Increase in the number of construction projects and project complexity. INDOT construction spending was $789 million in 2006, $1,080 million in 2010, and $1,165 million in 2013. The Ohio River Bridge (ORB) project includes four approach sections with over 8 million cubic yards of earthwork and over 120 bridges, and two major river crossings that used 49 million pounds of structural steel, 26 million pounds of reinforced steel, and 160k cubic yards of concrete.
2. Declines in resources available to construction inspection—since 2011 the authorized position for district construction staff has been reduced by 15%.
3. Loss of knowledge as experienced construction inspectors retire or leaving for private sectors.

INDOT is not alone in facing the challenge of lacking construction inspectors with adequate knowledge. Data collected in a synthesis of staffing requirements in state highway agencies reveal that between 2000 and 2010 the in-house state highway agency (SHA) personnel available to managing roadway infrastructure decreased by an average of 9.78% whereas the total lane-miles in the systems increased by an average of 4.1% (Taylor & Maloney, 2013). The loss of knowledge, especially in construction inspection, is having a much more profound negative impact on organizational efficiency in performing timely and quality inspection tasks to ensure the long-term performance of roadway infrastructure.

Therefore, there is a critical need for INDOT to develop alternative inspection strategies to allocate its limited resources to the riskiest areas and to establish a mechanism to retain the knowledge and equip novice employees with tools and guidance to perform the inspection effectively to ensure the reliability of the construction end products and minimize the risk to INDOT.

1.3 Overall Objective

The objective of this study is to develop a risk-based and performance related specification for construction inspection by finding answers to the following questions

1. What is being required to check?
2. Are we checking the right items?
3. What is the risk level of the inspection items?
4. To which critical items should we allocate limited resources?
5. When should an item be inspected?
6. How often to inspect?
7. How to inspect?
8. What are the acceptance criteria?
9. How to document?

The project scope includes pavement (both HMA and PCCP), earthwork (including embankment), and bridge decks. The four deliverables of the project are: (1) a state-of-the-practice map of INDOT's construction inspection; (2) a prioritized list of critical inspection items based on risk assessment; (3) a risk-based guideline for INDOT to allocate inspection resource to the riskiest areas; and (4) an ontology- and risk-based inspection system for retaining the knowledge, perform the inspection, and document the results.

1.4 Work Plan

To achieve the objective, the following seven specific tasks were included in this project. Figure 1.1 illustrates the overview of the work plan and how individual tasks work together to achieve the objective.

1. Compilation of INDOT practice and comparison with neighboring states.
2. Risk assessment and prioritization.
3. Alignment of the inspection activities with the construction process.
4. Determination of the inspection frequencies based on risk and the nature of the work being checked.
5. Extraction of check items from specification.
6. Connecting inspection activities, check items, and pay items.
7. Conceptual design of the ontology- and risk-based inspection system.

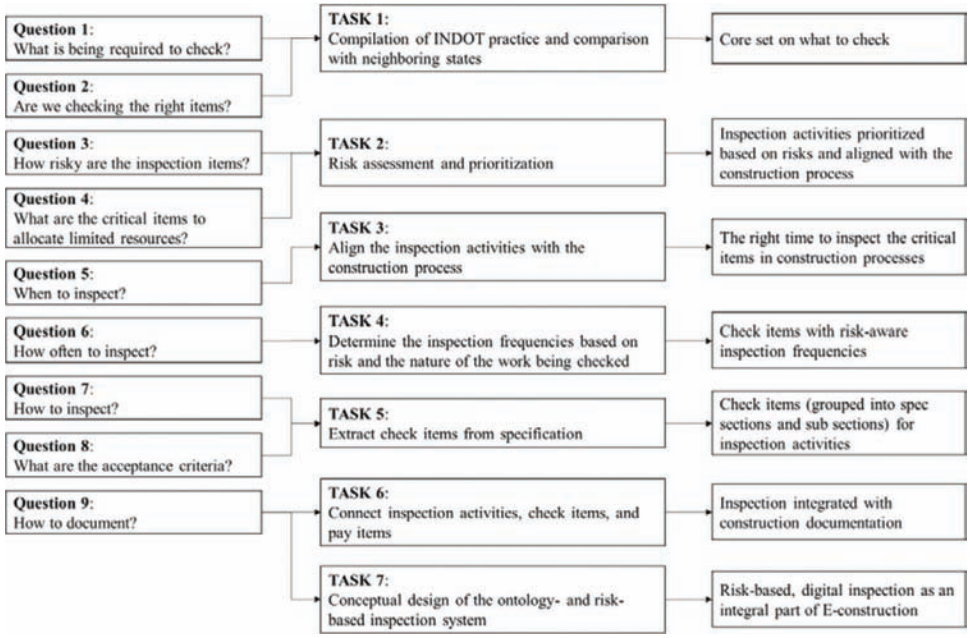

Figure 1.1 Overview of the work plan.

2. COMPILATION OF TESTING AND INSPECTION REQUIREMENTS AT INDOT

2.1 Introduction

The durability and long-term performance of pavement depends on design, materials, and construction. State highway agencies (SHAs) use two avenues to ensure the quality of materials and construction: material testing and construction inspection. Over the years, INDOT has developed and has been continuously updating its materials testing manual (INDOT, 2015) and standard specifications (INDOT, 2018). The materials testing manual specifies what materials to test, how frequently to test, the process for random sampling, and the methods for testing. The standard specification provides specific requirements on materials and construction.

In this chapter, we aim to identify the testing and inspection requirements at INDOT, using the materials testing manual, the standard specification, and the implementation of QC/QA at the ORB project that covers different various types of infrastructure construction tasks and is a very complex job.

2.2 Identification of Material Testing Requirements

The INDOT materials testing manual specifies the required number of samples, the locations and the time windows of taking samples, the testing methods and procedures, and the format for reporting testing results (INDOT, 2015). The research scope of this study covers earthwork, PCCP and HMA pavement, and bridge decks. Table 2.1 lists the 249 testing items (extracted from INDOT's materials testing manual) that are relevant to pavement and bridge construction, divided into eight main categories.

2.3 Identification of Inspection Requirements

To obtain INDOT's construction inspection items related to earthwork, PCCP and HMA pavement, and bridge decks, INDOT's standard specifications and the implementation at the ORB project were examined, resulting in 84 items. The items were categorized in three areas: concrete, asphalt pavement and component, and metal materials. Earthwork is included under both concrete and asphalt pavement. Table 2.2 shows these extracted construction inspection items from ORB project.

2.4 Findings and Observations

The *Manual for Frequency of Sampling and Testing and Basis for Use of Materials* is specific and explicitly regulates the sample size, sampling process, testing methods, and acceptance criteria for all materials. The specification covers both materials requirements and construction requirements. However, it does not provide explicit information on the frequency and methods on construction inspection. Many of the acceptance criteria are qualitative rather than quantitative, which requires the interpretation of construction inspectors and the implementation varies among different districts, projects, and individual inspectors.

TABLE 2.1
Materials Testing Items at INDOT

Main Category	Sub-Categories (Number of Items)
Concrete (22 Sub-Category/74 Items)	Concrete admixture (2), Concrete curing materials (3), Flowable backfill (1), Cellular concrete grout (1), Non-shrink (3), Bagged cements (2), Bagged mortar mix (1), Cement (1), Fly ash (1), Concrete pavement (11), Concrete superstructure (7), Concrete bridge approaches (4), Concrete structure (8), Concrete miscellaneous (4), Concrete barrier walls and sound walls (3), Latex-modified concrete (4), Patching PCCP (3), Precast/prestressed concrete members (5), Precast concrete units (3), Precast median barriers (2), Concrete end sections (1), Concrete MSE retaining walls (1), Modular concrete blocks (3)
Aggregates (11 Sub-Category/41 Items)	Composite aggregate (gradation [1], density [1], PI, LL, and density [1]) Aggregate shoulder drain, underdrains, seal coats, riprap, etc. (1), Aggregate for precast (fine [13], coarse [19]), aggregate snow and ice (1), Aggregates in concrete and HMA plant (1), Precast riprap for certified producers (1), Subbase, gradation (1), Subbase, density or stiffness (1)
Asphalt Pavement and Components (9 Sub-Category/26 Items)	Asphalt materials (3), QC/QA-HMA jobsite (3), SMA jobsite (2), QC/QA-HMA plant (1), HMA jobsite or mixturing plant (12), CMA (2), Cold patching mix (1), QC/QA-HMA and SMA (density-mainline) (1), QC/QA-HMA, density-shoulders (1)
Bridge Piles and Bearing (3 Sub-Category/16 Items)	Steel piles (3), H-pile splicer (1), Elastomeric bearing pads (12)
Earthwork (16 Sub-Category/33 Items)	Embankment density (1), Embankment moisture (1), Subgrade treatment, density (2), Geotextile for riprap (9), Geotextile for underdrains (7), Geogrid (1), Silt fence (1), Calcium and sodium chloride, ice and snow removal (1), Calcium and sodium chloride, all other uses (2), Hydrated lime (1), Hydrated lime and kiln dust (1), Water (1), B borrow/structure backfill, gradation (2), B borrow, density or stiffness (1), Structural backfill, density or stiffness (1), Structural backfill (1)
Joint Materials (7 Sub-Category/14 Items)	Rubber type gaskets (ring) (1), Mastic pipe joint sealers (1), Joint membrane system for precast concrete box culverts (1), Crack, joint and loop sealant (3), Crack and joint fillers (5), Expansion joints (2), High density bearing strip (1)
Masonry Units (5 Sub-Category/5 Items)	Bricks and blocks (2), Modular concrete blocks (3)
Metal Materials (11 Sub-Category/ 40 Items)	Fence materials (fabric-chain link [2], Farm field [2], Tension wire [2], Barbed wire [2], Posts and braces [3]), Steel structures (high strength bolts, nuts, and washers [2], High strength torsion control bolts [1], Permanent forms (Panel [5], Accessories [5], Clips [5]), Reinforcing steel (11)

TABLE 2.2
Construction Inspection Items Used on the INDOT Bridge Construction Project

Main Category	Items
Concrete (42 Items)	Mix design(s), Report of PDA testing, Verify grades and dimensions in field are in agreement with approved plans, Cold weather placement, Forms—removable, Forms—permanent, drainage, pipes and conduits, Roadway surface drainage, Placing concrete, Finishing concrete, Waterproofing, Field drilled holes in concrete (if required), Pile driving records/PDA results, Review final checklist and structure drawings, Pile group acceptance, Driving records, Mix designs for PCCP, Quality control plan, RFC drawings, PCCP mix, Preparation of grade, Preparation of sub-base, Alignment for paving, Placement, Concrete mixing and weather limitations, Placing concrete, Placing concrete protection, Finishing concrete, Surface texturing, Equipment, Review final checklist and structure drawings, Pavement inspection, Random crack remediation—transverse, Random crack remediation—Longitudinal, Opening to traffic, Pavement smoothness
Asphalt Pavement and Components (11 Items)	Drawings/submittals/work plans, Verify DMF has been approved by the Engineer, Verify JMF has been approved by the Engineer, Verify HMA producer is certified, Elevation verification, Subgrade and milled surface preparation, Mixture placement, Compaction, Joints, Smoothness
Metal Materials (31 Items)	Falsework design and calculations, Overhang drawings and calculations, Visual inspection of delivered material per WVC material receiving procedure, EFCO re-usable metal forms for columns and pier caps, Form liner, Span over active railroad tracks, Ties, Chamfers/bevels/drafts, cleanliness, Surface treatment, Removable metal forms, Thermal control and cooling tubes (if required), Removal of formwork and ties, Removal of falsework, Surface finish, Review final checklist and structure drawings, RFC drawings, SIP shop drawings and calculations, SIP MAS sheets with mill certs, Welder's certifications, SIP deck forms and supports, Form sheets, Welds, SIP deck form support systems, Concrete placement, Repair of galvanized coating, Inspection of concrete, Testing for soundness and bonding, Testing for soundness, Review final checklist and structure

3. COMPARISONS OF TESTING AND INSPECTION PRACTICES WITH NEIGHBORING STATES

3.1 Introduction

To gain insights into whether there exists difference between INDOT's practice and that of the neighboring states and whether the exploration of performance related specifications has made an impact on the material testing requirements, INDOT's 249 material testing items were compared to similar/same items at other SHAs in two rounds. The purpose of the first-round comparison is to determine if there is a difference between INDOT and its four neighboring states—Illinois, Kentucky, Michigan, and Ohio—and two states that are located in similar geographical zone—Minnesota and Wisconsin, with respect to materials testing practices. All 249 items were included in the comparison. The purpose of the second-round comparison is to determine if there is difference between states that have been involved in performance-related specification (PRS) for PCCP and states that have not implemented PRS for PCCP. Six more states were added to this round of comparison: Colorado, Iowa, Kansas, Missouri, Nebraska, and Pennsylvania. The first four were involved in PCCP PRS studies. The last two were added to balance the number of states in the PRS and non-PRS groups. In the second round, only PCCP items were compared.

3.2 First-Round Comparison: All 249 Material Testing Items

Table 3.1 provides an excerpt of the first-round comparison, which contains a portion under the "Bridge Piles and Bearing" category. Each item was compared to similar items in the other six states.

Table 3.2 summarizes the first-round comparison into eight main categories. The percentage in the table represents the percent of INDOT material testing items that are also tested in a different state. For instance, the cell on the first row (Concrete) in the second column (Illinois) shows a percentage of 83.3%, which means that 83.3% of INDOT's concrete material testing items are tested in Illinois. Overall, 74.7% of all INDOT material testing items are conducted in the six other states. Minnesota shares the largest (82.1%) common set of material testing items with Indiana, and Wisconsin shares the smallest (55.1%) common set with Indiana. Tests on concrete and aggregates are the categories with the largest percentages (over 80%), followed by earthwork (79.8%) and asphalt pavement (75.6%). A further

TABLE 3.1
Excerpt of Material Comparison Results (from "Bridge Piles and Bearing" Category)

ID	Inspection Item	Illinois	Kentucky	Michigan	Wisconsin	Minnesota	Ohio	Count*
bridge_001_01	Steel Piles, Uncoated Steel H Piles, Steel Encased Concrete Piles and Steel Piles	Y	Y	Y	Y	Y	Y	6
bridge_001_02	Steel Piles, Epoxy Coated Steel H Piles, Steel Encased Concrete Piles and Steel Piles	Y	Y	Y	Y	N	Y	5
bridge_001_03	Steel Piles, Steel Sheet Piles (Temporary)	Y	Y	Y	Y	N	Y	5
bridge_002	H-Pile Splicer, Uncoated Steel H Pile	Y	Y	Y	N	N	N	3
bridge_003	Elastomeric Bearing Pads (Bridge)	Y	Y	Y	Y	Y	Y	6

Y = yes, difference between state and INDOT; N = no difference.
*Count = number of yesses.

TABLE 3.2
Statistics on Material Comparison

Main Category	Illinois (%)	Kentucky (%)	Michigan (%)	Wisconsin (%)	Minnesota (%)	Ohio (%)	Average (%)
Concrete	83.3	80.0	86.7	*76.7*	86.7	80.0	82.2
Aggregates	87.2	100.0	82.1	*48.7*	97.4	79.5	82.5
Asphalt Pavement and Components	92.9	92.9	67.9	*42.9*	75.0	82.1	75.6
Bridge Piles and Bearing	75.0	*31.3*	43.8	75.0	81.3	81.3	64.6
Earthwork	81.8	93.9	72.7	*60.6*	81.8	87.9	79.8
Joint Materials	92.9	92.9	71.4	64.3	*14.3*	85.7	70.2
Masonry Units	66.7	50.0	50.0	*33.3*	66.7	100.0	61.1
Metal Materials	46.7	60.0	83.3	*36.7*	100.0	*36.7*	*60.6*
Total	**79.1**	**81.1**	**74.5**	***55.1***	**82.1**	**76.0**	**74.7**

Note: Values represent the percentage of INDOT material testing items also tested in that state. *Italics* represent the smallest number in each category.

investigation of those categories and states with lower percentages reveals that the root cause for the difference is the use of different materials. For instance, modular concrete block is used in Indiana, but not in Wisconsin. A reverse approach was taken to confirm this observation. For instance, the material testing specification of Wisconsin includes 196 testing items for PCCP. Of this group, 161 items (82.1%) are also used and tested in Indiana. The same approach was taken for the other five states and the observation was similar. Therefore, it is concluded that the percentages in Table 3.2 represent the common set of materials being used in different states.

3.3 Second-Round Comparison: PCCP Items

Table 3.3 lists the 13 states included in the second-round comparison of PCCP testing, separated into states that have been involved in PRS studies, and those not involved. Some state departments of transportation (including Indiana, Illinois, and Wisconsin, which were a part of the first-round comparison) implemented PRS (INDOT, 2018). For example, INDOT implemented a PRS field trial using full spec projects between 2000 and 2003, and its counterpart in Wisconsin implemented PRS on three occasions (a shadow spec project in 1997 and full spec projects in 2006 and 2011). The second-round comparison was conducted to investigate similarities between the 74 material testing items under the PCCP category used by states that implement PRS and those that do not. Table 3.4 presents the statistics on the comparison.

As shown in Table 3.4, the similarity among states that implement PRS is 83.3% and that among states that do not implement PRS is 79.4%. Between these two groups, 3.9% of items appear solely in the lists of states in one group. The contents of each list differ by approximately 10%–15% except "Concrete, Superstructure, Non QC/QA." This item was mentioned in five of seven lists of states that implement PRS, and only mentioned in one of six lists of states that do not implement PRS. The specifications of the states that did not mention this item (Kansas, Wisconsin, Kentucky, Michigan, Minnesota, Ohio, and Pennsylvania) were reviewed. Some of these states (e.g., Kansas, and Illinois) defined and considered "Non QC/QA" items as belonging to the "Concrete" category rather than "Bridge Superstructure." No obvious effect from the implementation of PRS on the material testing was observed.

TABLE 3.3
States That Implement PRS vs. States That Do Not

PRS Implemented States	Non-PRS Implemented States
Indiana	Michigan
Illinois	Ohio
Wisconsin	Minnesota
Missouri	Pennsylvania
Kansas	Kentucky
Iowa	Nebraska
Colorado	

3.4 Findings, Recommendations, and Implementation

It is worthwhile to point out that such comparisons were not conducted for construction inspection items because inspection practice at different states is very different and there is a lack of common ground for the cross-comparison.

The main findings are as follows.

- The overall similarity among the seven states regarding material testing is high. The few low percentages are mainly because of the use of different materials, e.g., materials used in INDOT are not used in Wisconsin.
- The comparison results showed that the testing items in states that implement PRS were also commonly tested in the states that do not implement PRS. The total difference is 3.9%. This lead to the observation that so far PRS has not significantly changed the material testing practice in SHAs.

TABLE 3.4
Statistics of the Comparison Results PRS-Implemented and Non PRS-Implemented States

ID	Inspection Item	Percentage of PRS Implemented States	Percentage of Non-PRS Implemented States	Difference (%)
Concrete_001_01	Concrete admixture, Type A, B, C, D, E, F, G, and Air entrainment	100.0	100.0	0.0
Concrete_001_02	Concrete admixture, Latex modifier	71.4	83.3	11.9
Concrete_002_01 Concrete_002_02	Concrete curing materials, Liquid membrane curing materials	100.0	100.0	0.0
Concrete_002_03	Concrete curing materials, Concrete sealers, Proprietary	85.7	100.0	14.3
Concrete_003	Flowable backfill	57.1	66.7	9.5
Concrete_004	Cellular concrete grout	42.9	33.3	9.5
Concrete_005	NON-Shrink grout (Air content, Slump, Visual stability index)	71.4	83.3	11.9
Concrete_006	Bagged cements	42.9	50.0	7.1
Concrete_007	Bagged mortar mix	14.3	0.0	14.3
Concrete_008	Cement	100.0	100.0	0.0
Concrete_009	Fly ash	100.0	83.3	16.7
Concrete_010	Concrete	100.0	100.0	0.0
Concrete_010_01-06	Concrete, Pavement, QC/QA	100.0	100.0	0.0
Concrete_010_07-11	Concrete, Pavement, Non QC/QA	85.7	66.7	19.0
Concrete_011_01-02	Concrete, Superstructure, QC/QA	100.0	83.3	16.7
Concrete_011_03	Concrete, Superstructure, Non QC/QA	71.4	16.7	*54.8**
Concrete_012	Concrete, Bridge	100.0	100.0	0.0
Concrete_013	Concrete, Structures	100.0	83.3	16.7
Concrete_014~015	Concrete, Miscellaneous	100.0	83.3	16.7
Concrete_016	Concrete, Latex-modified	57.1	66.7	9.5
Concrete_017	Concrete, Full-depth and partial depth patching-PCCP	85.7	66.7	19.0
Concrete_018_01~02	Precast/Prestressed concrete members, Aggregate	100.0	100.0	0.0
Concrete_018_03	Precast/Prestressed concrete members, Cement	100.0	100.0	0.0
Concrete_018_04	Precast/Prestressed concrete members, Reinforcing steel	100.0	100.0	0.0
Concrete_018_05	Precast/Prestressed concrete members, Strand	100.0	100.0	0.0
Concrete_019	Precast concrete units	100.0	100.0	0.0
Concrete_020	Precast median barriers, Permanent	85.7	100.0	14.3
Concrete_021_01	Precast concrete unit, End sections	100.0	100.0	0.0
Concrete_021_02	Precast concrete unit, Mechanically stabilized earth retaining walls	100.0	100.0	0.0
Concrete_022	Modular concrete block	28.6	16.7	11.9
Total		**83.3**	**79.4**	**3.9**

*Maximum difference (%).

4. CORE INSPECTION ITEMS ALIGNED WITH THE CONSTRUCTION PROCESS

4.1 Introduction

INDOT's standard specification and the Manual for Frequency of Sampling and Testing and Basis for Use of Materials contain specific guide on both construction inspection and material testing. Starting with these two documents and the QA implementation at the ORB project, a total of 333 inspection and testing items were extracted. With the help from both INDOT experts and industrial partners, the list was narrowed down to 126 core inspection items. All these core items were aligned with the construction process to facilitate risk assessment. Figure 4.1 illustrates the process for identifying core items.

4.2 Aligning Inspection Items with the Construction Process

Construction inspection is an activity-centered process (Yuan, McClure, Cai, & Dunston, 2017). Inspection

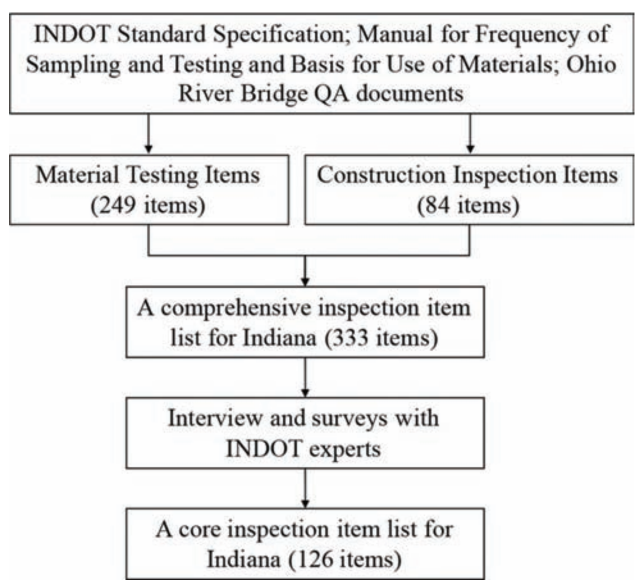

Figure 4.1 Identification of INDOT core inspection items.

TABLE 4.1
Typical QA Inspection Activities for PCCP and HMA Pavement Construction

Construction Process	PCCP Inspection Activities	HMA Inspection Activities
1. Receive and approve Designs/Plans	(1.1) Verify concrete mix designs (CMD) and concrete mix design for production (CMDP) have been approved by the engineer; (1.2) Verify quality control plan (QCP) has been approved by the engineer; (1.3) Design review (Stage 1, Stage 2, Released-for-construction (RFC), Final design, Working drawings and record drawings)	(1.1) Verify quality control plan (QCP) has been approved by the engineer; (1.2) Verify DMF has been approved by the engineer; (1.3) Verify JMF has been approved by the engineer
2. Material receiving and control	(2.1) Concrete mixtures; (2.2) Testing facility; (2.3) Admixtures; (2.4) Coarse aggregate, Class AP, size No. 8 or gradation as identified in QCP; (2.5) Fine aggregate, size No. 23, or gradation identified in QCP; (2.6) Portland cement; (2.7) water	(2.1) Asphalt materials (i.e., PG Binder); (2.2) Coarse aggregates; (2.3) Fine aggregates; (2.4) Fiber; (2.5) Certified HMA producer program
3. Pre-paving	(3.1) Preparation of sub-base; (3.2) Check condition of subgrade and subbase	(3.1) Preparation of surfaces to be overlaid; (3.2) Elevation verification of milled surface
4. Paving	(4.1) Alignment for pavement; (4.2) Placing PCCP joints; (4.3) Concrete mixing and transportation; (4.4) Weather constraints for PCCP placement; (4.5) Concrete field sampling for testing; (4.6) Placing concrete; (4.7)~(4.11) Quality acceptance testing and tolerance (slump; plastic unit weight; water/ cement ratio; flexural strength; air content)	(4.1) Weather constraints for HMA placement; (4.2) Spreading and finishing mixture; (4.3) Compaction procedure for asphalt pavement layer; (4.4) Material sampling, storage, and transport; (4.5) Asphalt mixtures calibration; (4.6)~(4.14) Asphalt mixtures sampling on jobsite (aggregate moisture content; extracted aggregate gradation; coarse aggregate angularity; binder drain down; binder content; bulk specific gravity; maximum specific gravity; density; Certification type D materials); (4.15) Preparation of mixture specimen in lab; (4.16) Asphalt mixture temperature; (4.17) Asphalt mixtures sampling in plant—Dolomite; (4.18)~(4.25) Quality acceptance testing conducted and the testing result are within the tolerance of asphalt mixtures (moisture content; extracted aggregate gradation; density; binder content; air void; VMA; binder drain down; thickness); (4.26) Tack coat; (4.27) Joints
5. Post-paving	(5.1) Placing concrete protection; (5.2) Sawing and sealing joints; (5.3) Finishing concrete; (5.4) Surface texturing; (5.5) Curing concrete; (5.6) Form removal; (5.7) Surface smoothness; (5.8) Surface thickness; (5.9) Patching; (5.10) Pavement defects inspection; (5.11) Random crack remediation—transverse; (5.12) Random crack remediation—longitudinal; (5.13) Open to traffic; (5.14) Review final checklist and structure drawings	(5.1) Sealing or filling cracks and joints; (5.2) Pavement corrugations; (5.3) Pavement smoothness; (5.4) Review final checklist and structure drawings

items are expected to be appropriate to the specific activities throughout the construction process to ensure that each inspection item can be tested, verified, or inspected at the right time. Table 4.1 lists the typical construction processes and inspection activities occurring in PCCP and HMA construction, which consisted of 37 inspection activities for PCCP and 41 for HMA in five general categories. Table 4.2 lists nine pavement-related earthwork inspection activities in the pre-paving category. Table 4.3 lists 31 inspection activities for bridge decks in seven general categories. It is noted that since earthwork activities are counted in both PCCP and HMA, the list of entire inspection activities has 118 items instead of 126 items.

TABLE 4.2
Typical QA Inspection Activities for Earthwork Linking to Pre-paving

Construction Process	Earthwork Inspection Activities
3. Pre-paving	(3.1)~(3.7) Preparation of subgrade (grade control; materials and lift thickness requirements and compaction; DCP; moisture control; chemically modified soil general, compaction and moisture content); (3.8)~(3.9) Subsurface drainage (longitudinal underdrain pipes; transverse outlet pipes, outlet protectors and other end sections, subsurface drainage elements)

TABLE 4.3
Typical QA Inspection Activities for Bridge Deck

Construction Process	Bridge Deck Inspection Activities
1. Receive and Approve Designs/Plans	(1.1) Verify QC/QA quality control plan (QCP) of superstructure; Concrete is approved by the engineer
2. Bridge Deck Material Receiving and Control	(2.1) General material requirement; (2.2)~(2.7) Concrete bridge floor slabs (i.e., bridge deck) material—castings; Concrete, Class C for IC-HPC; Joint materials; PVC; Reinforcing bars
3. Grade Control, Screeds, and Bulkheads	(3.1) Grade control and screed elevations control
4. Bridge Deck Forms	(4.1) Deck form installation; (4.2) Shear connectors installation; (4.3) Construction joints installation; (4.4) Expansion joints installation; (4.5) Miscellaneous items (drains, conduits, etc.)
5. Deck Reinforcement	(5.1) Bar placement; (5.2) Clearness; (5.3) Splices
6. Concrete Placement and Consolidation	(6.1) Concrete placement and consolidation (general); (6.2) Concrete placement and consolidation (cold weather); (6.3) Concrete field sampling for testing; (6.4)~(6.8) Quality acceptance testing is conducted and the testing result is within tolerance—Slump; Plastic unit weight; Water/cement ratio; Compressive strength; Air content
7. Concrete Finishing and Curing	(7.1) Finishing concrete; (7.2) Curing; (7.3) Waterproofing; (7.4) Concrete surface smoothness; (7.5) Tests for soundness and bonding to the forms; (7.6) Application of loads

5. RISK ASSESSMENT

5.1 Introduction

The 118 core items identified in Chapter 4 do not have the same level of risks. The objective in this chapter is to assess the risks associated with individual inspection items and prioritize them correspondingly for optimal resource allocation. Figure 5.1 illustrates the three-step protocol for doing so. Please note that Step 1 and Step 2 were described in Chapter 4. This chapter focuses on Step 3.

5.2 Risk Assessment Method

Surveys were conducted with eight INDOT experts with many years of experience in pavement materials, concrete and asphalt pavement construction, geotechnical construction, project management, and field inspection to assess the risk associated with the 118 core inspection items.

5.2.1 Survey Design for Risk Assessment

Since the risk for each inspection activity is a function of multiple attributes, the survey requested the expert's inputs for the list of questions shown in Table 5.1. Two formats of the survey were distributed. The first format, which included earthwork and PCCP, required the respondents to select the weight from values of low (1), medium (2), and high (3) to evaluate the overall likelihood of an inspection not meeting the requirements and the overall severity as a consequence of not meeting the requirements. The second survey format, which included HMA and bridge decks, requested the respondents to provide the weight from values of low (1), medium (2), and high (3) to evaluate the overall likelihood and provide a breakdown of the severity of the consequence from four aspects (safety, quality, time, and cost). In addition, the second format also sought input from the experts about the necessity of including the specific inspection activity in the list with a Yes (1) or No (0) option.

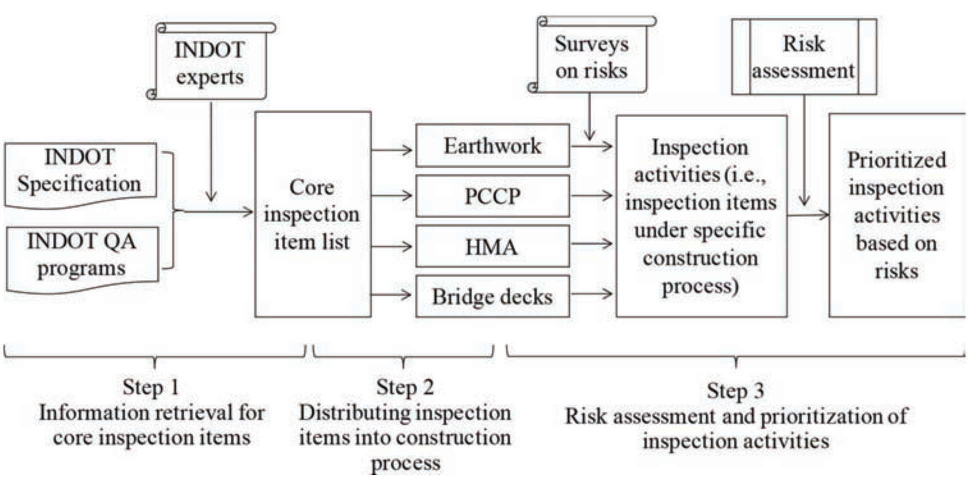

Figure 5.1 Flowchart for risk assessment of INDOT construction inspection activities.

TABLE 5.1
Direct Inputs Required in Four Surveys for Inspection Risk Assessment

Survey Inputs	Construction Scenario			
	Earthwork	PCCP	HMA	Bridge Deck
Necessity to be included	NA	NA	√	√
Overall likelihood of inspection not meeting requirements	√	√	√	√
Overall severity of consequence of the inspection not meeting requirements	√	√	NA	NA
Severity of consequence in safety	NA	NA	√	√
Severity of consequence in quality	NA	NA	√	√
Severity of consequence in time	NA	NA	√	√
Severity of consequence in cost	NA	NA	√	√

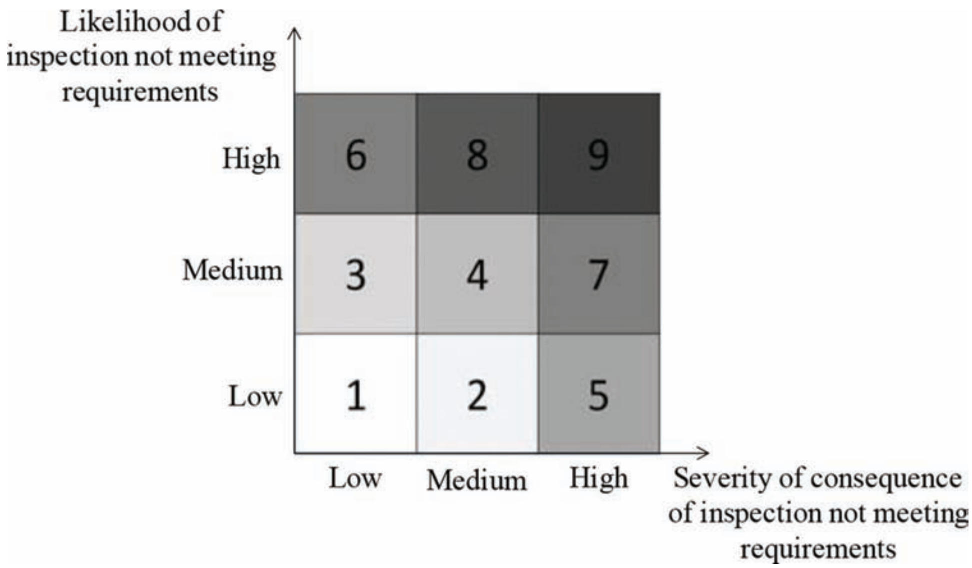

Figure 5.2 Matrix of composite index of risk in the surveys.

5.2.2 Risk Assessment Procedure

A 3x3 matrix was created to aggregate the two dimensions of the risks into one composite index, which is shown in Figure 5.2. The horizontal axis represents the severity of the consequence of the inspection not meeting the requirements, and the vertical axis indicates the likelihood of the inspection not meeting the requirements. For example, if a respondent chose high (3) for the severity of the consequence and medium (2) for the likelihood, the corresponding composite index was "7." In the surveys of earthwork and PCCP, a composite index was generated for each respondent, from which the mean values of the composite indexes from all the respondents were calculated. In the HMA and bridge deck survey, the severity of the consequences included the four aspects of safety, quality, time, and cost. Therefore, for each respondent, the maximum value of the severity weights in these four aspects was determined and used as the representative value in calculating the composite index.

The survey criteria to determine whether a specific inspection activity is critical are as follows.

- For earthwork and PCCP:

1. If the composite index is less than 5, the inspection activity is excluded from the critical inspection list unless additional information or comments were provided.
2. If the composite index is 5 or larger, but a better inspection alternative is available, the inspection activity is excluded from the critical inspection list.
3. The remaining inspection activities were included in the critical inspection list.

- For HMA pavement and bridge decks:

1. If fewer than 40% of the respondents replied YES (1) to the question pertaining to the necessity to include the specific inspection activity, the inspection activity is excluded from the critical inspection list.
2. If the composite index is less than 5, the inspection activity was excluded from the critical inspection list unless additional information or comment was provided.
3. If the composite index was 5 or larger than 5 and INDOT practice indicated that a better alternative is

available, the inspection activity is excluded from the critical inspection list.

4. The remaining inspection activities are included in the critical inspection list.

The survey statistics and observations were then summarized by the categories of earthwork, PCCP, HMA pavement, and bridge decks.

5.2.3 Risk Assessment Results

Seven valid responses were received for the earthwork survey. The mean value of the composite index is illustrated in Figure 5.3. The horizontal axis represents the earthwork inspection activities labeled with the ID defined in Table 4.2. Three activities have a mean composite index of less than 5: "ID 3.4: Preparation of Subgrade—Moisture Control," "ID 3.7: Preparation of Subgrade—Chemically Modified Soil—Moisture Content," and "ID 3.9: Subsurface drainage—transverse outlet pipes, outlet protectors and other end sections, surface drainage elements." Only the first two (illustrated with grey bars in Figure 5.3) were excluded from the critical inspection list. The third inspection activity (illustrated with a dotted-fill bar) remained on the critical list because it is important to remove subsurface water from the pavement as far and as soon as possible.

Five valid responses were collected for the PCCP survey. The mean value of the composite index is illustrated in Figure 5.4. The horizontal axis represents the PCCP inspection activities labeled with the ID defined in the PCCP column of Table 4.1. A total of six inspection activities (displayed with grey bars in Figure 5.4) have composite index means of less than 5, and they were excluded from the critical inspection list. Moreover, "ID 4.7: Quality acceptance testing and tolerance—slump" was suggested by both INDOT experts and industrial practitioners for exclusion from the critical inspection list because slump testing is more appropriate for quality control than for quality assurance.

Five valid responses were received for the HMA survey. The first question in this survey pertained to

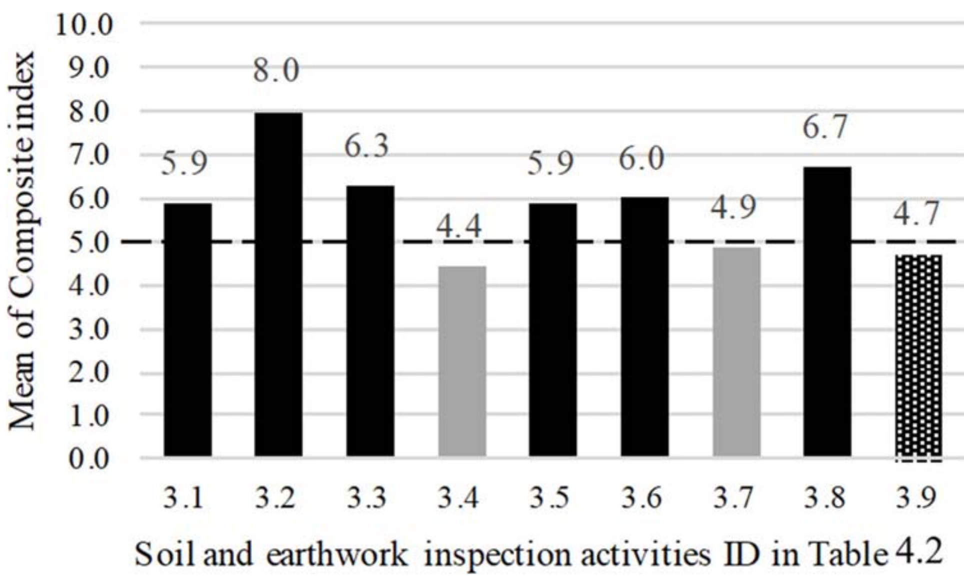

Figure 5.3 Survey results: mean value of the composite index for the earthwork.

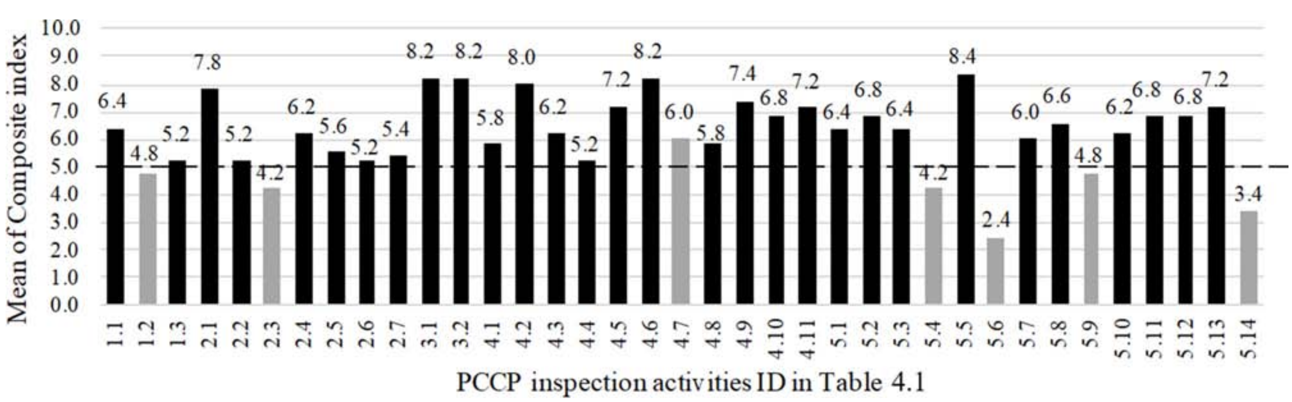

Figure 5.4 Survey results: mean value of the composite index for PCCP.

the necessity to include the inspection activity. Figure 5.5a shows that one inspection activity received fewer than 40% *YES* votes (≤2), and it therefore was excluded from the critical inspection list according to the criteria established. The second question in the HMA survey evaluated the severity of the consequences, and the maximum value among these four dimensions was selected. Figure 5.5b shows that 14 inspection activities received low composite indexes (<5) besides the one with low votes, which were excluded from the critical inspection list as well.

Five valid responses were received for the bridge decks survey. A process similar to the process implemented in the HMA survey analysis was used. Figure 5.6 illustrates that four inspection activities with either low votes (≤2) or low composite indexes (<5) were identified and hence were excluded from the critical inspection list. Three other inspection activities: "ID: 2.5: Concrete bridge floor slabs (i.e., bridge deck) material—Joint materials"; "ID 4.4: Expansion Joints installation"; and "ID 4.5: Miscellaneous Items (Drains, Conduits, etc.)" received a medium average composite index (4.8) and were included in the critical inspection list because expansion joints and drains are important to the performance of bridge decks.

Removing non-critical items resulted in a list of 90 critical inspection items.

5.2.4 Risk-Based Inspection Strategy

For the 90 critical inspection items, we extracted their acceptance criteria from the specification, developed corresponding check items, and recommended the inspection frequency and priority based on the risk and the nature of the associated work task. The deliverable is a list of customized strategy for every critical inspection item. Table 5.2 lists the information items associated with each inspection activity. Note that an inspection activity typically has multiple clauses of acceptance criteria and each clause corresponds to one check item. Tables 5.3 and 5.4 provide examples.

5.3 Findings and Recommendations

The main findings and recommendations are as follows.

- A list of 90 critical inspections was generated in the four categories of earthwork, PCCP, HMA pavement and bridge decks after less critical inspection activities were removed.
- Each inspection activity is aligned with a construction process to facilitate the risk assessment in terms of the failure probability and the severity of the consequence of the materials or the construction process not meeting the requirements.

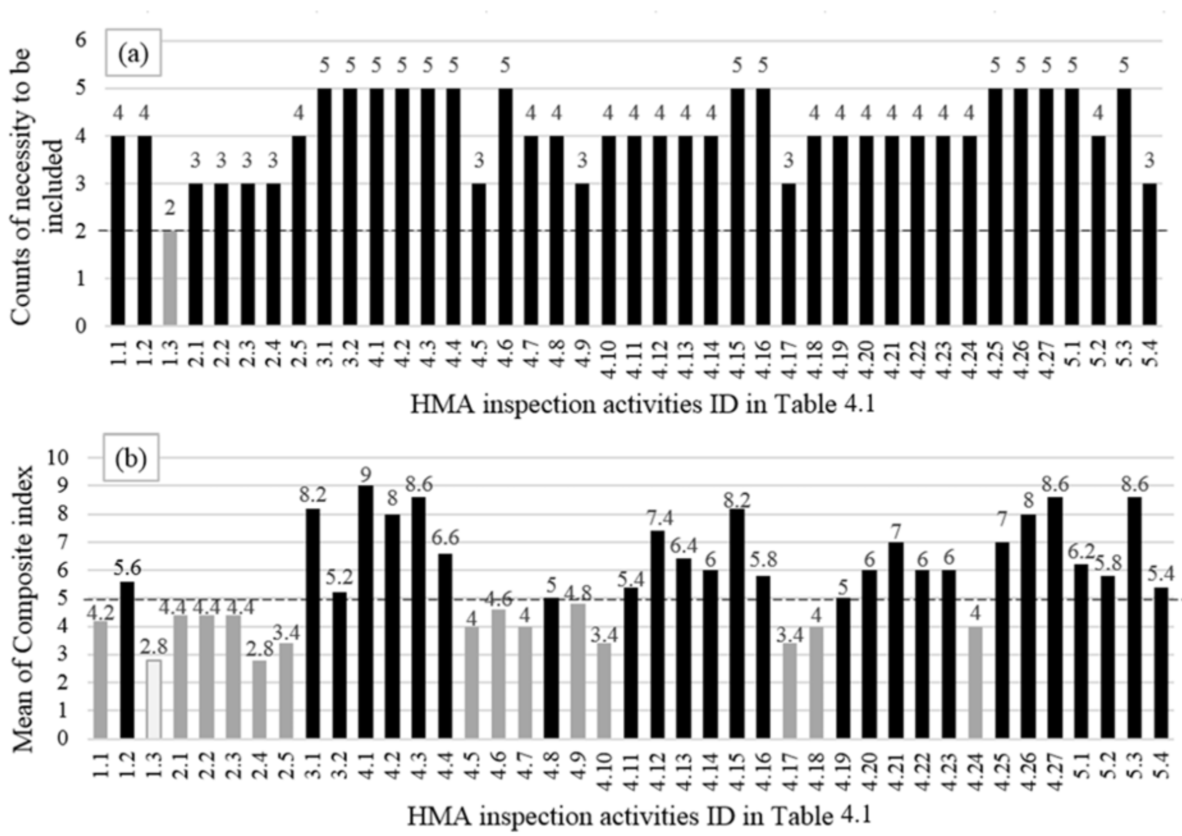

Figure 5.5 Survey results for HMA pavement: (a) counts of necessity to be included; (b) mean of the composite index.

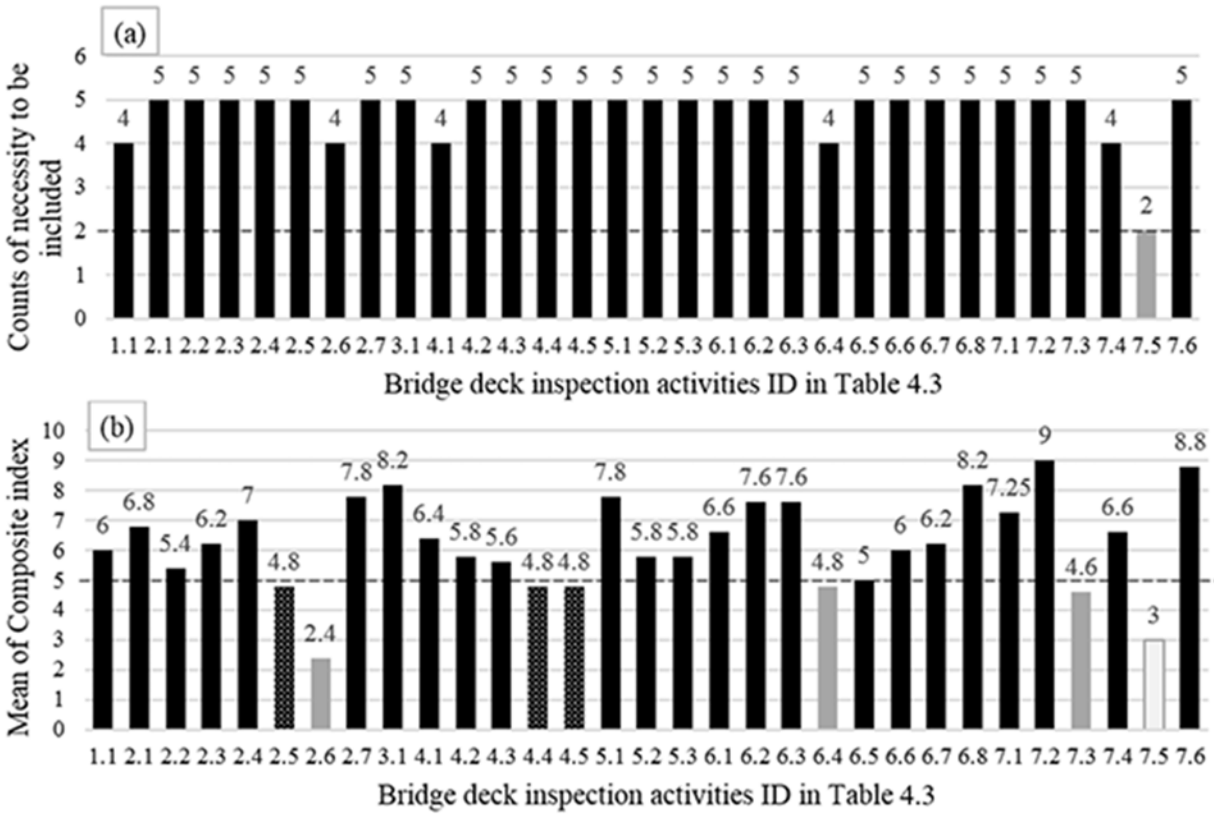

Figure 5.6 Survey results for bridge deck: (a) counts of necessity to be included; (b) mean of the composite index.

TABLE 5.2
Information Items in the Inspection Strategy for Each Inspection Activity

Item Name	Description
QC/QA Activity	Inspection activity
Composite Index	Composite risk index considering both likelihood and consequence severity
Consequence	Risk index in the aspect of consequence severity
Probability	Risk index in the aspect of likelihood of accepting inferior work
Acceptance Criteria	Acceptance criteria extracted from specification
Check Items	Check items that correspond to acceptance criteria
Sample/Inspection Frequency	Inspection frequency as specified in the specification and recommended based on the risk
Material Testing	Whether this is material testing and if yes, is it about raw or placed materials
Verification/Inspection	Whether this is inspection and if yes, is it verification or inspection that involves measurement. Verification—project management, e.g., drawings have been submitted and approved, and materials are from Materials Acceptance Sheet (MAS). Inspection—often involves measurements and is done in the field.

TABLE 5.3
Sample Inspection Strategy—Part I

QC/QA Activity	Composite Index	Consequence	Probability	Acceptance Criteria
Preparation of subgrade—grade control	Medium	High	Medium	(1) [401.11; 402.11; 502.07] The subgrade shall be shaped to the required grade and section, free from all ruts, corrugations, or other, irregularities. (2) [207.03] The grade and cross section of the subgrade shall be finished within a tolerance of 1/2 in. from the true subgrade. (Note: contractor provides grade elevations (proposed and actual) at the minimum of two per station, and they are all within the tolerance limit.)

TABLE 5.4
Sample Inspection Strategy—Part II

	Sample/Inspection Frequency		Material Testing		Verification/ Inspection	
Check Items	Specification	Recommend	Raw	Placed	Ver.	Ins.
( ) YES ( ) NO ( ) N/A—Subgrade is finished (i.e., free from ruts, corrugations, or other irregularities)	Once or as required (refer to WVC* … R-03 ITP** 001-IN Portland Cement Concrete Paving.pdf item 3.1 Preparation of Grade)	Entire subsurface grade (visually check)				1
( ) YES ( ) NO ( ) N/A—Subgrade elevation is confirmed	Each location (refer to WVC…R-04 ITP_037.2_IN QCQA HMA Paving.pdf item 3.2 subgrade and milled surface preparation)	All subgrade elevations			1	

*WVC is the prefix of all documents from the ORB project.
**ITP, Inspection and Testing Plans.

The proposed protocol can provide INDOT with a risk assessment framework that includes the likelihood of failure, the severity of the failure, the best inspection timing during the construction process and sampling and testing frequency.

6. DEVELOPMENT OF INSPECTION FORMS

6.1 Introduction

The objective in this chapter is to develop inspection forms to assist field crews in using the risk-based approaches to perform construction inspection. The inspection forms must be integrated with the construction documentation process that is centered around pay items. The individual check items in an inspection form align with the acceptance criteria and inspection method as outlined in the specification, and guide the inspection frequency and priority (corresponding to risk). These desired characteristics of the implementation demand a mechanism that link inspection activities (i.e., the 90 critical inspection activities), pay items, and check items which are extracted from specifications.

We have designed a risk-based and knowledge-based digital inspection system to not only implement a risk-based approach for construction inspection but also manage construction inspection knowledge.

6.2 Ontological Model for Construction Inspection

Viewing inspection activities, risk assessment, and check items extracted from specification as knowledge, we designed an ontological model for managing these data. Ontology is known to have the advantages of representing, sharing, and managing domain knowledge through a system of concept hierarchies (taxonomies), associative relations (to link concepts across hierarchies), and axioms that allow reasoning in a semantic way (El-Diraby, Lima, & Feis, 2005).

Figure 6.1 illustrates the highway construction inspection ontology (HCIOntology) model that was developed to capture the knowledge in the highway construction inspection domain. Each node in the graph represents a concept or object in the domain and each link in the graph represents the logical relation between these concepts or objects. A logic-based declarative sentence, for instance *Pay item–requires–Check item*, is composed of two nodes and a relational link. Aggregately, the concepts, the relations, and the derived logic-based declarative sentences represent the domain knowledge in highway construction inspection.

In the newly designed HCIOntology, the *Project* is the starting point for generating the project-specific inspection plan. According to the schedule of *Pay item*, the *Contractor* works on the *Project* and is paid by finishing the required *Pay item*. A *Project* involves a series of *Process*, *Activity*, and *Resource* to produce *Product* during the construction process. Field inspectors conduct *Inspection activity* as construction progresses to ensure the construction quality of the resulting *Product*. This connection is realized by the relational links among *Pay item*, *Inspection activity*, *Check item*, and *Inspector*. The applicable *Pay item* relate to the ongoing *Inspection activity* that needs attention for construction documentation. The *Inspector* ensures that *Pay item* is completed and meets the requirements of the *Check item*. The *Inspector* checks a given *Check item* by referring to the *Check detail* including the *Check frequency*, *Check attribute*, *Check object*, *Check criteria*, *Field data*, and *Check result*. The *Check result* can be inferred by comparing the collected *Field Data* with the *Check criteria*. With the newly established *relates to* relationship between *Pay item* and *Inspection activity* and the *requires* relationship between *Pay item* and *Check item*, the *requires* relationship between *Inspection activity* and *Check item* is established. Through these two linking mechanisms, the construction inspection work can be performed on prioritized inspection activities. Field inspectors can target the required pay items and check items using this *Inspection activity–Pay item–Check item* linking system. Finally, the domain *Attributes*, *Mechanisms*, and *Constraints* are used to support the knowledge representation of the highway construction inspection domain.

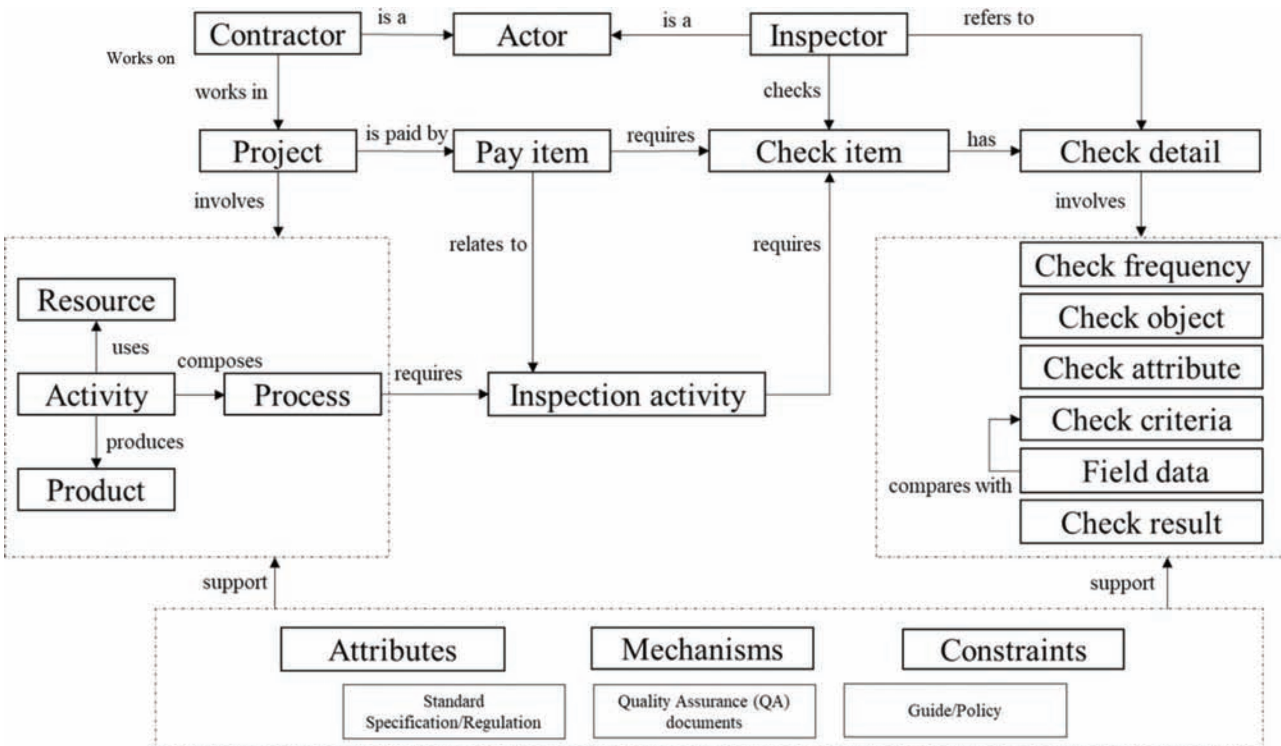

Figure 6.1 Proposed ontological framework for highway construction inspection.

6.3 Connecting Inspection Activities to Pay Items

Highway construction inspection is an activity-centered process while construction documentation is a pay item-centered process. Field engineers document construction and inspection data based on pay items in the contract, e.g., the contract information book (CIB) in INDOT. To integrate the inspection forms with the construction business process, we must establish the *Pay item–relates to–Inspection activity* relations in the model. This was accomplished through a linking mechanism based on matching specification sections.

Figure 6.2 illustrates the linking mechanism between the pay items and inspection activities. The INDOT standard specification serves as the connecting point to which both pay items and inspection activities refer. By matching the INDOT specification sections, the applicable pay items of a given inspection activity are determined, establishing the *relates to* relationship between the *Pay item* and the *Inspection activity*.

Table 6.1 provides examples of linking applicable pay items to inspection activities. All pay items are instances/individuals under the *Pay item* class of the ontology. The linking relationship is represented via the *relates to* property of the ontology. Such a linking mechanism enables retrieving the applicable pay items for any given inspection activity from the knowledge model in real time via a semantic and logic-based framework.

6.4 Connecting Check Items to Pay Items

The inspection check items were developed by paraphrasing the contract requirements of the INDOT standard specification into specific check items. Figure 6.3 illustrates how the individual check items were extracted from the specification and organized under the specification section, such as 201, with reference to their corresponding subsections (such as 201.03).

The specification also lists applicable pay items under each section. By examining each pay item in detail, their corresponding subsections were identified. Table 6.2 lists the pay items under Section 201 and their applicable subsections. For instance, pay item 201-01015 (Clearing and Grubbing) corresponds to subsection 201.03. Pay items and check items were linked by matching the subsections. Table 6.3 illustrates the identified check items that are applicable to pay item 201-01015 by matching subsection 201.03. Such a linking mechanism enables retrieval of the applicable check items for any given pay item from the knowledge model in real time in a semantic and logic-based manner. The linking relationship is represented by the *requires* property of the ontology between *Pay item* and *Check item*.

With the newly established *relates* relationship between the pay item and the check item and the *requires* relationship between *Pay item* and *Inspection activity*, the *requires* relationship between *Inspection activity* and

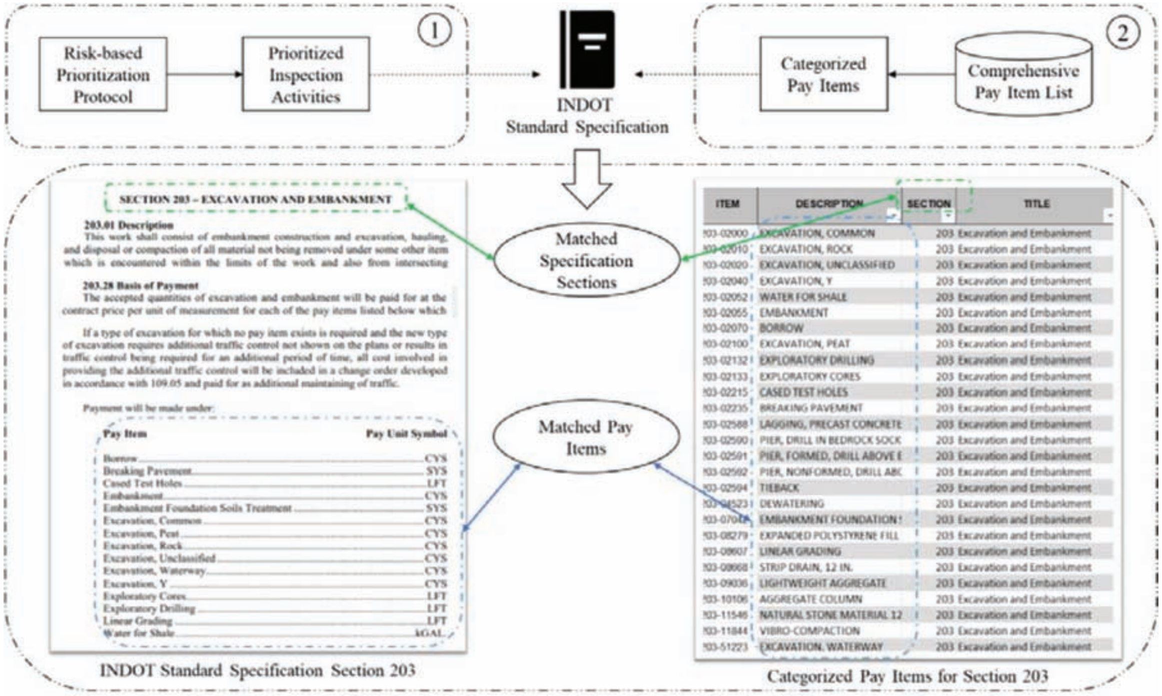

Figure 6.2 Proposed approach to linking inspection activities and applicable pay items.

TABLE 6.1
A Partial List of Linking Results of Risk-Based Prioritized Earthwork Inspection Activities and Their Corresponding Pay Items

Inspection Activity	Matched Section	Applicable Pay Item
Preparation of subgrade: materials and lift thickness requirements and compaction	Section 203 Section 207	203-02055 Embankment 203-02100 Excavation, peat 203-04523 Dewatering 203-11844 Vibro-compaction 207-08262 Subgrade treatment, type I
Surface drainage: transverse outlet pipes, outlet protectors and other end sections, surface drainage elements	Section 702 Section 715	702-51110 Grates, basins, fittings, and cast iron 715-04547 Pipe ductile iron 30? 715-04596 Water service

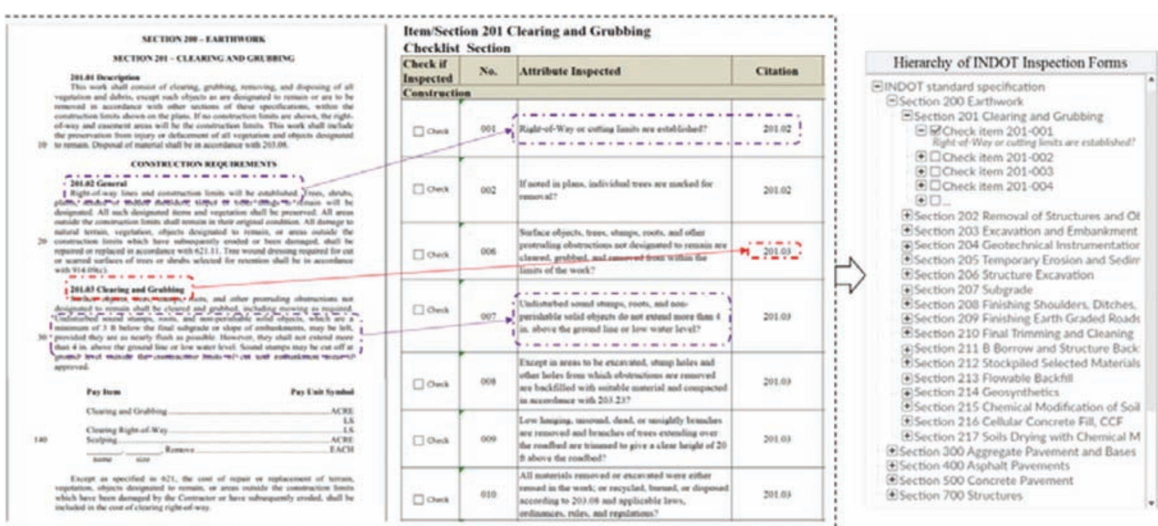

Figure 6.3 Development of check items from specification and the resulting hierarchy of check items.

TABLE 6.2
Applicable Subsections for Pay Items Under Section 201

Pay Item ID	Description	Subsection	Subsection Title
201-01015	CLEARING AND GRUBBING	201.03	Clearing and grubbing
201-01025	SCALPING	201.04	Scalping
201-02245	TREE 6 IN., REMOVE	201.05	Hedge removal
201-06587	CLEARING AND GRUBBING	201.03	Clearing and grubbing
201-12044	CLEARING AND GRUBBING	201.03	Clearing and grubbing
201-52370	CLEARING RIGHT OF WAY	201.03	Clearing and grubbing
201-90788	DEBRIS, REMOVE STRUCTURE NO.	201.03	Clearing and grubbing

TABLE 6.3
Applicable Check Items for Pay Item 201-01015 (Clearing and Grubbing)

Pay Item ID	Check Item ID	Check Item
201-01015	201-006	Surface objects, trees, stumps, roots, and other protruding obstructions not designated to remain are cleared, grubbed, and removed from within the limits of the work?
	201-007	Undisturbed sound stumps, roots, and non-perishable solid objects do not extend more than 4 in. above the ground line or low water level?
	201-008	Except in areas to be excavated, stump holes and other holes from which obstructions are removed are backfilled with suitable material and compacted in accordance with 203.23?
	201-009	Low hanging, unsound, dead, or unsightly branches are removed and branches of trees extending over the roadbed are trimmed to give a clear height of 20 ft. above the roadbed?
	201-010	All materials removed or excavated were either reused in the work; or recycled, burned, or disposed of according to 203.08 and applicable laws, ordinances, rules, and regulations?

Check item also was established. Through these two linking mechanisms, the construction inspection work can be performed on prioritized inspection activities. INDOT field inspectors can easily target the required pay items and check items using this *Inspection activity–Pay item–Check item* linking system.

6.5 Check Details

Each *Check item* has *Check detail* that covers *Check frequency*, *Check attribute*, *Check object*, *Check criteria, Field data,* and *Check result*. In this study, *Check frequency* is defined at three levels: Level 1: Full-time continuous inspection; Level 2: Intermittent inspection; and Level 3: Once per job/component/as needed. Table 6.4 provides two examples to illustrate the check details.

6.6 Inspection Data

For each check item, field inspectors collect field data and the collected data are compared against the acceptance criteria. *Field data* and *Check result* are defined to host field data and check result respectively, and the comparison is done automatically. INDOT can use *Field data* and *Check result* to track all the inspection work and generate inspection reports for future operations and maintenance tasks.

When the risk-based prioritized inspection activities, linked pay items, linked check items, and extracted check details are created as instances under the proposed ontological model, a knowledge base for INDOT highway construction inspection is formalized. Figure 6.4 illustrates an excerpt of the final instantiation result with selected instances.

TABLE 6.4
Examples of Check Details

Check Item	Is the spreading of chemicals being performed when air temperature is above 40°F and the soil is not frozen?	Is soil being compacted using a vibratory, footed roller weighing at least 10 tons?
Check Frequency	Level 3: Once per job/component/as needed	Level 3: Once per job/component/as needed
Check Object	Spreading of chemicals	Vibratory footed roller
Check Attribute	Air temperature	Weight
Check Criteria	Above 40°F	At least 10 tons

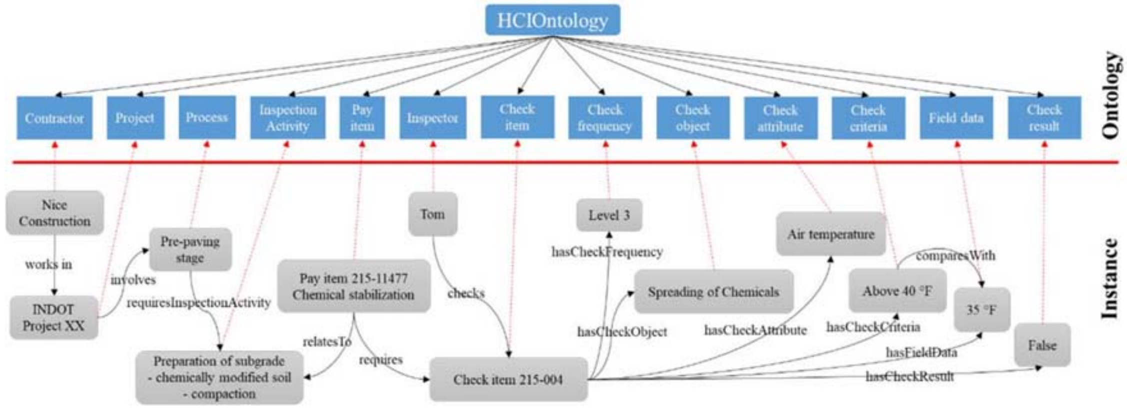

Figure 6.4 Example: inspection knowledge.

6.7 System Implementation Mockup

A prototype for the digital inspection system was developed using a database management system with the following functions/capabilities: (1) prioritizing inspection activities based on risk, (2) retrieving pay items relevant to an inspection activity, (3) retrieving a list of check items applicable to a given pay item, (4) providing check details for a given check item and automatically comparing field data with acceptance criteria for compliance checking, and (5) providing training materials on demand. Figure 6.5 illustrates the user interface and the typical workflow of using the system with an example. Figure 6.6 illustrates the retrieval of training materials on demand. A tab is dedicated to each of the five capabilities. Upon receiving the field data, the system automatically compares the field data to the acceptance criteria and reports the checking result. A user can access the training material associated with a check item at any time.

6.8 Pilot Project for Testing

The newly developed system is currently being implemented at INDOT to develop a digital inspection system as part of its e-Construction initiatives. Project R-30397 Pavement Replacement was chosen as the pilot to test the system. This project involves pavement replacement using precast concrete pavement on US 27 from south of O street to 0.16 mile north of SR 227 AT Sim Hodgin Parkway in Richmond, Indiana. Among the 13 applicable pay items, 4 pay items (202-02240, Pavement Removal; 406-05520, Asphalt for Tack Coat; 211-0926x, Structure Backfill, Type 1/2/5; and 718-52610, Aggregate for Underdrains) belong to the sections in the standard INDOT specification for which the extraction of check items and the matching of check items to pay items have been completed at the time of the preparation of this report. Following the linking mechanism presented in this report, dynamic inspection forms were generated in real time on an as-needed basis for any given pay item(s). Figure 6.7 illustrates the dynamic inspection form for pay item 202-02240 (pavement removal). During the project coordination meeting, the application was successfully demonstrated. Field-testing is being postponed to spring 2019 and will be conducted as a post-construction mock exercise.

6.9 Findings and Recommendations

Main findings are as follows:

- The ontology-based approach is effective in retaining and managing inspection knowledge and data.
- The specification sections and subsections can be used to connect risk-prioritized inspection activities, check items, and pay items so that dynamic inspection forms can be generated in real time on an as-needed basis.
- Training materials can be embedded in the system and retrieved to train field inspectors and provide them with necessary guide.

Three main limitations are:

- Check items (with check details) are manually extracted from INDOT's specification, making this process very time-consuming and error-prone. Maintaining the consistency is also very challenging.
- Matching of check items, pay items, and inspection activities to subsections requires manual checking.
- Mismatch could exist between the extracted check items and updates/revisions/additions to specifications.

Our recommendation is to adopt the proposed ontology-based and risk-based system for construction inspection and test it on pilot projects. We also recommend automating the tasks of extracting check items with details and matching through subsections by leveraging computational technologies such as natural language processing and machine learning. This automation will improve the efficiency, assure the accuracy, and more importantly, stay updated with the modifications and changes to the specification over time.

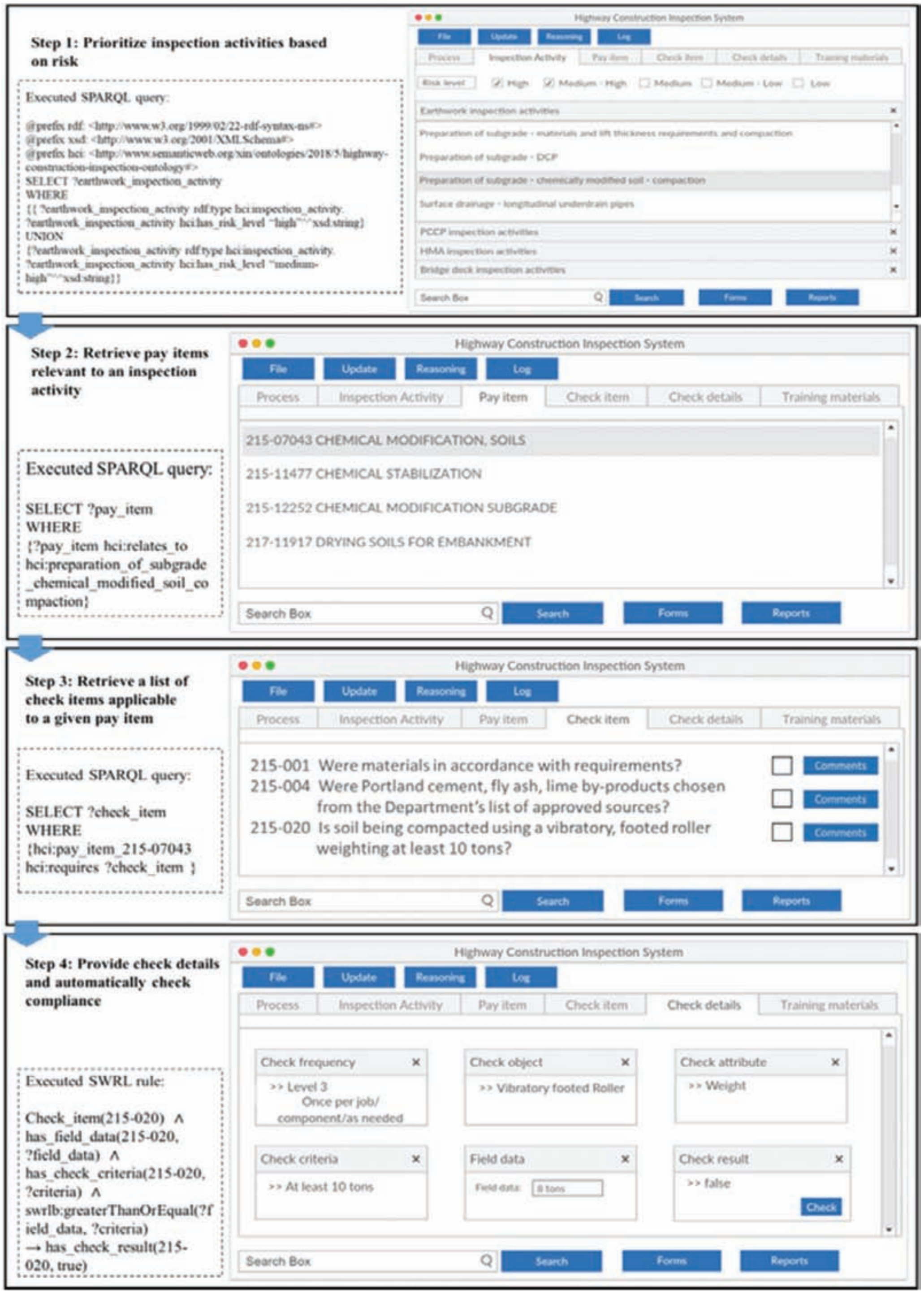

Figure 6.5 Implementation: risk-based highway construction inspection system.

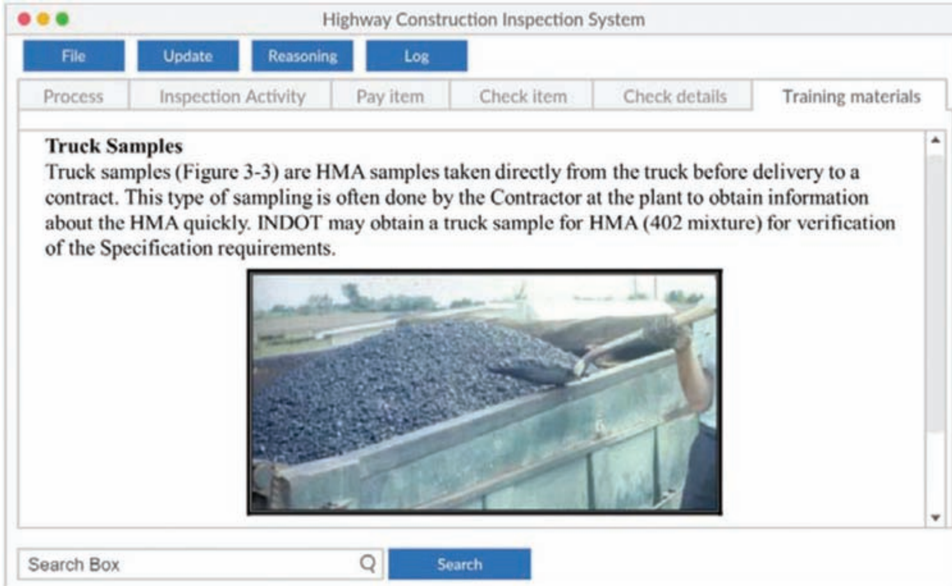

Figure 6.6 Example: retrieving training materials.

Inspection Quality Checklist
Pay Item 202-02240 Pavement Removal
Checklist Section

Check if Inspected	No.	Attribute Inspected	Citation
Removal of PCCP, Sidewalks, Curbs, RCBA, and Reinforced Concrete Moment Slabs			**202.05**
☐ Check	001	Pavement layers or courses removed as indicated in plans?	202.05
☐ Check	002	Concrete walks and steps removed as indicated in plans?	202.05
☐ Check	003	Concrete curbs and gutters or stone curbs removed as indicated in plans?	202.05
☐ Check	004	Concrete traffic dividers removed as indicated in plans?	202.05
☐ Check	005	All unreinforced PCCP, sidewalks, curbs, gutters, and other unreinforced concrete elements designated for removal shall be: (a) broken into pieces and used for riprap on the project; or (b) broken into pieces, the maximum weight of which shall be 150 lb, and incorporated into the work as directed; or (c) otherwise disposed of in accordance with 202.02.	202.05
☐ Check	006	Removal of PCCP, sidewalks, curbs, gutters, and other unreinforced concrete elements designed for removal is in accordance with 202.05?	202.05

Figure 6.7 Dynamic inspection form for pay item 202-02240 (pavement removal).

7. SUMMARY AND RECOMMENDATIONS

7.1 Summary

This study addresses the staff shortage and loss of inspection knowledge issues at INDOT by developing a risk-based and knowledge-based inspection system with answers to what, when, how, and how often to inspect. A comprehensive list of 333 testing and inspection activities was extracted from INDOT's material testing manual, INDOT's standard specification, and the QA implementation at the Ohio River Bridge (ORB) project. This list was compared to the neighboring states and national guidance documents. It was narrowed down to a core set of 126 items based on survey responses and interviews with INDOT domain experts and industrial partners. Testing and inspection activities in the core set were aligned with the construction process. The risk associated with each inspection activity was assessed by considering both the probability of failure and consequence severity of failure in four dimensions: cost, time, quality, and safety. A composite risk index was devised as a single measure for the overall risk. All inspection activities were prioritized based on the composite index, resulting in a total of 90 critical items that were identified as the riskiest areas. For implementation, a linking mechanism was developed to link inspection activity, pay item, and check items (extracted from specification). Such a design aligns with the business process of construction inspection at INDOT: starting with a pay item, field inspectors retrieve the associated check items and their inspection priority (based on risk), inspection frequency, and inspection criteria. A digital, ontology- and risk-based inspection system was proposed and its conceptual model was delivered to INDOT for its incorporation in the field application of construction documentation, a component of the e-Construction initiative at INDOT. It is being tested on Project R-30397 as a pilot study and is expected to reduce the workload of field inspectors.

7.2 Findings and Recommendations

Key findings have been summarized in the Executive Summary section and are repeated as follows.

- The materials testing manual explicitly regulates the sample size, sampling process, testing methods, and acceptance criteria for all materials. The standard specifications cover both materials and construction requirements, but do not provide explicit information on the frequency and methods of construction inspection. Many of the acceptance criteria are qualitative rather than quantitative, which requires the interpretation by construction inspectors. Consequently, the implementation varies among districts, projects, and individual inspectors.
- There is high similarity among the seven states regarding material testing and construction inspection requirements. The implementation of performance related specification (PRS) has not changed the requirements.
- Using the risk assessment framework, a total of 90 critical inspection items in earthwork, PCCP, HMA pavement and bridge decks were identified to be the riskiest areas. Each of them is aligned with the construction process with recommended inspection frequency and priority based on the risk.
- The ontology-based approach is effective in retaining and managing inspection knowledge and data.
- The specification sections and subsections can be used to connect risk-prioritized inspection activities, check items, and pay items so that dynamic inspection forms can be generated in real time on an as-needed basis, which aligns well with INDOT's business process.
- Manual extraction of check items from INDOT's specifications is time-consuming and error-prone. Inconsistencies among different sections have been noticed. The suggestion is to leverage natural language processing tools to automate this process.

The following are the recommendations.

- Apply the developed risk assessment framework to assess the risk of other construction inspection items/activities that are outside of the scope of this project (i.e., earthwork, HMA and PCCP, and bridge deck).
- Adopt the risk-based approach for construction inspection.
- Fully develop a risk-based and knowledge-based, digital inspection system based on the prototype and its testing in the pilot project.
- Develop tools through future research to automate the extraction of check items and the matching among pay items, check items, and inspection activities.

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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.

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