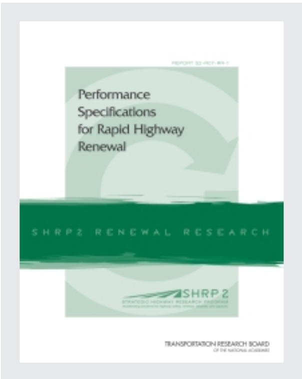

Performance Specifications for Rapid Highway Renewal

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The Second
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SHRP 2 REPORT S2-R07-RR-1

Performance Specifications for Rapid Highway Renewal

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The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

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Notice

The project that is the subject of this report was a part of the second Strategic Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical committee selected to monitor this project and review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical committee and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

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SHRP 2 STAFF

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The work was performed under a prime contract managed by Trauner Consulting Services, Inc., in association with Hill International, Inc., and TDC Partners, Ltd. Sidney Scott III (Hill) served as the co-principal investigator, supported by Linda Konrath (Hill) as project manager and Ted Ferragut (TDC) as co-principal investigator. Additional members of the research team included

- Stuart Anderson, Ivan Damnjanovic, Ali Nejat, and Meena Nagreeb of Texas A&M University;
- Gerald Huber of the Heritage Research Group;
- Jim Katsafanas of Michael Baker Jr., Inc.;
- Kevin McGhee, Michael Sprinkel, Celik Ozyildirim, and Brian Diefenderfer of the Virginia Center for Transportation Innovation and Research;
- David Merritt and Dan Dawood of the Transtec Group;
- Keith Molenaar and Shekhar Patil of the University of Colorado at Boulder;
- Michael C. Loulakis of Capital Project Strategies, LLC;
- Vernon R. Schaeffer and Alekhya K. Kondalamahanthy of Iowa State University; and
- David White and Thomas Cackler of Iowa State University.

The team is also indebted to all those from AASHTO, FHWA, industry, and academia who gave their time to participate in workshops and meetings to share their expertise, vet the performance specifications and implementation guidelines, and help advance the demonstration projects. A listing of those individuals is provided in Appendix A.

FOREWORD

James W. Bryant, Jr., PhD, PE, *SHRP 2 Senior Program Officer, Renewal*

The majority of specifications used by state departments of transportation (DOTs) attempt to describe how a construction contractor should conduct certain operations using minimum standards of equipment and materials. These prescriptive specifications, commonly known as method specifications, have generally worked well in the past. However, with changes in the technology and the emphasis on providing more rapid solutions, more innovative specifications may be required in the future. Performance specifications can be used as a communication tool that translates the owner's performance requirements into language that will allow the contracting industry to understand, plan, and build the project to meet the requirements.

Over the past decades many transportation agencies have experienced workforce reductions, thus diminishing the level of experience and number of engineers and inspectors. These demands have caused some agencies to experiment with the use of performance specifications in an effort to meet both the initial quality and long-term durability needs of the constructed products. Performance specifications have been used successfully on a project-by-project basis, but a general framework is needed to help agencies use performance specifications systematically.

This report and the associated materials provide a framework that state DOTs can use to develop performance specifications; they include sample specifications language and implementation guidelines for both managers and specification writers.

The objective of this project was to develop performance specifications and strategies to accelerate construction, minimize disruption to traffic and community, and produce long-life facilities in the interest of rapid renewal. The final report documents the methodology used to create the products that were developed as part of the project. The products of the research include (1) guide performance specifications for different application areas and contracting mechanisms, which agencies can tailor to address project-specific requirements; (2) an implementation guide for executives and decision makers, which presents a broad overview of the benefits and challenges associated with implementing performance specifications; and (3) a guide for specification writers, which provides a step-by-step "how-to" guide for developing performance specifications and using the model performance specifications that were developed as part of this project.

The report, supporting guidelines, and model guide specifications will be useful to state DOTs, municipal agencies, consultants, and construction contractors. These products provide a starting point for an agency that wants to investigate the use of performance specifications as part of its routine operations.

CONTENTS

Abstract

This report documents the results of the SHRP 2 R07 project to develop and implement performance specifications for rapid highway renewal. The project adopted a broad definition of performance specifications to address not only the performance of the physical products of construction (including pavements, bridges, and earthwork) but also contractor performance in terms of time, safety, work zone traffic control, and other important project parameters. Performance specifications were considered in the context of different project delivery methods—including design-bid-build and design-build—and other innovative contracting variations involving warranties or maintenance and operation agreements. The products of the research include guide performance specifications for different application areas and delivery methods that users may tailor to address project-specific goals and conditions. Implementation guidelines were also prepared to accompany the guide specifications. To validate these materials, demonstration projects were conducted for geotechnical and bridge deck applications. The findings of the study generally support the use of performance specifications as a viable option for agencies interested in empowering the private sector to provide creative solutions to save time, minimize disruption, and enhance durability in the interest of rapid renewal.

Executive Summary

Project Background

The conventional approach to highway construction places the burden on owners to design, specify, and control the work. Contractors are hired on the basis of lowest price with the expectation that they will execute the work in accordance with the prescriptive requirements provided in the plans and specifications.

Given societal changes and economic conditions, this traditional approach may no longer be sufficient to keep pace with the growing demands placed on our national highway system to move people and goods safely and efficiently. Recent infrastructure report cards indicate that the system is deteriorating and facing increasing congestion. At the same time, agencies are facing shrinking budgets and dramatic reductions in both the numbers and experience levels of inspectors and engineers. The complexity of high-speed construction, nighttime construction, and rehabilitation work amid traffic—all of which the public demands—further stretches available agency resources.

In response to this widening gap between investment needs and available resources, transportation agencies have begun experimenting with alternative specifications and contracting strategies that place more responsibility for performance on the private sector. The traditional way of doing business—using prescriptive requirements that tell the contractor how to perform the work—does not motivate the contractor to provide more than the prescribed minimum. The addition of performance specifications to an agency's toolbox would provide the means to motivate and empower contractors to find creative solutions to save time, minimize disruption, and enhance safety and quality in the interest of rapid renewal.

Within the Renewal focus area of the second Strategic Highway Research Program (SHRP 2), the R07 project was tasked with the development and implementation of performance specifications for rapid highway renewal. The project adopted a broad definition of performance specifications to address not only the performance of the physical products of construction (including pavements, bridges, and earthwork) but also contractor performance in terms of time, safety, work zone traffic control, and other important project parameters. Performance specifications were considered in the context of different project delivery methods—including design-bid-build and design-build—and other innovative contracting variations involving warranties or maintenance and operation agreements.

Research Objectives

The stated objectives for this research project included the development of performance specifications and strategies to accelerate construction, minimize disruption to traffic and community, and produce long-life facilities in the interest of rapid renewal. Performance specifications can advance those objectives by reducing mandatory method requirements and defining end-product performance parameters that relate more directly to long-term performance. The project entailed developing a suite of performance specifications for use in various highway project types and contracting scenarios. In addition, implementation guidance was written to address project selection, specification development, risk allocation, and the transition from method to performance specifications.

Approach and Findings

A review of the state of the practice of performance specifying in the highway construction industry suggested that performance specifications can be viewed at either the product level (i.e., more prescriptively) or at a very high level (i.e., in terms of safety, worker satisfaction, innovation, and other project goals). The choice depends on the project's scope and objectives, as well as the project delivery approach and risk allocation strategy. European highway agencies have developed and used performance specifications for longer and to a greater extent than their U.S. counterparts. Lessons learned from the European models suggest that successful implementation of performance specifications requires changing the business model to promote collaboration, early contractor involvement, and integrated services (Cox et al. 2002; Egan 1998; Scott and Konrath 2007).

The team established a step-by-step process for developing performance specifications, filtering existing performance specifications through the criteria established in the specification development framework to identify viable performance parameters and measurement strategies. Any existing performance measures that met the framework criteria were considered promising and formed the basis for initial brainstorming sessions conducted among the team's internal experts. Those existing measures, coupled with the team's own project experience, led to the development of draft performance requirements. In turn, those requirements were discussed and vetted with external representatives from the American Association of State Highway and Transportation Officials (AASHTO), industry, and academia in formal workshop settings.

While critical to a project's success, a well-drafted performance specification will not in itself ensure that an agency's performance goals will be met. Cultural, organizational, and legal issues can also affect the successful implementation of performance specifications. For this reason, the team prepared implementation guidelines to accompany the guide specifications. In doing so, the team reviewed the existing literature, had discussions with practitioners from agencies and industry, and identified lessons learned from demonstration projects to address the following points:

- How the decision to use performance specifications could affect an agency's traditional project delivery phases, from project planning and preliminary engineering through construction completion and possibly beyond to maintenance and asset management;
- Any natural progression or transition from more traditional contracts and specifications that should precede the decision to use performance specifications (i.e., a learning curve to attune both the agency and industry to a new business model); and
- General mechanics of administering performance contracts (e.g., the procurement process and document and database management).

The team also assessed the potential value of using performance specifications to promote innovation, reduce inspection costs, enhance quality, and accelerate construction. The assessment generally supported the conclusion that using performance specifications will add value to a project. However, the value added is contingent on project objectives, project type and characteristics, degree of flexibility extended to the contractor to meet performance objectives, and the type of project delivery system used. These considerations were incorporated into a project selection process included in the implementation guidelines.

Two demonstration projects were undertaken with the Missouri Department of Transportation (Missouri DOT) and the Virginia Department of Transportation (Virginia DOT) to implement performance specifications for pavement foundations and bridge decks, respectively. The team also advised the Louisiana Transportation Research Council (LTRC) on the development of geotechnical and pavement performance specifications and data collection for an ongoing Louisiana Department of Transportation and Development (Louisiana DOTD) US-90 Frontage Roads demonstration project. Important lessons learned from these demonstrations were incorporated into both the implementation guidelines and the guide specifications, as applicable, to provide agencies with the tools needed to develop and successfully implement performance specifications.

Research Products

The R07 team developed guide performance specifications and associated implementation guidelines to help support the application of performance specifications across a wide range of work and projects.

Performance Specifications

To help agencies develop and implement performance specifications, the team drafted a set of AASHTO-formatted guide specifications to be used by engineers and specifiers as a template for developing project-specific performance specifications for various topic areas. Performance specifications were developed in the areas of hot-mix asphalt (HMA) and portland cement concrete (PCC) pavement, concrete bridge decks, geotechnical application areas, work zone traffic control, and quality management.

The specifications include commentary to help specifiers select performance parameters and performance measurement strategies (test methods, sampling plans, target values, pay adjustment mechanisms) that best align with the project's goals and the capabilities of the agency and local industry. The specifications emphasize the use—to the extent possible—of new and emerging nondestructive testing (NDT) techniques that facilitate rapid renewal and performance parameters that validate mechanistic models of design.

As applicable, the team tailored the guide specifications to specific delivery approaches (design-bid-build, design-build, warranty, and design-build-operate-maintain). The chosen approach can significantly affect how much performance risk can be placed on the private sector. Thus the team factored in both possible changes to traditional roles and responsibilities with respect to design, quality management, and postconstruction maintenance, and the level at which performance parameters may be set.

If properly implemented, the guide specifications will provide agencies with a useful tool to motivate and empower the private sector to offer innovative solutions to save time, minimize disruption, and achieve long life in the interest of rapid renewal.

Implementation Guidelines

To accompany the guide specifications, the team also prepared a two-volume set of implementation guidelines.

Strategies for Implementing Performance Specifications: Guide for Executives and Project Managers provides a broad overview of the benefits and challenges associated with implementing performance specifications. It provides recommendations on project selection criteria, procurement and project delivery options, industry and legal considerations, and the various cultural and organizational changes needed to support the implementation of performance specifications.

Framework for Developing Performance Specifications: Guide for Specification Writers presents a flexible framework for assessing whether performance specifying is a viable option for a particular project or project element. If it is, this volume explains how performance specifications can be developed and used to achieve project-specific goals and satisfy user needs. In addition to providing a step-by-step “how to” guide for developing performance specifications, the document also contains guidance on application areas (e.g., pavements, bridge decks, earthworks, and work zones) found to have the greatest need or potential for performance specifying. Specifiers may use this volume alone or in conjunction with the guide specifications to develop and tailor project-specific performance specifications.

Recommendations for Future Activities and Implementation

The team has identified potential follow-on activities that would help move the products of this research effort into practice. These activities include demonstration projects, outreach and training, continued specification development, and automated tools for specification development.

Demonstration Projects

Demonstration projects are a proven tool for validating and fine-tuning new procedures, specifications, or contracting practices resulting from research. According to the representatives of the various departments of transportation who participated in specification vetting workshops, significant opportunities remain for additional demonstrations of performance specifications.

Performance specifications could be further validated by conducting long-term postconstruction performance monitoring to assess the relative value of performance specifications. Demonstration of the long-term performance outcomes for warranty and maintenance specifications that include postconstruction performance requirements would be particularly useful. Suitable project types for this scenario would likely involve pavement applications but could also include bridge or structural elements with long-term performance evaluations (i.e., health monitoring).

Outreach and Training

Before initiating the SHRP 2 R07 project, FHWA sponsored an expert technical group (ETG) with representatives from AASHTO, industry, and academia to provide guidance and outreach for the continued development of performance specifications, with particular focus on performance–related specifications (PRS) for rigid and flexible pavements. The research team sees a need to reestablish a performance specification ETG to provide continued support, training, and guidance for implementation of the performance specifications developed under the R07 project and to identify additional performance specifications to test and implement. The ETG’s activities could potentially include assisting with the adoption of selected performance specifications as AASHTO guide specifications or test methods through additional vetting and discussions with AASHTO subcommittees. The ETG could also sponsor training (webinars and presentations), build the business case, and provide institutional support within AASHTO agencies for the use of performance specifications. It could also address industry concerns related to risk allocation, insurance and bonding, and subcontractor relationships.

Continued Specification Development

Continued performance specification development would be beneficial for products not addressed by the R07 research. For pavements, advancement is needed in the areas of NDT methods and acceptance criteria that more directly relate to performance (e.g., mechanistic-based properties). Additional testing and demonstrations of PRS are under way for pavements (i.e., FHWA-sponsored demonstrations using PaveSpec for PCC and predictive models for HMA). For bridges, performance specifications can be developed for structural elements (e.g., piers, beams, or whole bridge performance); and performance criteria are needed for field acceptance of modular bridge components or innovative bridge technology (e.g., fiber-reinforced polymer composite bridges). Lastly, health monitoring of long-term bridge performance needs further development to address data management and evaluation standards.

Geotechnical performance specifications for ground improvement and pavement foundations need further development to establish testing and acceptance criteria based on mechanistic properties such as stiffness. For work zone traffic control, further development is needed in the areas of performance-monitoring technology, standardization of methods to calculate incentives and disincentives, data management, and independent verification. Lastly, performance specifications can be developed for additional highway construction elements (e.g., lighting, signals, signage, pavement markings, guardrails, and landscaping).

A Web-Based Specification Development Tool

Consistent with current agency trends toward developing and maintaining web-based specifications, an automated tool could help specification writers develop performance specifications for particular applications. The tool could be database driven with standard language and templates for different types of product specifications. The tool could guide the specification writer through steps or decision points with various options to consider depending on the project scope and characteristics. The level of effort needed to develop such a tool would depend in part on the product areas and types of performance specifications to be considered. One possible approach would be to develop the tool incrementally, focusing on a specific product area (e.g., pavements) and developing a beta version for testing. The beta version should be compatible or work in conjunction with other web-based specification development tools, for example, SpecRisk Quality Assurance Specification Development and PaveSpec software tools.

CHAPTER 1

Introduction

Background

Transportation agencies are under increasing pressure to improve mobility while maintaining existing facilities with limited resources. In response to this pressure, agencies have begun experimenting with ways to accelerate construction and minimize disruption to existing users while improving mobility, safety, and long-term performance. To help advance such initiatives, Congress established the second Strategic Highway Research Program (SHRP 2) in 2006 to pursue research in four focus areas: Safety, Reliability, Renewal, and Capacity.

The Renewal area looks at improving the aging and increasingly congested infrastructure through design and construction methods that accelerate construction, cause minimal disruption to road users and the community, and produce long-lasting facilities. Traditional method specifications may act as a barrier to the innovation often needed to achieve those objectives. Thus, SHRP 2 Project R07 was tasked with developing performance specifications that could motivate and empower the contracting industry to provide creative solutions to save time, minimize disruption, and enhance durability in the interest of rapid renewal.

What Are Performance Specifications?

As used in this document, the expression *performance specifications* serves as an umbrella term, broadly encompassing various nontraditional specification types used or proposed for use in the highway construction industry. They include end-result specifications, quality assurance (QA) specifications, performance-related specifications (PRS), performance-based specifications (PBS), and warranty and long-term maintenance provisions. (For more detail on these different specification types, refer to the definitions provided in Appendix B.)

In general, these specification types represent a progression toward increased use of higher-level acceptance parameters that are more indicative of how the finished product will perform over time. To varying degrees, they attempt to shift more performance risk to the contractor in exchange for limiting prescriptive requirements related to the selection of materials, techniques, and procedures. By relaxing such requirements, performance specifications have the potential to foster contractor innovation and thereby improve the quality or economy, or both, of the end product.

Figure 1.1 places these specification types along a continuum of increasing contractor responsibility for performance. At one end of the continuum are the traditional method specifications through which the agency retains primary responsibility for end-product performance. Moving along the continuum, performance specifications that allow for quality price adjustments based on end-result testing or predictive models begin to shift performance risk to the contractor. At the other end of the continuum, postconstruction performance provisions are designed to monitor and hold the contractor accountable for actual performance over time.

Rationale for Using Performance Specifications

While the motivation for using performance specifications will likely vary from agency to agency and from project to project, the literature suggests that implementing performance specifications has the potential to improve quality and long-term durability, encourage innovation, accelerate construction, and reduce an owner's quality assurance burden during construction (particularly if the contractor has postconstruction responsibilities).

Such objectives (whether set internally by the agency or externally, as in a legislative mandate) will influence both the development and the use of performance specifications.

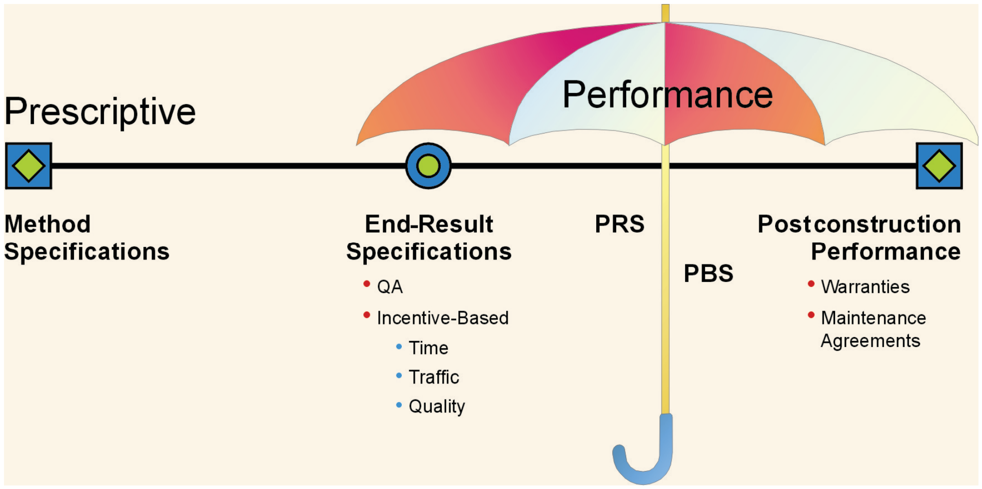

Figure 1.1. Continuum of highway specifications.

Understanding the basic rationale for using performance specifications is therefore an important first step toward ensuring successful implementation. Once identified, these objectives must be prioritized and then communicated, understood, and accepted by all parties involved. In addition to agency personnel, the parties may include the public, legislators, industry, and sureties.

Deciding Between Method and Performance Specifications

As summarized in Tables 1.1 and 1.2, both performance and method specifications hold unique advantages and disadvantages. Those differences should be carefully weighed when considering how best to specify requirements for a particular project or project element.

The likelihood of realizing the advantages of each specification type tends to correlate with project complexity. Performance specifications are typically most advantageous when the nature of the project provides ample opportunity for the industry to innovate and influence performance outcomes. That is often the case on complex projects involving major reconstruction or new capacity, multiphased work zone management, major or nonstandard structures, and high traffic volumes requiring accelerated design and construction.

In contrast, unless the agency allows significant latitude with regard to the selection of alternative designs, materials, or construction methods, noncomplex projects (e.g., those involving minor resurfacing or restoration of the pavement surface, or the use of standard structural components to match existing facilities) tend to be less than ideal candidates for performance specifications. When more latitude is allowed, even minor resurfacing projects can benefit from the use of performance specifications. For example, a specification based on mechanistic testing and models (e.g., S-VECD) can provide an indication of the expected long-term performance of a mix design, allowing the agency (or the contractor) to tweak the design to improve its expected performance.

Table 1.1. Advantages and Disadvantages of Performance Specifications

Advantages	Disadvantages
• Performance specifications promote contractor innovation. • The contractor assumes more performance risk. • Contractors have the flexibility to select materials, techniques, and procedures to improve the quality or economy, or both, of the end product. • A performance specification can provide a more rational mechanism for adjusting payment based on the quality or performance of the as-constructed facility.	• The agency can exert less control over the work. • Opportunities for smaller, local construction firms may be reduced. • It can be challenging to identify all of the parameters critical to performance and establish related thresholds. • Roles and responsibilities of the contractor and agency can become blurred if not adequately defined in the specifications or contract documents. • Staff may be reluctant to assume new responsibilities.

Source: FHWA 2010.

Table 1.2. Advantages and Disadvantages of Method Specifications

Advantages	Disadvantages
• Method specifications are well established, easily understood, and applicable to a wide range of topic areas. • Agency can exert significant control over the work (however, this may come at the expense of increased agency inspection efforts). • Requirements are based on materials and methods that have worked in the past, minimizing risk associated with newer or less proven methods or varying contractor performance.	• The contractor has little opportunity to deviate from the specifications and, provided that the specifications are met, is not responsible for performance deficiencies of the end product (i.e., the agency retains performance risk). • Method specifications lack built-in incentives for contractors to provide enhanced performance (e.g., cost, time, quality, etc.). • The prescribed procedures may prevent or discourage the contractor from using the most cost-effective or innovative procedures and equipment to perform the work. • Contractor payment is not tied to the performance or quality of the work. • Acceptance decisions based on test results of individual field samples can increase the potential for disputes.

Source: FHWA 2010.

Research Products

As an outgrowth of its research efforts, the R07 team developed guide specifications and associated implementation guidelines to support the application of performance specifications across a wide range of work and projects.

Guide Specifications

To help agencies with the specification development process, the team prepared a set of guide performance specifications that specifiers may use as a template from which to develop project-specific performance requirements. These guide specifications provide comprehensive examples of performance specifications for different project elements and delivery methods (design-bid-build, design-build, warranty, design-build-operate-maintain). Given the difficulty of anticipating every rapid renewal need, the guide specifications are limited to the application areas that demonstrated either the greatest need or the potential for performance specifying:

- Asphalt pavement;
- Concrete pavement (cast-in-place and precast);
- Concrete bridge deck; and
- Work zone traffic management.

As provided in Appendix C, specifications were also developed to advance the use of intelligent compaction techniques for acceptance of embankment/pavement foundations. These specifications are not ready for immediate implementation on a construction project because of training needs and limitations in technology, data analysis software, and endorsed test methods and standards. Nevertheless, they present an approach for establishing target values for acceptance on the basis of engineering parameters that relate to design assumptions.

Commentary has been built into the specifications to help specifiers select performance parameters and performance measurement strategies (test methods, sampling plans, target values, pay adjustment mechanisms) that best align with the project's goals and the capabilities of the agency and local industry. The specifications emphasize the use—to the extent possible—of new and emerging nondestructive testing (NDT) techniques that facilitate rapid renewal and performance parameters that validate mechanistic models of design.

Implementation Guidelines

To accompany the guide specifications, the team also prepared a two-volume set of implementation guidelines. *Strategies for Implementing Performance Specifications: Guide for Executives and Project Managers* provides a broad overview of the benefits and challenges associated with implementing performance specifications. Recommendations in this executive guide address project selection criteria, procurement and project delivery options, industry and legal considerations, and the various cultural and organizational changes needed to support the implementation of performance specifications. The guidance is geared primarily to an audience of decision makers but is intended to be accessible to all members of a project team.

The second volume, *Framework for Developing Performance Specifications: Guide for Specification Writers*, is written to help specifiers tasked with preparing project-specific performance requirements. The specification writers guide presents a flexible framework for assessing whether performance specifying is a viable option for a particular project or project element. If it is, this volume explains how performance specifications can be developed and used to achieve project-specific goals and satisfy user needs. Specifiers may use this volume alone or in conjunction with the guide performance specifications to develop and tailor performance specifications to help achieve project goals.

Research Scope and Objectives

The specifications and implementation guidelines were designed to meet the following stated objectives of the R07 project:

- Reduce the completion time of renewal projects while maintaining or improving quality;
- Encourage further innovation by reducing mandatory method requirements and defining end-product performance;
- Develop different performance specifications for highway construction (pavements, bridges, work zone, etc.) with various contracting scenarios (design-bid-build, design-build, warranties, etc.);
- Develop recommendations on the transition to and use of performance specifications; and
- Address strategies to equitably manage and minimize risk to all parties.

A four-phase research effort was performed to develop products capable of meeting those objectives.

Phase I

Phase I entailed performing a comprehensive literature review to establish the current status of performance specifying in the highway construction industry. The primary resources included relevant reports from the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), and National Cooperative Highway Research Program (NCHRP), as well as additional reports and specifications from departments of transportation and industry. The team also focused on contracts and specifications from long-term performance-based maintenance and design-build-operate-maintain contracts from Canada, Europe, and Australia. Several of these international contracts represent a second- or third-generation attempt at performance specifying; thus they provided valuable insight into how performance requirements may evolve as technology advances and the local performance contracting industry matures.

Phase I also included an assessment of the various risks associated with performance specifications, such as a lack of understanding of long-term material behavior, limitations with performance prediction models, and gaps associated with measurement and testing technology. Effective allocation and management of these risks is a key component of the specification development process described in the specification writers guide.

Phase II

The ideas explored in Phase I were advanced further during Phase II. The team established quantitative performance measurement strategies specific to particular aspects of highway construction (e.g., pavements, bridges, geotechnical applications, and so on) in the context of various contract delivery and risk allocation approaches. In a related task, the team prepared detailed specification outlines that formed the foundation for the specification development work performed during Phase III.

As part of Phase II, the team also performed an assessment of the potential value of implementing performance specifications to promote innovation, reduce inspection costs, enhance quality, accelerate construction, and achieve similar performance goals. The potential benefits were then considered during a related task: to develop procedures for deciding whether to use performance or method specifications for a specific project or element of a project. These procedures were incorporated into the project selection process described in Chapter 5 of the executive guide.

Phase III

Building on the efforts of the prior phases, during Phase III the team established a step-by-step process for developing performance specifications:

1. Identify user and societal needs and goals.
2. Translate user needs and goals into functional performance parameters.
3. Consider contract delivery approach.
4. Determine the appropriate measurement strategy.
5. Structure incentive strategies and payment mechanisms.
6. Identify gaps (in parameters, measurement, testing, etc.).
7. Identify and evaluate risks related to performance requirements.
8. Draft specification language.

This framework was used to develop draft performance specifications for vetting or validation during Phase IV.

Phase IV

During Phase IV, the draft performance specifications were reviewed and vetted through a series of joint agency and industry forums. Additionally, two demonstration projects were conducted to evaluate the use of performance specifications for pavement foundations and bridge decks. Performance data were collected and results were compared with standard specification practices.

Report Organization

This final report documents the results of the R07 research effort. As summarized in this introductory chapter, the primary focus of the project was the development of guide performance specifications and associated implementation guidelines. Chapter 2 addresses the methodology by which the team developed these products.

Chapter 3 summarizes the current state of performance specifying in each research area, how the guide specifications attempt to advance the state of practice, and what additional developments would be necessary for the specifications to evolve further. Chapter 3 also documents the team's efforts to validate the performance specifications through vetting workshops and demonstration projects. Finally, Chapter 4 presents the key findings from this research study as well as recommendations for advancing the use of the research products.

CHAPTER 2

Research Methodology

Performance specifications emphasize desired outcomes and results, challenging owners and their industry partners to think in terms of user needs and to recognize that more than one solution may achieve the project objectives. Incorporating such concepts into a specification represents a distinct departure from today's build-to-print culture and demands a new approach to specification writing, contract administration, and construction execution.

To help advance this new approach, the R07 research team developed guide specifications and associated implementation guidelines to support the application of performance specifications across a wide range of work and projects. In preparing these documents, the team focused its research efforts on addressing the following fundamental questions:

- What are performance specifications?
- How are effective performance specifications developed and drafted?
- Why use performance specifications?
- What are the risks associated with using performance specifications?
- When should performance specifications be used instead of method specifications?
- Who is affected by the implementation of performance specifications and how are they affected?

What Are Performance Specifications?

Context drives how performance specifications are defined within the construction industry. For example, the U.S. Department of Defense (DoD) describes a performance specification as one that

> states requirements in terms of the required results and the criteria for verifying compliance, without specifically stating how the results are to be achieved. A performance specification describes the functional requirements for an item, its capabilities, the environment in which it must operate, and any interface, interoperability, or compatibility requirements. It does not present a preconceived solution to a requirement. (DoD 2009)

In addition to addressing end-product performance, as contemplated by the DoD definition, requirements for a highway construction project could conceivably extend to project-related performance in terms of work zone management, safety, and timely completion. Postconstruction and operational performance, as found in warranties and maintenance agreements, also could be included.

The first task for the research team was therefore to conduct a comprehensive literature review to establish what the term *performance specifications* encompasses when applied to the highway construction industry.

Literature Review

To provide focus to the literature review, the team first determined which elements of a rapid renewal project would benefit from the development and implementation of performance specifications. Bearing in mind the objectives of rapid renewal (i.e., accelerated construction, minimal disruption, and long-life facilities), the team identified both physical products of construction (bridges, earthwork and geotechnical systems, and asphalt and concrete pavements) and project-level requirements (work zone management, public relations, quality indexing, and time incentives) as areas for possible application of performance specifications.

To provide additional structure to the literature review, the team also established baseline definitions (presented in Appendix B) of specification types and contracting methods that would fall under the umbrella term performance specifications. As described in Chapter 1, performance specifications may be viewed in terms of a continuum. Categorizing specifications (e.g., as end-result specifications or PRS) helps identify the advancement of performance specifications in a particular topic area.

The literature review effort itself entailed collecting and reviewing reports, specifications, contract documents, and similar information to determine the status of performance specifying in each of the topic areas considered. The primary resources consulted included relevant FHWA, AASHTO, and NCHRP reports, as well as additional reports, contracts, and specifications from departments of transportation, industry, and international sources. Particular emphasis was placed on obtaining documents that addressed product performance measures, incentives, measurement and verification strategies, risk allocation techniques, legal and administrative issues, and other information relevant to the development and implementation of performance specifications.

Content Analysis

The collected literature was classified according to specification type (e.g., end-result, PRS, warranty, and so on), topic area (e.g., pavement, bridge, work zone management, and so on), and project delivery approach (e.g., design-bid-build, design-build, design-build-operate-maintain). Then it was screened for perceived applicability to subsequent specification development efforts on the basis of containing or suggesting the following:

- Progressive or creative performance parameters, measurement strategies, test methods (NDT or otherwise), or acceptance criteria appropriate to the rapid renewal environment;
- Techniques to transfer performance responsibility from the owner to the contractor;
- Actual or potential value of performance specifications; and
- Conditions appropriate for the use of performance specifications.

An annotated bibliography of documents is included in Appendix D. In addition, an index of existing performance specifications, collected as part of the literature review, is available at the R07 report web page (http://www.trb.org/main/blurbs/169107.aspx).

How Are Effective Performance Specifications Developed and Drafted?

Historically, efforts at performance specifying (particularly in the pavement area) focused on the development and use of complex predictive models to establish specification requirements. The research study undertaken for the R07 project adopted a more pragmatic approach that is amenable to, but not reliant on, the use of such models to define performance needs.

The step-by-step process balances user needs and project goals against available technology and industry's appetite for assuming performance risk, recognizing that such factors are often closely tied to the selected project delivery method. As illustrated by the suite of guide performance specifications prepared under this research study, the inherent flexibility of this approach makes it readily adaptable to different project elements and delivery methods.

The complete performance specification development process is presented in the specification writers guide, Chapter 2. Agencies are encouraged to use the implementation guidelines in conjunction with the guide specifications to tailor performance requirements to project-specific conditions. Alternatively, agencies may develop additional performance specifications for needs not addressed by the current set of guide specifications.

Specification Development Framework

The primary function of a specification, whether prescriptive or performance oriented, is to communicate a project's requirements and the criteria by which the owner will verify conformance with the requirements. In this respect, performance specifications are similar to conventional method specifications. Where they differ is the level at which performance must be defined. Figure 2.1—which was adapted from a model developed by the Netherlands Ministry of Transport, Public Works, and Water Management—illustrates the possible requirement levels for a hypothetical pavement project (van der Zwan 2003). Taken as a whole, the pyramid depicted in the figure is intended to represent the entirety of knowledge and experience related to pavement design and construction. Taking and evaluating each level individually, the specifier can create a specification that is entirely prescriptive (if based solely on the material and workmanship properties defined on the lowest levels) or one that is more performance oriented (if based on the user needs and functional requirements described on the higher levels).

For a particular project, the appropriate mix of performance requirements is driven by the project's scope and objectives as well as the chosen project delivery approach and risk allocation strategy. In practice, specifications typically include elements from several of the levels shown in Figure 2.1. Determining the appropriate balance between prescriptive and performance-oriented requirements is one of the main objectives of the eight-step specification development process illustrated Figure 2.2. Chapter 2 of the specification writers guide describes this specification development framework in detail, systematically leading a specifier through each step in the process. However, as suggested by a review of the guide

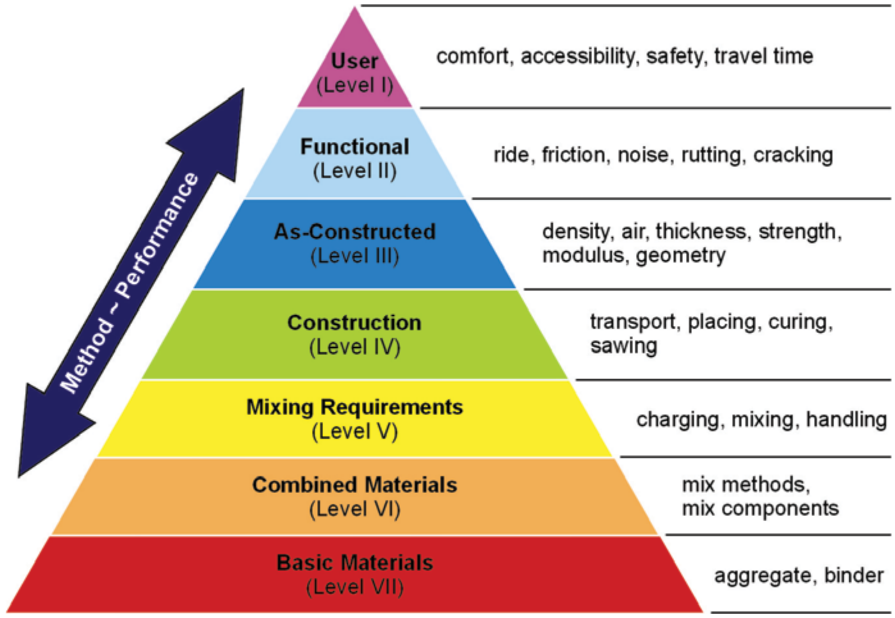

Figure 2.1. Pyramid of performance.

specifications themselves, some steps are more critical to certain topic areas than to others. For example, although project delivery approach (Step 3) plays a large role in shaping the development of a performance specification for pavements and bridges, it has less influence on establishing performance requirements for work zone management and geotechnical features.

Application of the Performance Specification Framework

To apply this framework to the main research areas of pavement, bridges, geotechnical systems, and work zone management, the team first reviewed a cross section of existing performance specifications obtained through the literature review effort. Coordination with other SHRP and FHWA research projects provided additional information on topic areas that complemented the R07 effort to develop performance specifications for rapid renewal. The relevant projects addressed the following topics:

- Advances in nondestructive testing techniques {e.g., SHRP 2 R06; FHWA Transportation Pooled Fund study [Project No. TPF-5(128)] on intelligent compaction};
- Innovative materials (e.g., SHRP 2 R19A); and
- Mechanistic-based performance prediction (e.g., FHWA research study DTFH61-08-H-00005).

The team carefully reviewed the collected literature, filtering existing performance specifications through the criteria established in the specification development framework to identify viable performance parameters and measurement strategies. Existing performance measures that met the framework criteria formed the basis for initial brainstorming sessions conducted among the team's internal experts. Those existing measures, coupled with the team's own project experience, led to the development of draft performance requirements which were then discussed and reviewed with external representatives from agencies and industry in formal workshop settings. The input from external experts was used to refine and finalize the guide specifications and associated commentary. Chapter 3 provides a more detailed summary of the findings from the literature review and outreach efforts in the context of the development of the guide specifications.

To develop specifications that would be suitable for adoption by AASHTO, to the extent possible, the team adhered to the principles set forth in the National Highway Institute (NHI) Course No. 134001, *Principles of Writing Highway Construction Specifications,* and the FHWA Technical Advisory, *Development and Review of Specifications* (FHWA 2010). Even so, the team recognized that the typical AASHTO five-part format (Description, Materials, Construction, Measurement, Payment) may not be appropriate for every project delivery approach. For example, the lump-sum nature of a design-build contract may make measurement and payment sections unnecessary, whereas a warranty provision would require additional requirements related to bonding, distress evaluations, and required remedial action during the warranty period.

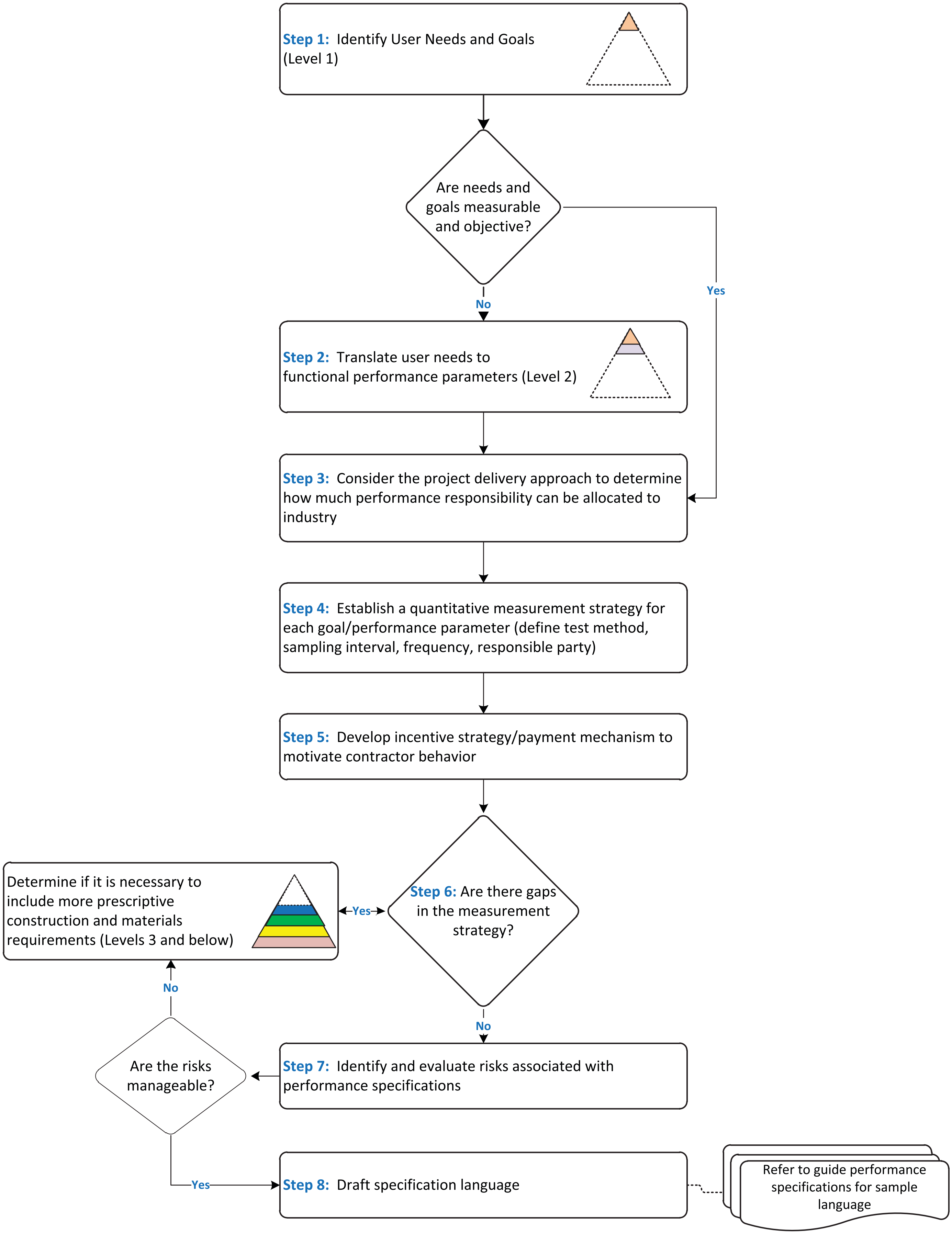

Figure 2.2. Performance specification development process.

Why Use Performance Specifications?

Successful implementation of performance specifications will likely require a departure from traditional project development and delivery processes. To gain support for necessary changes, best practice suggests first establishing a compelling business case as to why performance specifications represent a desired addition to an agency's contracting toolbox.

Literature Review

To establish the rationale for using performance specifications, the team first performed a literature review to document any prior efforts to identify the actual or potential value received through the use of performance-based, incentive-based, and performance warranty contracts and specifications in the highway construction industry.

Recognizing that performance specifications have not been widely applied to transportation projects in the United States, the team expanded its literature search to include research and practice from outside the highway industry. For example, the use of performance-based service contracts has become a standard business practice for some federal agencies, such as the Department of Defense (DoD), and the benefits of these contracts have been validated by research studies and best practice guides (OFPP 1998a; OFPP 1998b; DoD 2000). Although the benefits may not directly translate to the value added or lost by applying performance specifications to a highway construction project, they do provide general insight into the advantages of using performance contracting strategies.

Value Assessment

Research and practice, particularly from outside the highway industry, suggest that implementing performance specifications has the potential to provide several advantages, including decreased life-cycle costs, reduced inspection, and improved quality and customer satisfaction. However, the literature contains little data quantifying the actual value added or lost by implementing performance specifications.

Despite the lack of quantitative data, the literature does reflect the perception that using performance specifications or a performance contracting system will result in enhanced value (or performance) for highway agencies and road users. The literature also makes evident that these enhancements can be attributed, at least in part, to alternative project delivery systems that provide more flexibility and shift more responsibility to the private sector to achieve performance goals.

Comparative Framework

The team felt it was necessary to develop a comparative structure to assess performance specifications against a benchmark. That comparison would allow consideration of how project delivery approaches could affect the actual or potential value received from implementing performance specifications.

On the basis of the literature review and consultation with subject matter experts, the team generated a list of viable delivery schemes for performance specifications. The results of that effort led the team to use the following delivery methods as the basis for assessing the perceived value of performance specifications:

- Prescriptive (method) specifications (benchmark);
- Design-bid-build, with some performance requirements, but no warranty (DBB+P);
- Design-bid-build, with short-term warranty (DBB+STW);
- Design-build, with no warranty (DB);
- Design-build, with short-term warranty (DB+STW); and
- Design-build-maintain (DBM).

Recognizing that project conditions could also affect the value received from performance specifications, the comparative framework considered the impact of different project characteristics such as the following:

- Road class (local, state highway, interstate, toll);
- Type of construction (preservation, reconstruction, new construction);
- Traffic [low, moderate, or high annual average daily traffic (AADT)];
- Location (urban, rural);
- Complexity (depending on project phasing, right-of-way requirements, utilities, environmental issues, etc.); and
- Climate (depending on moisture and temperature, by region).

In the context of these delivery approaches and project characteristics, the team turned to expert participation in surveys and workshops to assess the perceived value of using performance specifications. Such nonexperimental research techniques were found to be applicable given the nature of the study. Factors such as delivery methods and project characteristics can be shown to affect the perceived value placed on the implementation of performance specifications on highway construction projects. However, the effect or extent of the relationship cannot be determined with precision, as any one of the other factors can lead to the same or a similar effect. Therefore, the team relied on nonexperimental techniques, including surveys and documentation of experts' comments elicited in a workshop setting, as means for data collection.

Delphi Analysis

Although the survey method is a detailed and systematic method of data collection, response rates can be poor and the participating experts can leave out vital information. To bolster this technique, the team applied the Delphi method.

The Delphi method is an adaptation of the survey method and is used to obtain the judgment of a panel of experts on a complex issue or topic. It is a systematic method of data collection and structured discussion that aims to minimize the effects of bias given the characteristic lack of anonymity in interviews and general surveys. The method is particularly useful in situations in which empirical means are not suitable and research results rely heavily on the subjective opinions of experts.

In brief, a Delphi analysis entails an iterative process in which experts' opinions are processed and used as feedback for further refinement of opinions generated in earlier survey rounds. The iterative nature of the process is expected to yield more reliable results than a single survey round. The Delphi analysis required the team to (1) assemble the Delphi expert group; (2) develop and administer survey questions; (3) receive and process the survey responses; (4) conduct a structured workshop to present, discuss, and clarify the survey results; (5) conduct a second survey round assessment; (6) summarize the outcomes of the Round 2 assessment, and (7) conduct a Round 3 assessment and summarize results.

Appendix E provides a detailed summary of the design and results of this data collection effort. The Delphi survey results are provided in Appendix G.

Demonstration Projects

Perhaps the most powerful way to identify and communicate the potential benefits of performance specifications is through demonstration projects. The SHRP 2 R07 project therefore included an implementation phase designed to validate the guidelines and performance specifications developed during the research effort.

The first step toward this end was to identify candidate agencies that would be willing to participate in a demonstration project. A survey questionnaire was developed to gauge the interest and experience of a representative sample of highway agencies in the United States, particularly those known to have experience or interest in performance specifications or alternative project delivery methods. The survey included a brief description of the R07 project, including the project objectives and scope of the demonstration program.

The survey document further explained that the team was seeking to work with two or more transportation agencies in implementing performance specifications on demonstration projects to test and validate the use of performance specifications for rapid highway renewal projects. The R07 team offered to provide resources to work with agency personnel to select an appropriate project or projects, develop the necessary performance specifications and contracting provisions, and assist with the administration of the project during design and construction, and, if applicable, during the maintenance and operation phase.

Most important, the survey sought information as to (1) the likelihood that the agency would have projects suitable for a demonstration of performance specifications in the 2010–2011 construction seasons and (2) the areas for which the agency would be most interested in performance specifying.

Ten agencies returned questionnaires or sent e-mail responses indicating interest in participating in a SHRP 2 R07 demonstration project. From those responses, the team identified the following projects as viable candidates for demonstrations:

- Virginia DOT Route 208 Lake Anna Bridge Deck Rehabilitation Project—a shadow demonstration of the use of performance parameters that related more to long-term durability and performance;
- Missouri DOT Route 141 Roadway Improvement Project—a demonstration of the use of nondestructive roller-integrated compaction monitoring (RICM), or intelligent compaction, to provide real-time and improved quality control of soil compaction operations; and
- Louisiana DOTD U.S. Frontage Roads—a demonstration of the use of RICM and mechanistic-based in situ point measurements on a new pavement section.

A more detailed discussion of these demonstrations is provided in Chapter 3.

What Are the Risks Associated with Implementing Performance Specifications?

Risk in the context of performance specifications relates to the existence of any uncertain event or condition that, if it occurs, has a positive or negative effect on the objectives of the specification. The FHWA's *Guide to Risk Assessment and Allocation for Highway Construction Management* presents a continuous, cyclical approach to risk assessment, involving the following steps: identify, assess and analyze, mitigate and plan, allocate, and monitor and update (Ashley et al. 2006). A similar approach was used to address the risks associated with performance specifications.

As a key component of the specification development framework, the discussion of risk related to performance specifications (i.e., identification and evaluation of risks) is addressed in the specification writers guide. The entire process of developing a performance specification is in a sense a risk management exercise designed to identify, allocate, and mitigate the risks associated with implementing a performance specification.

The generally accepted approach to project-level risk management—as described in FHWA's *Guide to Risk Assessment* (Ashley et al. 2006) or the SHRP 2 R09 *Guide for the Process of Managing Risk on Rapid Renewal Projects* (Golder Associates et al. 2013)—is useful in developing a general framework for identifying risks; it is less useful in terms of analysis (e.g., quantifying the frequency and impacts of specification-related risks). In some cases the specification risks, such as gaps in performance measurement, are difficult to quantify given the current state of the practice (or level of understanding). For example, given the interest in the use of NDT and mechanistic properties for performance measurement, further research is needed to quantify the effects of risk related to variability or reliability of NDT versus traditional tests, or opportunities related to the use of mechanistic versus traditional performance measures. Additional long-term data collection will be needed to make valid quantitative risk assessments.

The risk process described in the specification writers guide is geared to identifying risks and gaps and qualitatively deciding whether performance specifications are appropriate. Further, the guide assists in determining how to develop a performance specification to allocate risk among the project participants considering the current state of the practice. Further assessment of performance specification risks are needed to quantify the impacts or opportunities related to their use.

When Should Performance Specifications Be Used?

Performance specifications are not ideal for every construction contract or project circumstance. However, they may hold significant advantages over traditional method specifications when certain criteria or conditions are met. To integrate performance specifications into an agency's contracting toolbox, a process is needed to evaluate when to use or not to use performance specifications.

The decision to use method or performance specifications is often a matter of degree (how much and at what level). Both approaches may be appropriate for specific elements within a project. In choosing the appropriate level of performance specifications, an organization's culture, statutory restrictions, project objectives and characteristics, project delivery approach, and risk appetite all may play important parts in defining specifications. The interaction among these key factors will likely determine the preference for one type of specification over the other.

The decision to use performance specifications versus method specifications can involve a relatively straightforward screening test, followed by a more in-depth analysis of the level and type of performance specifying appropriate for the project characteristics and contracting type. Thus, the implementation guidelines (see the executive guide, Chapter 5) present a two-part decision process for evaluating when to use or not to use performance specifications. Part 1 of this decision process considers a project's scope and goals. Part 2 addresses the project delivery considerations that could also affect the decision.

Who Is Affected by Performance Specifications and How Are They Affected?

For agency personnel, developing and implementing a scope of work in terms of user needs and end-result performance is often much more challenging and resource intensive than simply adhering to the agency's standard specifications. For contractors, an initial investment may be needed to acquire the necessary knowledge, skills, and equipment to assume more responsibility for performance.

While critical to a project's success, a well-drafted performance specification will not in and of itself ensure that an agency's performance goals will be met. Cultural, organizational, and legal issues can also affect the successful implementation of performance specifications. For this reason, the team prepared a set of implementation guidelines to accompany the guide specifications. In doing so, the team reviewed the existing literature, had discussions with practitioners from agencies and industry, and identified lessons learned from the demonstration projects. The goal was to address the following considerations:

- The effect the decision to use performance specifications could have on an agency's traditional project delivery phases, from project planning and preliminary engineering through to construction completion and possibly beyond to maintenance and asset management;
- Any natural progression or transition from more traditional contracts and specifications that should precede the decision to use performance specifications (i.e., a learning curve to attune both the agency and industry to a new business model); and the
- General mechanics of administering performance contracts (e.g., procurement process, document and database management, and so on).

This information, along with the key takeaways drawn from the other research tasks, was incorporated into both the implementation guidelines and the guide specifications, as applicable, to provide agencies with the tools needed to develop and successfully implement performance specifications.

CHAPTER 3

Findings

This chapter presents the general findings from the R07 research effort to develop and implement performance specifications. The discussions primarily focus on addressing the following points:

- How the performance specification framework introduced in Chapter 2 was applied to each of the research areas;
- What benefits and risks are associated with performance specifying; and
- What conditions or characteristics tend to make a project an ideal candidate for using performance specifications.

Performance Specifications

The performance specification framework introduced in Chapter 2 was applied to each of the research areas to produce guide performance specifications capable of promoting rapid renewal. For each research area, the team summarized the current state of performance specifying on the basis of a review of the literature as well as expert opinions obtained through workshops with representatives from agencies and industry. The summaries address how the guide specifications attempt to advance the state of the practice and what additional developments would be necessary for the specifications to evolve further. As applicable, the team addressed demonstration projects in the context of identifying lessons learned and opportunities for further advancement of the current guide specifications.

Notably, both the state of the practice and opportunities for further advancement are highly dependent on the subject matter. For example, application of performance specifications is more evolved and prevalent for pavements than for the other discipline areas considered in the research, such as bridges and geotechnical features.

Concrete Pavement

State of the Practice in Performance Specifications

Much of the research and debate related to performance specifying for concrete pavement has focused on the application of quality- or performance-related pay adjustment systems. As summarized here, two general approaches have emerged. One, as promoted in current quality assurance (QA) specifications, involves statistically based sampling and testing plans that consider the measured variability of the product to determine pay factors. The other entails the use of predictive models to assign more rational pay adjustments on the basis of the difference between the as-designed and as-constructed life-cycle cost (LCC) of the pavement.

Statistically Based Specifications. Statistically based acceptance plans and pay adjustment systems have been widely applied to concrete pavement construction. However, many of the properties emphasized in current specifications do not necessarily reflect performance. Properties related to concrete durability (e.g., air quality, permeability, unit weight, steel placement, thickness, and mix uniformity) can be more critical to pavement performance than strength, yet they are often excluded from acceptance plans.

Commonly used acceptance quality characteristics (AQC) include compressive strength, thickness, and smoothness. (Agencies concerned with freeze–thaw resistance also often use air content as a screening test before concrete placement but not as a pay factor.)

Agencies differ on the methods and weights used to combine pay factors, with most relying on experience and engineering judgment to establish a composite pay factor (CPF) equation. The following equation from NCHRP 10-79 synthesizes the various pay equations reportedly being used by departments of transportation across the country (Hughes et al. 2011):

$$CPF = 0.25(PF_{strength}) + 0.35(PF_{thickness}) + 0.40(PF_{smoothness})$$

Performance-Related Specifications. Much of the more performance-oriented research in the concrete pavement area has focused on the development of performance-related specifications (PRS) that use mathematical models to predict future performance on the basis of select quality characteristics measured at the end of construction. PRS are often referred to as the next generation of QA specifications, because they attempt to use predictive models to assign rational pay adjustments on the basis of the difference between the as-designed and as-constructed life-cycle cost of the pavement.

The basic premise behind PRS methodology is that lower or more variable quality levels will result in reduced pavement performance, requiring an agency to incur maintenance and rehabilitation expenditures sooner and more frequently than would otherwise be the case. By using bonuses or penalties to pass the expected consequences of particularly good or bad construction quality onto the contractor, a more rational acceptance and payment methodology can be achieved (Hoerner and Darter 1999a).

PRS have been fully implemented on select projects in Indiana, Florida, California, Tennessee, and Wisconsin (Hoerner and Darter 1999b; Evans et al. 2005; Rao et al. 2007; Evans et al. 2008). Other states, including Iowa, New Mexico, and Kansas, have demonstrated PRS as a "shadow" specification (that is, results did not affect contractor pay).

The PRS for these projects were developed using PaveSpec 3.0 software, which supports pay adjustments for the following AQCs (Hoerner et al. 2000a, 2000b):

- Concrete strength (either compressive or flexural, depending on normal agency practice);
- Slab thickness;
- Initial smoothness; and
- Entrained air content.

The software also allows use of Percent Consolidation Around Dowels as an acceptance parameter. However, it has not been used in any portland cement concrete (PCC) pavement PRS to date, presumably because of the difficulty of measuring that property in the field.

One important feature of the PaveSpec software is that it allows users to adjust calibration factors and coefficients to reflect the agency's actual experience. While this methodology and software provide a sound process for developing PRS, the software does have some limitations, including the following:

- The software considers only jointed plain concrete pavement (JPCP) and not continuously reinforced concrete pavement (CRCP) or jointed reinforced concrete pavement (JRCP).
- Performance prediction models consider only transverse joint faulting, transverse fatigue cracking, transverse spalling, and roughness progression/international roughness index (IRI).

Work is under way to finalize and pilot PaveSpec version 4.0 software, which will incorporate the latest *Mechanistic–Empirical Pavement Design Guide* (MEPDG) JPCP models and support a more comprehensive set of AQCs. However, some of the limitations seen with the current software will still remain:

- Pay factors are independent (i.e., interaction between AQCs is not explicitly considered in the simulation).
- Models do not address durability, longitudinal cracking, and other long-term distresses.

Ideally, PRS will evolve to incorporate all of the important AQCs of PCC pavement that not only affect performance but are also under the contractor's control. Incorporation of more robust mechanistic-empirical models, such as those developed for and used in mechanistic-empirical design procedures, may enhance the current PRS methodology. But it will not eliminate the challenge of how to tie design assumptions to actual field data and acceptance tests.

Achieving the ideal PRS will require advances in nondestructive sampling and testing and improved understanding of long-term material behavior. FHWA-RD-98-155 defines the various stages of PRS implementation as follows (Hoerner and Darter 1999a):

- Level 1 or "Simplified" PRS use standard agency monitoring and testing practices as much as possible. Independent pay factors are developed for each AQC and then combined manually through a composite pay factor equation. The PRS that have been implemented to date are considered Level 1 PRS.
- Level 2 or "Transitional" PRS seek to better quantify future performance by comparing as-designed and as-constructed LCCs. The Level 2 PRS encourage use of more in situ and nondestructive sampling and testing. The pay schedules developed under a Level 2 PRS consider the interaction of the various AQCs to directly compute a pay factor through computer simulation.
- Level 3 or "Ideal" PRS will consider as many AQCs as possible in the LCC evaluation and will use only nondestructive, in situ testing to measure those AQCs. Many issues need to be addressed before Level 3 PRS can be achieved, such as development of new test methods and identification of all critical AQCs.

Warranty Provisions. Moving beyond QA and PRS specifications, warranty provisions have also been applied to PCC pavements to address actual performance over time. One of the advantages of a warranty specification is the ability to cover certain types of distresses and functional characteristics that would be difficult to address using predictive models. For example, corner cracking, deterioration cracking or material-related distress, popouts, texture loss, scaling, and sealant damage or loss are some of the distresses commonly found in warranty provisions for PCC pavement. Warranties can also address certain functional characteristics that would be difficult to predict using mathematical models, such as texture or texture loss and skid resistance.

Warranties have not been as widely applied to PCC pavement as they have to hot-mix asphalt (HMA). Warranties can be successful in protecting against premature failure (i.e., ensuring that distresses resulting from materials and workmanship—such as plastic shrinkage cracking and surface deterioration or scaling—are corrected). But they do not serve as effective guarantees of long-term performance. Concrete pavements tend to fail in a nonlinear fashion, with deterioration occurring rapidly after some threshold point in the pavement life, which generally occurs well beyond the 5-year duration of most short-term warranties. To successfully ensure long-term performance, the warranty period would have to be long enough to allow indicators of long-term performance issues to appear within the warranty period such that future problems could be averted through corrective action. Unfortunately, difficulties in obtaining bonds have generally precluded long-term warranties.

Higher-level performance parameters directly addressing user needs (e.g., comfort, safety, accessibility, and so on) have primarily been implemented for pavements only under longer-term design-build-operate-maintain (DBOM) contracts. The more progressive of these specifications attempt to view the pavement and underlying soil layers as an integrated system, more akin to how the traveling public views a roadway. Such specifications promote a paradigm shift in how pavements are designed and constructed (e.g., by allowing developers to adjust their pavement design based on the as-constructed subgrade conditions).

Guide Specifications

Cast-in-Place Concrete Pavement. The R07 research team drafted a family of guide performance specifications for PCC pavement. The specifications were drafted with a specific delivery approach in mind; that is, the recommended performance parameters and materials and construction requirements included in each specification are tied to the roles and responsibilities and risk allocation deemed appropriate for a design-bid-build (DBB), design-build (DB), warranty, or design-build-operate-maintain (DBOM) project.

To advance the state of practice under the DBB and DB cases, the guide specifications attempt to incorporate quality management and acceptance criteria that more closely correlate to durability. The overall objective of these specifications is generally consistent with the statistically based acceptance procedures and pay factor adjustments found in current QA and PRS specifications. The specifications have therefore been structured to both complement existing practice when possible and highlight (through provided commentary) when a different approach may be necessary or beneficial to advance the goals of rapid renewal.

To promote rapid renewal, the guide specifications

- Emphasize properties known to affect durability, such as air quality, permeability, unit weight, steel placement, joint conditions, thickness uniformity, and mix uniformity;
- Recommend test methods that are more conducive to rapid renewal, such as maturity meters and thickness probes;
- Encourage contractors to use tools, such as HIPERPAV (HIgh PERformance concrete PAVing) software, stringless paving, and real-time smoothness devices, to improve workmanship process control;
- Promote the use of NDT devices, such as ground penetrating radar and magnetic imaging tomography, which reduce the need for destructive core samples; and
- Incorporate financial incentives/disincentives to promote enhanced quality or durability.

Even with recent advancements in mechanistic-empirical design procedures and nondestructive evaluation (NDE) methods, current gaps in knowledge and modeling and testing techniques suggest that, in the near term, performance specifications implemented under DBB or DB will likely retain some prescriptive elements or surrogate properties to ensure equitable risk allocation between the agency and the contractor.

More freedom can be extended to the contractor under warranty and maintenance provisions containing functional performance parameters that monitor and evaluate the actual performance of the pavement over time. However, organizational and industry-related issues may make it difficult for an agency to immediately assign postconstruction responsibilities to industry. Additional training, guidance, and mentoring will likely be needed before responsibility and control of performance can be shifted from agency to industry staff. On the one hand, this may involve retraining agency staff to "step back," not prescribe how to perform the work, and adopt more of an oversight role to ensure that performance targets are met. On the other hand, industry may need to invest in the tools and training to take on greater responsibility for the entire project life cycle, including design, construction, and long-term performance. The executive guide addresses organizational and industry considerations related to implementing performance specifications.

Recognizing such technological and business-related challenges to the advancement of performance specifications, the guide specifications incorporate a tiered implementation approach. This approach balances a project's needs and goals against available technology and resources, the capabilities of local industry (including materials suppliers and testing firms), associated costs, and industry's appetite for assuming performance risk. The tiers generally represent a progression from minimal departure from current practice to a substantial shift in practice and organizational culture. The latter would require technological advancement, improved understanding of long-term material behavior, and possibly a new business model.

- **Tier 1** requirements do not require a substantial departure from current practice, yet they place more emphasis on properties known to affect performance (e.g., air content) and encourage the use of NDT techniques (e.g., maturity meters and thickness probes) as a rapid renewal consideration.
- **Tier 2** requirements incorporate more performance-oriented parameters (e.g., permeability and air quality), for which test methods may be currently available but which would require further advancement or refinement to provide the repeatability and accuracy needed for acceptance purposes.

  To implement other Tier 2 requirements, contractors may need to make some investment to acquire the necessary knowledge, skills, and equipment to fulfill their obligations under a performance specification without passing on excessive risk pricing to the agency. For example, if noise reduction is an agency goal, a functional parameter could be developed based on the noise generated from pavement-tire interaction, as measured using onboard sound intensity (OBSI) techniques. However, until industry gains sufficient understanding of how to modify its standard means and methods to meet a certain decibel level, simply using a prescriptive texturing specification to accomplish the same objective may be more cost-effective.
- **Tier 3** requirements assume improved understanding of long-term material behavior as well as advances in technology, particularly in the area of NDT technology. Such advances could permit the inclusion of acceptance parameters that better reflect the future performance and design life of the pavement.

Figure 3.1 summarizes the three tiers and the motivations for implementing each. Although the figure suggests a time frame for implementation, to some extent, this will be agency specific. For example, warranty provisions and long-term DBOM agreements may fall into the Tier 2 and Tier 3 categories, respectively, among agencies that first have to foster the necessary internal and external support for assigning such postconstruction requirements to industry. Some agencies, however, have already implemented such specifications and can provide a roadmap for agencies interested in pursuing a similar program.

Tables 3.1 through 3.3 summarize the suggested performance specification strategy for each of the tiers. To help determine the appropriate tier, users should consider what would best fit the needs of their particular project or program, bearing in mind that possible barriers or gaps may preclude the immediate implementation of all of the proposed parameters and test methods. For example, some agencies may have difficulty implementing even an "immediately implementable" Tier 1 parameter if they lack the historical data needed to assign reasonable thresholds and targets. An effort to document or showcase the experience of agencies that are already using Tier 1 parameters would further promote implementation.

Precast Concrete Pavement. Modular pavement technology is a relatively new method for pavement construction. However, with the implementation of precast concrete pavements (PCP) in dozens of states and for hundreds of lane-miles of pavement, it is now recognized as a mature and no-longer-experimental technology. Although typically more costly than cast-in-place pavement, precast systems offer a viable solution for rapid renewal that can be deployed during short lane closures, minimizing disruption to the traveling public.

To help increase the comfort level with modular pavement technology, the R07 team prepared a guide performance specification focusing on PCP. It highlights the requirements that have been determined to be most critical for the successful use of this technology. Much of the specification content was developed under the SHRP 2 R05 project, which specifically focused on development of modular pavement guidance and specifications for rapid renewal (Tayabji et al. 2012). Although the guide specification focuses on precast systems, it can also serve as a template for specifying other modular systems addressed by the R05 project, such as rollable asphalt.

The R07 team tailored the R05 recommendations to a performance specification framework. The result was a specification that promotes competition among different precast systems and incorporates many of the functional performance parameters, such as ride quality, that are important to road users and are commonly applied to conventional concrete pavements.

A key component of the guide specification, described in greater detail in the R05 effort, is the system approval and trial installation process (Tayabji et al. 2012). A number of proprietary PCP systems are currently available and proven for PCP construction. These systems typically use patent-protected components and details for fabrication and installation of the precast panels. While such systems should not be precluded from use, agencies are typically unable to specify a sole-source proprietary product for use on a project unless no other comparable alternatives are available. Similar to a

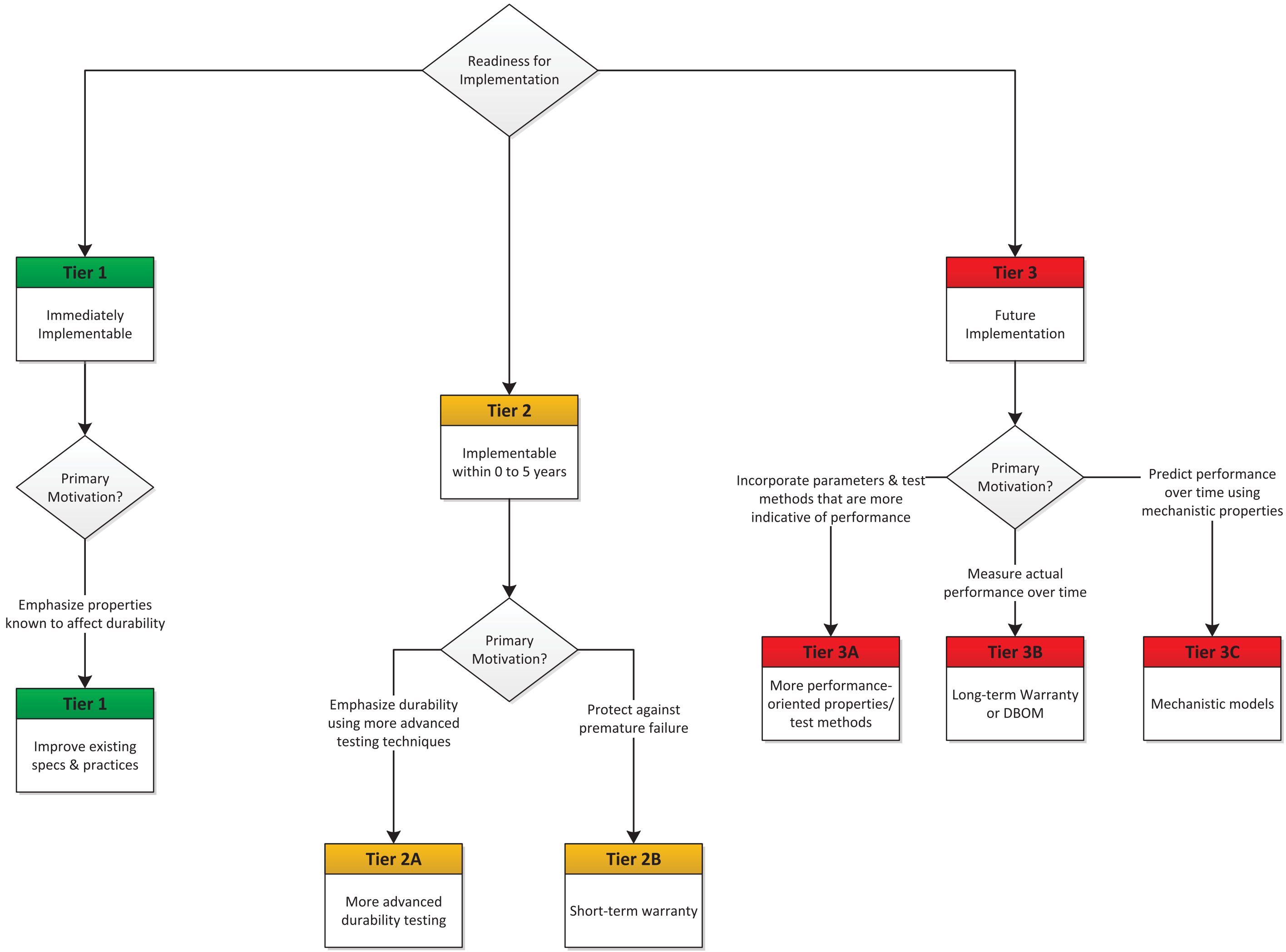

Figure 3.1. Implementation tiers for PCC pavement.

Table 3.1. PCC Pavement, Tier 1 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 1	**Existing Specs and Practices** • Place more emphasis on properties known to affect durability. • Use test methods that are more conducive to rapid renewal.	**Quality Control** *Fresh Concrete:* • Unit weight • Slump • Air content (by pressure test) • Placement temperature • Evaporation rate • Thickness (by probing) *Hardened Concrete:* • Strength (by maturity)	**Construction Acceptance** • Surface distress • Thickness (by probing) • Strength (by maturity method) • Hardened air content • Ride quality • Joint deficiencies (visual) *If using the existing PRS model as a basis for rational payment adjustments, PaveSpec 3.0 simulation software supports pay adjustments for the following quality characteristics:* • Strength • Thickness • Initial smoothness • Entrained air content • Percent consolidation around dowels	• Some additional funds for testing will be needed. *If using the existing PRS model as a basis for rational payment adjustments, additional issues may include the following:* • DOT and industry acceptance of predictive model will be needed. • A database of local measurement values needs to be developed. • Not all factors that could affect performance are considered in the existing PRS simulation software (PaveSpec 3.0).	• Measure unit weight as part of process control. (This will help ensure that the mix that is poured meets the mix design.) • Reduce importance of strength as an acceptance parameter. • As a rapid renewal consideration, use maturity method to estimate in-place concrete strength.

Table 3.2. PCC Pavement, Tier 2 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 2A	**Performance-Oriented Testing** • Place more emphasis on properties known to affect pavement performance.	**Quality Control** *Fresh Concrete:* • Unit weight • Slump • Air quality (by AVA) • Placement temperature • Evaporation rate • Thickness (by probing) *Hardened Concrete:* • Strength (by maturity) • Permeability **Workmanship Process Control** • HIPERPAV software • Stringless paving	**Construction Acceptance** • Surface distress • Thickness (by MIT Scan T2) • Strength (by maturity method) • Air quality (by AVA) • Ride quality • Permeability testing (by chloride ion penetration resistance) • Joint deficiencies • Load transfer efficiency (by FWD) • Tire-pavement noise (OBSI)	• Additional funds for testing will be needed. • Training and more advanced skills will be required. • The chloride ion permeability test is more representative of bridge decks than pavements.	• Measure additional properties that are more performance-oriented (e.g., permeability, tire-pavement noise). • Measure properties using techniques that are more indicative of performance (e.g., AVA). • Incorporate use of nondestructive evaluation techniques.
Tier 2B	**Short-Term Warranty** • Protect against early failure. • Open up requirements affecting short-term design life or materials close to the surface.	**Quality Control** *Fresh Concrete:* • Unit weight • Slump • Air quality (by AVA) • Placement temperature • Evaporation rate • Thickness (by probing) *Hardened Concrete:* • Strength (by maturity) • Permeability **Workmanship Process Control** • HIPERPAV software • Stringless paving	**Construction Acceptance** • Surface distress • Thickness (by probing) • Strength (by maturity method) • Air quality (by AVA) • Ride quality • Joint deficiencies • Load transfer efficiency (by FWD) • Permeability (by chloride ion penetration resistance) • Tire-pavement noise • Skid resistance **Postconstruction Acceptance** • Ride quality (IRI) • Skid resistance • Cracking • Surface defects	• Potential institutional, legal, and organizational barriers will need to be overcome. • Additional agency monitoring and testing postconstruction will be needed. • Reasonable thresholds based on the duration of pavement warranty and maintenance agreements will need to be set.	• Provide less agency oversight and testing during construction. • Make no payment adjustments at the end of construction. • Emphasize postconstruction monitoring.

Note: FWD = falling weight deflectometer; AVA = air void analyzer; MIT = magnetic imaging technology; OBSI = onboard sound intensity; IRI = international roughness index.

list of preapproved products that an agency may create for a particular material to be used during construction, the system approval and trial installation process provides a method for vetting and approving the use of PCP systems, whether proprietary or not. Contractors will be able to submit virtually any PCP system for use so long as it meets the requirements of the system approval and trial installation process.

Asphalt Pavement

State of the Practice in Performance Specifications

Similar to PCC, asphalt performance has been the subject of numerous research studies over the years. That research has supported the progression of asphalt pavement specifications from predominantly method statements to the end-result and statistically based QA requirements prevalent in current standard pavement specifications. Warranties have also been commonly applied to HMA pavement. A methodology for creating PRS for HMA has been developed, but it remains in the validation stage.

Statistically Based Specifications. Statistically based acceptance plans—following a percent within limits (PWL) approach—and pay adjustment systems have been widely applied to asphalt pavement construction. AQCs for HMA are often separated into materials and construction categories. Acceptance of materials is normally based on plant-tested samples, while acceptance of construction is based on field samples.

Table 3.3. PCC Pavement, Tier 3 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 3A	**Performance-Oriented Testing** • Incorporate parameters and test methods that are more indicative of pavement performance.	**Quality Control** *Fresh Concrete:* • Unit weight • Slump • Air quality (by AVA) • Placement temperature • Evaporation rate • Thickness (by probing) *Hardened Concrete:* • Strength (by maturity) • Permeability **Workmanship Process Control** • HIPERPAV software • Stringless paving • Real-time smoothness	**Construction Acceptance** • Surface distress • Thickness (by MIT Scan T2) • Strength (by maturity method) • Air quality (by AVA) • Ride quality • Permeability (oxygen permeability index) • Joint deficiencies • Load transfer efficiency (by FWD) • Tire-pavement noise • Skid resistance • Dowel bar alignment (MIT Scan or GPR) • Steel location (GPR or MIT Scan)	• Additional agency funds for testing will be needed. • Training and more advanced skills will be required.	• Measure additional properties that are more performance oriented (skid resistance). • Measure properties using techniques that are more indicative of performance (e.g., oxygen permeability index).
Tier 3B	**Performance Warranty or DBOM** • Reduce oversight during construction. • Open up design and material requirements affecting design life.	**Quality Control** • Submit QMP	**Construction Acceptance** • Conformance with design, QMP, and performance requirements **Postconstruction Acceptance** • Ride quality (IRI) • Cracking • Surface defects • Skid resistance • Structural integrity	• Only P3s or long-term concession agreements will work. • Potential institutional, legal, and organizational barriers will have to be overcome. • Pay adjustment systems will have to be administered, and contractor performance self-reporting will have to be monitored. • Reasonable thresholds will have to be set. • Appropriate handback criteria will have to be identified. • Adaptation to changes in technology will be necessary over time.	• Shift complete performance risk to the contractor. • Monitor actual performance over time. • Emphasize postconstruction performance monitoring, with less oversight during construction.
Tier 3C	**Measurement of Mechanistic Properties** • Improve understanding of performance (measuring design input values).	**Quality Control** *Fresh Concrete:* • Unit weight • Slump • Air quality • Placement temperature • Evaporation rate • Thickness (by probing) *Hardened Concrete:* • Strength (by maturity) • Permeability	**Construction Acceptance** • As-built conditions meet as-designed	• A database of mechanistic properties will have to be built for inclusion in and refinement of MEPDG. • DOT and industry acceptance of predictive models will be needed.	• Incorporate as-built materials properties and construction conditions into mechanistic design models to predict performance and adjust pay.

Note: AVA = air void analyzer; GPR = ground-penetrating radar; QMP = quality management plan; P3 = public-private partnership; MEPDG = *Mechanistic–Empirical Pavement Design Guide.*

Commonly used materials AQCs include asphalt content, lab compacted air voids, and voids in mineral aggregate (VMA). Commonly used construction AQCs include density, thickness, and ride quality.

Agencies differ on the methods and weights they use to combine pay factors; most rely on experience and engineering judgment to establish a composite pay factor equation. AASHTO R 42, *Standard Practice for Developing a Quality Assurance Plan for Hot-Mix Asphalt,* suggests the following pay factor equation:

$$CPF = 0.35(PF_{density}) + 0.20(PF_{asphalt\ content}) + 0.35(PF_{air\ void}) + 0.10(PF_{VMA})$$

Performance Related Specifications. In the mid to late 1990s, a major effort was undertaken to develop PRS for HMA pavements through the full-scale accelerated load testing at the WesTrack project in Nevada (Epps et al. 2002). The intent of WesTrack was to examine how deviations in materials and construction properties (e.g., asphalt content and degree of compaction) affect long-term pavement performance, so that true PRS and PRS software could be developed for HMA construction. The project was also intended to provide early validation of the Superpave volumetric mixture design procedure developed through the original SHRP program. The AQCs considered in the WesTrack experiment were HMA surface layer thickness, initial smoothness, asphalt content, air void content, and an aggregate gradation parameter (percentage passing the No. 200 sieve). The primary distresses monitored during the experiment were permanent deformation (rutting), fatigue cracking, and friction loss.

The pavement sections constructed at WesTrack performed as expected in terms of the response of the different sections to changes in asphalt content and in-place density. But some unexpected results were also encountered: coarse mixtures, contrary to experience, were the most sensitive to asphalt content and in-place density. Forensic investigations of this phenomenon led the team to hypothesize that the use of thinner pavement sections (to induce distresses more quickly) had unintentional effects on the experiment, making the data from this experiment less useful for the development of PRS (Huber and Scherocman 1999).

In 2000 an attempt was made under NCHRP Project 9-22 to advance the HMA PRS software (HMA Spec) developed in the WesTrack project. However, the capabilities of the WesTrack PRS software proved too limited for general use across the United States. An attempt to directly adapt the MEPDG software to use as an HMA PRS was then abandoned; instead, the team used the spreadsheet solutions of the MEPDG originally developed in NCHRP Project 9-19 as specification criteria for the simple performance tests for permanent deformation and fatigue cracking. This final version of the HMA PRS was named the quality-related specification software (QRSS).

The QRSS is a stand-alone program that calculates the predicted performance of an HMA pavement from the volumetric and materials properties of the as-designed HMA and compares it with the properties of the as-built pavement calculated from the contractor's lot or sublot quality control data. It computes a predicted life difference (PLD) on the basis of fatigue, rutting, and thermal cracking; and the PLD can be used to reward and/or penalize contractors for their product (Moulthrop and Witczak 2011).

Warranties. In contrast to PCC pavements, materials and workmanship issues capable of affecting long-term asphalt pavement performance can generally be observed within a few years of construction. For this reason, asphalt pavement warranties have been more readily adopted than those developed for PCC. The most benefit can be gained from using HMA performance warranties to protect the agency from early failure of the pavement (Gallivan 2011). The performance parameters typically monitored during the warranty period include the following:

- Ride quality—typically measured with laser-based inertial profilers and calculated as IRI;
- Rutting and permanent deformation—commonly measured with laser-based or ultrasonic-based inertial profilers and reported as average rut depth;
- Friction—typically measured with a skid trailer and reported as a friction number; and
- Cracking—typically mapped using visual condition surveys and reported in terms of severity and extent (length or area).

Longer-term DBOM contracts in the United States (e.g., 20 years to 99 years) have also been applied to asphalt pavement and other roadway features. Examples of projects involving public-private partnership, long-term warranty, or operation and maintenance agreements for HMA and other features include New Mexico DOT US-550/NM SR-44 (20 years), Florida DOT I-595 P3 corridor roadway improvements (35 years), and the Capital Beltway 495 Express Lanes P3 Project (80 years). The operation and maintenance specifications provide for monitoring postconstruction performance parameters similar to those found in a warranty provision. They also address the condition of the roadway at "handback" (i.e., when responsibility for the asset reverts to the agency), using parameters such as structural capacity expressed in terms of a modulus value, deflection, or residual life [e.g., in years or remaining equivalent single axle loads (ESAL)].

Guide Specifications

A set of guide performance specifications for asphalt pavement was prepared under the R07 research project. Each specification was drafted with a specific delivery approach in mind. The recommended performance parameters and materials and construction requirements included in each specification are therefore tied to the roles and responsibilities and the risk allocation deemed appropriate for a DBB, DB, warranty, or DBOM project.

To promote rapid renewal, the guide specifications attempt to

- Incorporate quality management and acceptance criteria that more closely correlate to performance (mechanistic structural and mix design properties);
- Promote use of NDT techniques, such as ground-penetrating radar, which provide continuous in situ measurements and reduce the need for taking core samples;
- Encourage contractors to use tools such as compaction rollers enabled with a global positioning system (GPS) device to ensure adequate roller pass coverage and improve uniformity; and
- Incorporate financial incentives and disincentives that promote enhanced quality.

One of the biggest challenges to implementing performance specifications, particularly under the DBB and DB scenarios, relates to the use of end-result properties that act more as surrogates than as direct indicators of future performance. Ideally, as more agencies move toward using mechanistic-empirical design procedures, measurement strategies may evolve to incorporate parameters that better correlate field data to design assumptions. However, even as testing methods and predictive models mature, certain materials and workmanship issues that cannot be measured or modeled effectively may still affect pavement performance. For this reason, warranties and long-term DBOM contracts will likely remain viable options for certain projects.

The guide specifications provide a comprehensive example of the possible performance requirements that could be used to promote the construction of long-lasting pavements. From this menu of requirements, users should select those that best fit the needs of their particular project or program, bearing in mind that certain barriers or gaps may preclude the immediate implementation of all of the proposed parameters and test methods. For example, a performance measure may be technically valid but difficult to implement. Obstacles may include a need for specialized equipment or expertise, a lack of standardized test methods, absence of historical data for calibration of design or predictive models, and so on.

Each agency will have to identify and address possible gaps (particularly those related to historical data and specialized training) on the basis of their own unique experience and needs. However, current technology and business practices generally point to three tiers of performance specifications for asphalt pavement; they range from minimal departure from current practice to a substantial shift in practice and organizational culture that will require technological advancement, improved understanding of long-term material behavior, and possibly a new business model.

- **Tier 1** requirements do not require a substantial departure from current practice, yet they place more emphasis on properties known to affect the performance of asphalt pavements, including volumetric properties such as air voids, asphalt content, and VMA, and as-constructed properties such as in-place density, joint compaction, and thickness.
- **Tier 2** requirements encourage agencies to use for acceptance purposes more rapid and continuous nondestructive evaluation methods, such as ground penetrating radar, which, although currently available, would require capital investment and/or further advancement to incorporate into a specification.

  As an option under Tier 2 (specifically, Tier 2B), agencies may wish to prequalify or screen the contractor's mix design using mechanistic, performance-based properties such as dynamic modulus, rutting resistance, and fatigue performance.
- **Tier 3** requirements assume improved understanding of long-term material behavior as well as advances in technology, particularly in the area of NDT technology, which may allow for the inclusion of acceptance parameters, such as stiffness, which better reflect the future performance and design life of the pavement.

Figure 3.2 summarizes these different tiers and the motivations for implementing each. Although the figure suggests a time frame for implementation, to some extent, this will be agency-specific. For example, warranty provisions and long-term DBOM agreements may fall into the Tier 2 and Tier 3 categories, respectively, for agencies that would first have to foster the necessary internal and external support for assigning such postconstruction requirements to industry. Several agencies, however, have already implemented such specifications and can provide a roadmap for agencies interested in pursuing a similar program.

In general, the three tiers represent a progression toward parameters and test methods that are more indicative of in-place pavement performance. Tables 3.4 through 3.6 summarize the suggested performance specification strategy for each of these tiers. To help determine the appropriate tier, users should consider what would best fit the needs of their particular project or program. For example, if the goal is simply to reduce construction oversight, a short-term warranty may be a better option than investing in new mechanistic or NDT equipment.

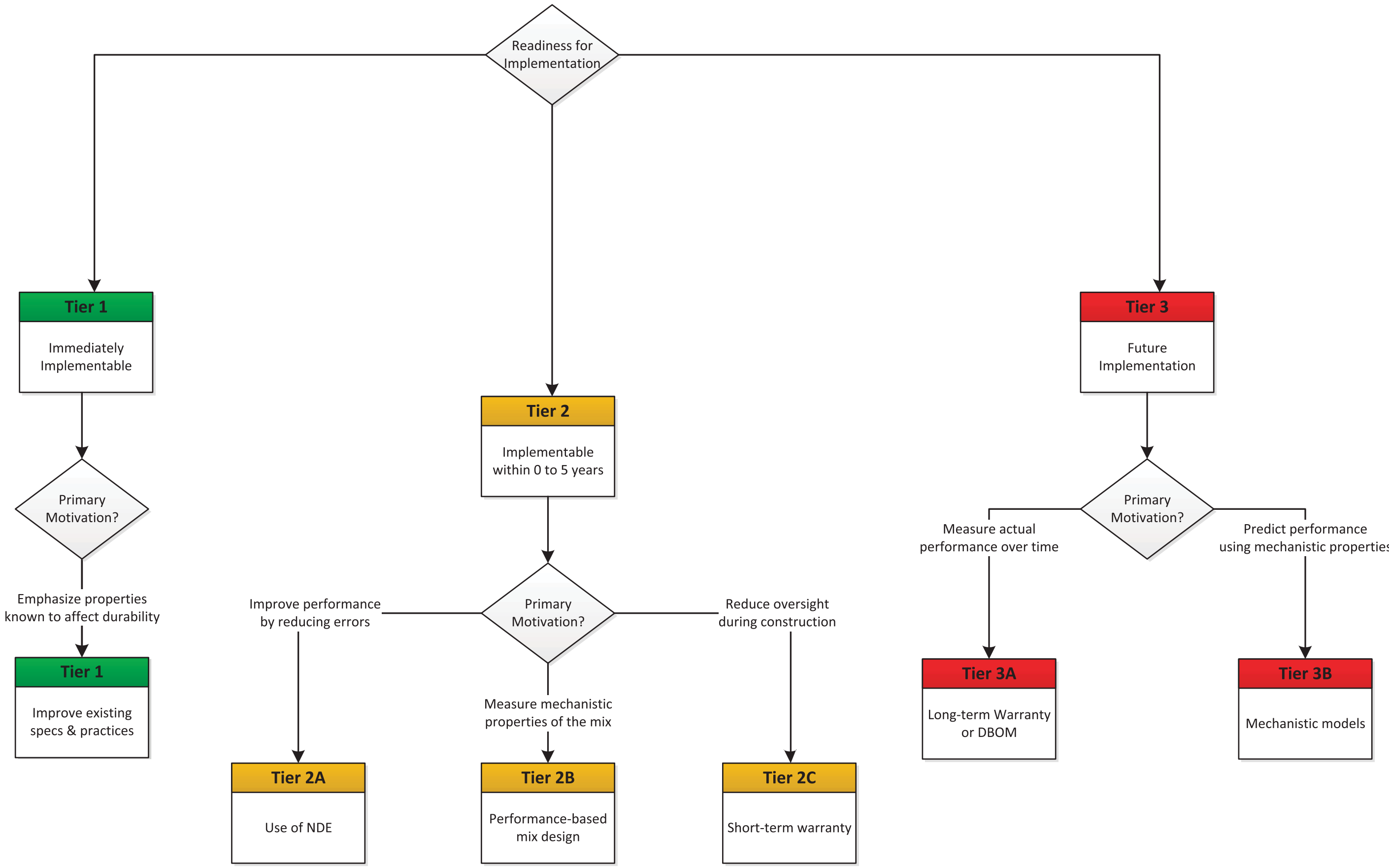

Figure 3.2. Implementation tiers for HMA pavement.

Table 3.4. HMA Pavement, Tier 1 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 1	**Existing Specifications and Practices** • For rapid renewal, improve durability. • Reduce likelihood of poor performance.	**Quality Control** • Asphalt content • Air voids • VMA • Compaction • Smoothness • Thickness • Moisture damage • Mix temperature • Gradation **Workmanship Process Control** • Temperature bar • GPS-enabled roller pattern mapping (coverage)	**Construction Acceptance** • Asphalt content • Air voids • VMA • Compaction • Joint compaction • Surface defects • Smoothness (IRI or straightedge) • Thickness	• Payment by the square yard will change the business model (e.g., lump sum versus unit-priced contracts). • Additional funds for testing will be needed. • Existing DOT man-power and skill level is acceptable. • Additional contractor equipment will be needed.	• Eliminate gradation as an acceptance parameter. • Measure VMA, thickness, and joint compaction for acceptance purposes. • If measuring thickness, consider paying by the square yard. • Encourage contractors to improve process control by using a temperature bar and GPS-enabled rollers.

Note: VMA = voids in mineral aggregate; GPS = global positioning system; IRI = international roughness index.

Table 3.5. HMA Pavement, Tier 2 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 2A	**NDE of Tier 1 Properties** • Implement rapid, continuous sampling and testing. • Improve performance (reduce risk of errors). • Reduce oversight (coring/testing).	**Quality Control** • Asphalt content • Air voids • VMA • Compaction • Smoothness • Thickness • Moisture damage • Mix temperature • Gradation **Workmanship Process Control** • GPS-enabled roller pattern mapping (coverage)	**Construction Acceptance** • Asphalt content • Air voids • VMA • Compaction (GPR correlated to cores) • Joint compaction (GPR correlated to cores) • Surface defects • Smoothness (IRI) • Thickness (GPR)	• Additional agency funds for testing will be needed. • Training and more advanced skills will be required (to interpret GPR results). • Testing methods need to be monitored to ensure accuracy of results.	• Measure the same properties but use different measurement techniques. • Sample continuously. • Reduce destructive testing (i.e., cores).
Tier 2B	**Mechanistic Mix Design** • Improve understanding of performance (measuring design input values). • Build database of mechanistic properties for inclusion in, or refinement of, MEPDG.	**Performance-Based Mix Design** • E* (dynamic modulus) • Rutting resistance • Fatigue (beam fatigue or S-VECD) **Quality Control** • Asphalt content • Air voids • VMA • Compaction • Smoothness • Thickness • Moisture damage • Mix temperature • Gradation • GPS-enabled roller pattern mapping (coverage)	**Construction Acceptance** • Asphalt content • Air voids • VMA • Compaction (GPR correlated to cores) • Joint compaction (GPR correlated to cores) • Surface defects • Smoothness (IRI) • Thickness (GPR)	• Use predictive models for collecting data on mechanistic properties; until predictive models become standard practice, traditional parameters for payment adjustment should be used. • Postconstruction monitoring will be needed to validate expected performance. • Additional agency funds for testing will be needed. • Training and more advanced skills will be required.	• Prequalify the mix on the basis of mechanistic properties. • Measure design-based properties. • Use advanced testing methods and devices. • Reduce destructive testing.
Tier 2C	**Short-Term Warranty** • Reduce oversight during construction. • Open up requirements affecting short-term design life or materials close to the surface.	**Quality Control** • Asphalt content • Air voids • VMA • Compaction • Smoothness • Thickness • Moisture damage • Mix temperature • Gradation	**Construction Acceptance** • Compaction (cores or GPR) • Joint compaction (cores or GPR) • Thickness **Postconstruction Acceptance** • Ride quality (IRI) • Rutting • Cracking • Surface defects • Skid resistance	• Potential institutional, legal, and organizational barriers will need to be overcome. • Additional agency monitoring and testing postconstruction will be necessary. • Training will be needed because of changes in roles and responsibilities. • Reasonable thresholds based on duration of pavement warranty and maintenance agreements will have to be set.	• Reduce agency oversight and testing during construction. • Make no payment adjustments at the end of construction. • Perform postconstruction monitoring.

Note: NDE = nondestructive evaluation; VMA = voids in mineral aggregate; GPS = global positioning system; GPR = ground-penetrating radar; IRI = international roughness index.

Table 3.6. HMA Pavement, Tier 3 Summary

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 3A	**Performance Warranty or DBOM** • Reduce oversight during construction. • Open up design and material requirements affecting design life.	**Quality Control** • Submit QMP	**Construction Acceptance** • Conformance with design, QMP, and performance requirements **Postconstruction Acceptance** • Ride quality (IRI) • Rutting • Cracking • Surface defects • Skid resistance • Structural integrity • Other measures defined by contractor	• Only P3s or long-term concession agreements will work. • Potential institutional, legal, and organizational barriers will have to be overcome. • Agencies will have to administer the payment adjustment system and audit contractors' self-reporting of postconstruction performance results. • Training will be needed because of changes in roles and responsibilities. • Reasonable thresholds based on duration of pavement warranty and maintenance agreements will have to be set. • Adaptation to changes in technology (testing, materials, etc.) over time will be necessary.	• Shift complete performance risk to the contractor. • Monitor actual performance over time. • Emphasize postconstruction performance monitoring, with less oversight during construction.
Tier 3B	**Predictive Models** • Predict the performance of the as-constructed pavement to establish a basis for rational acceptance and payment decisions. • Obtain a better understanding of the expected behavior and life of the as-constructed pavement to help plan for future maintenance needs.	**Performance-Based Mix Design** • E* (dynamic modulus) • Rutting resistance • Fatigue (beam fatigue or S-VECD) **Quality Control** • Asphalt content • Air voids • VMA • Compaction • Smoothness • Thickness • Moisture damage • Mix temperature • Gradation • GPS-enabled roller pattern mapping (coverage)	**Construction Acceptance** • Compaction • Joint compaction • Smoothness • Thickness • Stiffness • Rutting • Fatigue	• DOTs and industry will have to accept predictive models. • Additional funds for testing will be needed. • Training and more advanced skills will be required.	• Measure design-based properties. • Base payment on predictive models. • Use advanced testing methods and devices.

Note: DBOM = design-build-operate-maintain; QMP = quality monitoring plan; IRI = international roughness index; P3 = public-private partnership; VMA = voids in mineral aggregate; GPS = global positioning system.

Demonstration Project

For longer-term contracts involving integrated services, a performance specification for the entire pavement system (i.e., pavement plus foundation) could be developed. Recent performance specifications developed in the United Kingdom and Texas for DBOM contracts have attempted to consider the entire pavement system—most importantly the foundation conditions including subbase and base or existing pavements—as part of the solution.

Intelligent compaction (IC) technology may ultimately provide a means to develop a comprehensive specification for the entire subgrade/pavement system. To explore this possibility, the team worked with the Louisiana Transportation Research Center (LTRC) during the first quarter of 2010 to identify a suitable Louisiana Department of Transportation and Development (Louisiana DOTD) project on which to demonstrate the use of IC technology on an entire pavement section (subgrade, stabilized subgrade, base course, and HMA layers). The selected project, US-90 frontage roads (between Darnall Road and LA-85), involves the construction of new frontage roads along each side of U.S. Hwy 90 in Iberia Parish. The project objectives include the following:

- Demonstrate the value of real-time quality control of compaction operations to accelerate construction, reduce rework, and improve uniformity;
- Improve value of field data and reduce frequency of traditional sampling through improved construction process control;
- Evaluate the reliability and potential use of IC data for acceptance and measurements of in situ stiffness of the constructed earth materials; link to properties that relate more directly to design (e.g., modulus) and in-service performance;
- Establish the value of using IC and mechanistic-based point measurement technologies for rapid renewal projects by benchmarking against sections built using standard construction techniques; and
- Establish long-term monitoring sections and monitoring protocols and assessments for LTRC to document the value of implementing this specification approach and technologies.

Bridges

State of the Practice in Performance Specifications

Bridges pose a unique challenge for developing performance specifications. Unlike other components of highway infrastructure, bridges may last several decades because of advances in materials and structural design. At the same time, long-term degradation processes such as corrosion, scour, and settlement make it difficult to predict performance over a bridge's design or service life. As a result, mechanisms such as warranties and predictive models that may be effectively applied to pavements are not as amenable to bridge projects.

Published research related to developing performance specifications for bridges primarily addresses specific material requirements and, to a lesser extent, design requirements rather than overall bridge performance. The most common areas of research to genuinely target performance criteria are working toward hybrid specifications for structural concrete and bridge decks that couple more performance-oriented parameters with the prescriptive details needed to ensure the agency's goals will be met.

As with end-result specifications for pavements, the literature related to structural and deck concrete primarily focuses on identifying quality characteristics, such as strength, stiffness, permeability (rapid chloride penetration and conductivity), and air content—all of which can provide some indication of future performance (Tikalsky et al. 2004; Haldar et al. 2004; Olek et al. 2002; Hughes and Ozyildirim 2005; Obla and Lobo 2005; ORTA 1987; Sprinkel 2004; Wenzel 2000). Several of these studies devote considerable effort to optimizing mix design toward improved material performance.

A review of current bridge specifications, however, indicates a general lag in applying this research at the project level. Specifications have remained relatively prescriptive, requiring that concrete be batched, mixed, placed, and cured in accordance with the plans and specifications. The quantity and location of reinforcement is also specified. Attempts to incorporate higher-level performance parameters are more commonly seen under longer-term contracts involving integrated services (design, construction, operation, maintenance), but the underlying design requirements often still reference agency or other FHWA-approved standards. Nonconventional materials, such as fiber-reinforced polymer (FRP) composites for bridge decks and superstructures, and accelerated bridge construction techniques have generally been applied only on a pilot basis through the use of proprietary or prescriptive specifications. Agencies have not typically designed and used high-level performance specifications to motivate industry to offer such solutions in response to durability, completion time, or other renewal goals.

Guide Specification

Developing and implementing performance specifications for bridges presents several challenges. First and foremost, the general reluctance exhibited by safety-conscious bridge engineers to entrust contractors with decision-making responsibility provides few opportunities for innovation and risk transfer. Second, the comparatively long service lives expected of most bridge components suggests that short-term warranties or maintenance agreements would not provide agencies with an effective means of mitigating the risk of inferior materials and workmanship. Similarly, the length of time that would be required to make long-term warranties meaningful in the bridge environment tends to make them impractical from a business standpoint (e.g., the contracting entity might dissolve or the initial costs would be too high). The most viable options for performance specifications therefore include hybrid specifications implemented under DBB or DB for individual elements of the bridge and higher-level performance specifications for the entire bridge structure implemented under long-term DBOM contracts. The contracts proposed for the Goethals Bridge Replacement Project (35- to 40-year concession), the North Carolina Mid-Currituck Bridge (50-year concession), and the Indiana East End Bridge (35-year maintenance term) are examples.

The bridge community will not likely embrace a performance specification for an entire bridge structure until it has seen the successful implementation of hybrid specifications for major bridge elements. Such hybrid specifications could begin to incorporate more performance-oriented parameters into otherwise prescriptive specifications. Given the current state of practice, the team felt that preparing a hybrid specification for a hydraulic cement concrete deck would provide the best opportunity to begin building the support needed to transition toward a higher-level performance specification addressing the entire bridge (see Figure 3.3). A comprehensive bridge deck specification could then be tailored to other bridge elements, such as piers and abutments, by removing extraneous requirements.

As further summarized in Table 3.7, to advance the state of practice, the guide bridge deck specification includes the following recommendations:

- Emphasize end-result parameters that relate to the durability of the in-place concrete (such as permeability, rebar cover, and cracking), instead of the traditional measures of compressive strength and thickness.
- Incorporate pay factor adjustments to reward the contractor for providing superior product and penalize the contractor for providing product that is of lesser quality than specified. (Pay adjustments should be determined using a PWL approach to encourage contractors to produce consistent quality work.)
- Address surface characteristics, such as ride quality and possibly skid resistance.

The parameters and test methods included in the guide specification were based on state-of-the-practice testing technology, which may or may not provide rapid and repeatable results, be representative of the anticipated field conditions, or relate directly to field performance (particularly if based on laboratory testing). For example, although permeability is a critical durability parameter, some questions remain regarding the accuracy and repeatability of the currently available test methods for evaluating this parameter (e.g., ASTM C 1202). Advancements in standardized test methods would eliminate some of the perceived risk in using performance specifications.

Further development of nondestructive testing techniques, such as those being studied under the SHRP 2 R06A project, will also help advance rapid renewal goals. However, as these

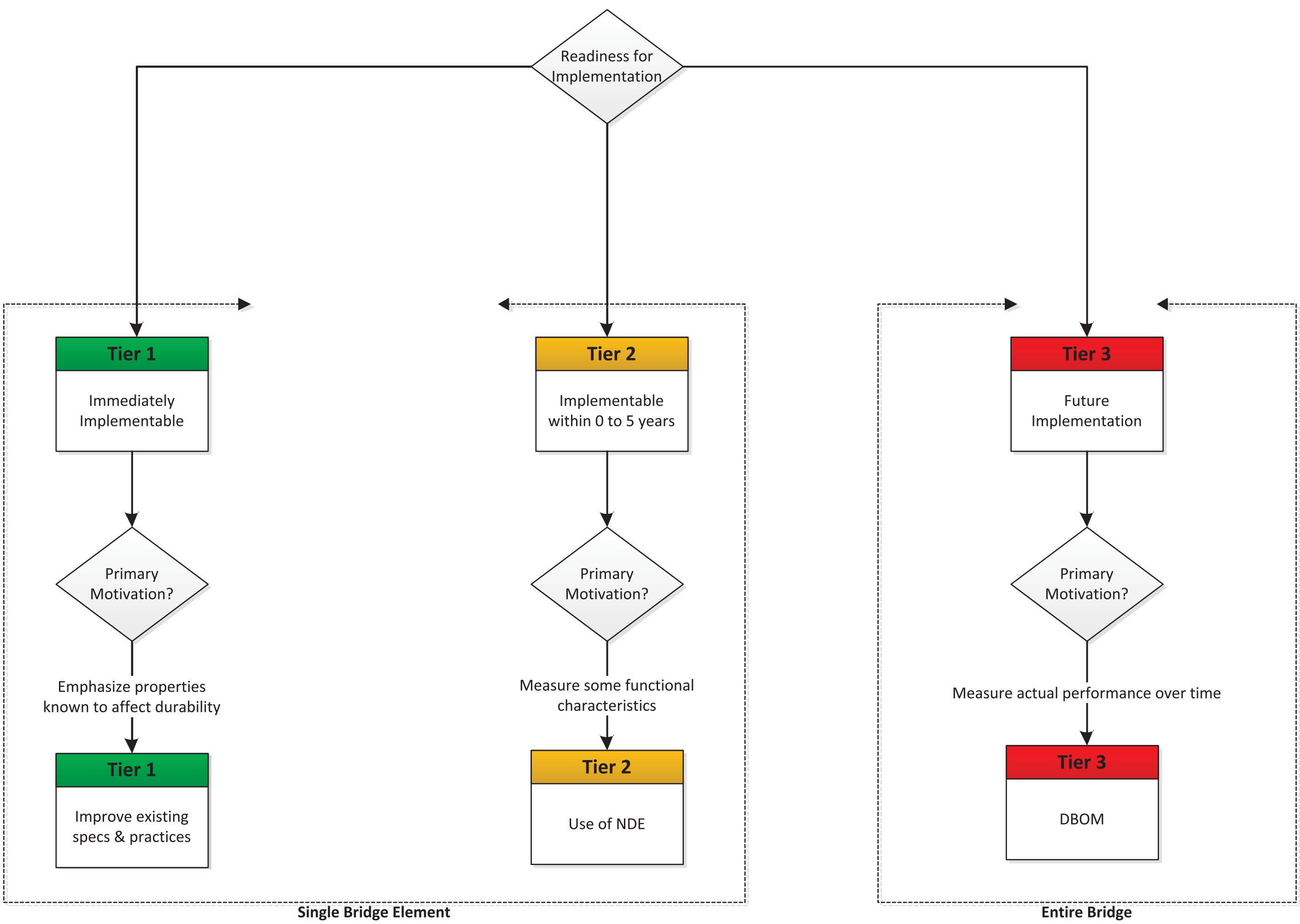

Figure 3.3. Implementation tiers for bridges.

Table 3.7. Summary of Bridge Performance Tiers

	Motivation	Contractor Quality Management	Acceptance	Implementation Issues	Differences from Current Practice
Tier 1 (Concrete Bridge Deck)	**Existing Specifications and Practices** • Place more emphasis on properties known to affect durability.	**Quality Control** *Fresh Concrete:* • Density • Slump • Air content • Water content • Placement temperature • Segregation • Setting time • Evaporation rate • Thickness *Hardened Concrete:* • Compressive strength • Permeability • Shrinkage • Freeze-thaw resistance • Scaling resistance • Alkali-aggregate reactivity resistance • Abrasion resistance	**Construction Acceptance** • Rebar location • Thickness (by probing) • Cover depth • Strength • Permeability [by chloride ion penetration resistance (ASTM C1202)] • Air content • Cracking (visual) • Joint condition (visual) • Cross slope • Cracking (visual)	• Some additional funds for testing will be needed. • Questions remain regarding the accuracy and repeatability of the chloride ion permeability test.	• Reduce importance of strength and thickness as acceptance parameters and instead emphasize durability of the in-place concrete by measuring parameters such as rebar cover, permeability, and cracking. • Incorporate pay factor adjustments for key acceptance parameters.
Tier 2 (Concrete Bridge Deck)	**Performance-Oriented Testing** • Place more emphasis on functional properties.	**Quality Control** *Fresh Concrete:* • Density • Slump • Air content • Water content • Placement temperature • Segregation • Setting time • Evaporation rate • Thickness *Hardened Concrete:* • Compressive strength • Permeability • Shrinkage • Freeze–thaw resistance • Scaling resistance • Alkali–aggregate reactivity resistance • Abrasion resistance	**Construction Acceptance** • Rebar location • Thickness (by probing) • Cover depth • Strength • Permeability (by resistivity meter) • Air content • Cracking (visual) • Joint condition (visual) • Cross slope • Cracking (visual) • Skid resistance • Ride quality	• Some additional funds for testing will be needed. • Historical data will be needed to identify appropriate thresholds for ride quality and skid resistance.	• Measure functional surface characteristics such as smoothness and skid resistance. • Incorporate use of nondestructive evaluation techniques.
Tier 3 (Entire Bridge)	**DBOM** • Open up design and material requirements affecting design life.	**Quality Control** • Submit QMP	**Construction Acceptance** • Conformance with design, QMP, and performance requirements **Postconstruction Acceptance** • Loading • Condition rating • Geometry • Deflection/vibration • Settlement • Ride quality • Noise • Other measures defined by contractor	• Instrumentation techniques, NDT technologies, monitoring, and 3D modeling will need to be integrated to support bridge condition assessment. • Data management systems, particularly for health monitoring, will be needed. • Adaptation to changes in technology (testing, materials, etc.) over time will be necessary.	• Shift complete performance risk to the contractor. • Monitor actual performance over time. • Emphasize postconstruction performance monitoring.

Note: QMP = quality management plan; NDT = nondestructive testing.

technologies (e.g., impact echo, ground-penetrating radar) are primarily suited for evaluating problems with deteriorated structures, they will be more applicable to specifications and delivery methods that include postconstruction responsibilities than to the DBB or DB case in which acceptance is based on end-of-construction measurement. A DBOM specification developed for the entire bridge structure could incorporate promising NDT devices, as well as other bridge health monitoring techniques, as possible means of conducting postconstruction performance monitoring and condition assessments in a rapid and accurate manner that minimizes traffic disruption.

An ideal DBOM specification would also operate on a high enough level to encourage contractors to consider nontraditional materials and technologies, such as those addressed under the SHRP 2 R19A project, to achieve bridge service lives of 100 years and beyond. Given that several of the methods may have higher initial costs, a postconstruction maintenance period or a best-value selection process that considers life-cycle costs may be required to motivate contractors to consider using such techniques.

Demonstration Project

The focus on durability parameters included in the guide bridge deck specification is a first step in moving the industry toward constructing longer-lasting bridge decks. To evaluate the performance requirement options contained in this specification, the team partnered with the Virginia DOT on a demonstration project on the Route 208 bridge over Lake Anna on the Spotsylvania–Louisa County line. The performance requirements were implemented as a shadow specification, with acceptance and payment based on the Virginia DOT's end-result specification for concrete bridge deck.

Compared with the Virginia DOT specification, the pay factors for the R07 performance specification would have resulted in a more severe penalty for certain parameters (e.g., cover depth and thickness) and a higher bonus for others (e.g., strength and air content). This finding suggests that an important consideration for implementing a specification is the need to carefully set limits for performance parameters and use pay adjustment formulas that balance targeted performance with what industry can reasonably achieve.

Another important lesson learned from this demonstration project is that workmanship issues can have a large effect on performance outcomes. Such issues may not necessarily be addressed or identified through the use of performance parameters measured through end-result testing. As a result, the team developed a checklist addressing inspector certification, transportation and handling, preplacement and placement inspection, and postplacement inspection for use as a companion document with the guide specification.

Complete details regarding this demonstration project are provided in Appendix F.

Geotechnical Features

State of the Practice

Geotechnical projects face several unique challenges in defining and evaluating performance:

- Geotechnical materials are among the most variable construction materials. Higher testing frequencies are therefore needed to obtain statistically valid assessments of performance.
- Because soil properties can change over time (e.g., as a result of postconstruction saturation), predicting long-term performance is problematic.
- The subsurface aspect of geotechnical projects makes postconstruction maintenance and repairs difficult, if not impossible. This emphasizes the need to construct geotechnical infrastructure systems properly up front with defined levels of risk.
- Warranty provisions are difficult to implement because little historical data is available to establish targets and thresholds. Furthermore, extensive exclusions may be required (e.g., to address changes in groundwater conditions or vegetation over the life of the system).

Given these obstacles, geotechnical specifications have traditionally been prescriptive in nature. Although the literature contains several papers and reports describing performance measurements (e.g., settlement), monitoring techniques (e.g., in-ground instrumentation), and test methods (e.g., falling weight deflectometer) for evaluating geotechnical infrastructure systems, only a limited number of geotechnical performance specifications exist. They are generally a hybrid of prescriptive and end-result requirements (e.g., requiring a minimum number of roller passes in addition to achieving 95% compaction).

The challenge in developing a more performance-oriented specification is to move beyond the use of acceptance properties—which act only as surrogates for performance (e.g., density)—to the use of mechanistic measures (e.g., stiffness)—which can be more directly correlated with performance and the assumptions used in the pavement design process. Including new and emerging technology, such as intelligent compaction (IC), in the QA process provides a means to advance the current end-result specifications for earthworks.

Roller compaction monitoring technologies with GPS documentation are particularly attractive for rapid renewal purposes. They offer 100% coverage information with real-time data visualization of compaction data, which is a significant improvement over traditional QA plans involving tests at discrete point locations. Several equipment manufacturers have been developing these technologies for both earthwork and asphalt materials over the past 30+ years. By making the compaction machine a measuring device, the compaction process can potentially be managed and controlled to improve quality, reduce rework, maximize productivity, and minimize costs. With data provided in real time, a contractor could alter the process control parameters (e.g., moisture control, lift thickness, and so on) to ensure acceptance requirements are met the first time. Project schedules would thereby be reduced, and delays resulting from postprocess inspections and rework could be avoided.

To date, results from research and demonstration projects have shown the application of the IC technologies for earthwork construction to be promising, although results are somewhat limited. The FHWA has been actively engaged in an IC demonstration program, working with agencies to further develop and promote IC technology. To date FHWA has conducted more than 15 demonstrations to collect data and compare density with machine operation measurement values for earthwork and asphalt pavements. The FHWA has also developed a website (http://www.intelligentcompaction.com) dedicated to IC that includes information on the technology, benefits, implementation guidance, software for compiling and analyzing geospatial data, and draft IC specifications based on density control. FHWA plans to continue with demonstration projects, collect additional performance data, and further develop IC specifications.

In addition to the FHWA demonstration program, a few pilot specifications have been and are being developed by state agencies in the United States (e.g., Minnesota DOT), and a few specifications from European countries exist. Additional work is needed in the United States before IC machine values can be implemented for acceptance purposes. Clearly, differences in IC equipment and machine measurement values, materials, GPS systems, data management, quality control (QC), and verification methods need to be resolved or standardized before IC technology and specifications can be more widely implemented. The earthwork performance specification included in Appendix C addresses the obstacle of differences in IC equipment manufacturer machine measurement values; the specification was field tested on a demonstration project in cooperation with Missouri DOT. Details of the demonstration project are summarized later in this section, and the full project report is available through the R07 report web page (http://www.trb.org/main/blurbs/169107.aspx).

Beyond compaction technologies, other recent developments in the geotechnical field warrant consideration of performance-oriented specifications, including shallow and deep ground improvement technologies. In the past, only a handful of basic technologies were used, but now many options exist. In the field of vertical support elements, upwards of eight or more possible systems could now provide suitable solutions for soft ground improvement. Unfortunately, implementation of many of the new technologies has been slow because of their proprietary nature. Implementation of performance-oriented specifications that focus on achieving overall settlement control or bearing capacity requirements would reduce barriers associated with proprietary technologies and increase competition, a circumstance which should result in best-value solutions.

Shallow ground improvements for pavement rehabilitation applications are another area in which performance-oriented specifications should improve competition and allow use of propriety technologies. Several states (e.g., Missouri, Pennsylvania, and Ohio) are developing specifications for pavement foundation rehabilitation.

Guide Specifications

Challenges with long-term monitoring and the general absence of performance prediction models generally preclude the application of PRS and warranty provisions to geotechnical projects. The guide specifications are therefore primarily end-result specifications, suitable for use under any delivery method. The end-result criteria, however, are directly linked to performance characteristics when possible. In some cases, limitations on the agency's ability to directly measure key engineering parameter values limits the applicability of performance specifications for geotechnical applications. Ideally, advancements in measurement technologies will reduce this obstacle.

Earthwork/Pavement Foundation Systems. Recent developments and improvements to in situ testing devices and integrated machine sensors (e.g., intelligent compaction rollers with accelerometer-based measurements of ground stiffness) have provided opportunities to develop more performance-oriented specifications in the areas of embankment and pavement subgrade/subbase construction.

Two guide specifications related to pavement foundation systems were prepared under this research effort. The first, and perhaps easiest to implement, entails substituting traditional forms of proof rolling with roller-integrated compaction monitoring (RICM) proof mapping to verify that pavement subgrade support conditions are satisfactory. Compared with traditional proof rolling, proof mapping can provide the following:

- Geospatially referenced documentation of a RICM measurement value (MV);
- Real-time information to the contractor during the construction process; and
- Results that can be correlated to subgrade support values such as bearing capacity and stiffness.

The second guide specification represents a more comprehensive attempt to specify the construction of embankment and pavement foundation materials in terms of performance measures and quality statements. This specification includes the following key features:

- Use of RICM technology to provide 100% sampling coverage to identify areas needing further work;
- Acceptance and verification testing using performance measures and parameters, such as elastic modulus testing, shear strength, and permeability, that relate to design assumptions;
- Protocols for establishing target values for acceptance;
- Quality statements and assessment methods that require achievement of at least some overall minimal value during construction, and achievement of a minimum level of spatial uniformity in a given lot area; and
- Protocols for data analysis and reporting such that the construction process is field controlled in an efficient manner to ensure the final product meets design assumptions.

The specification contains two different implementation options.

1. **RICM-MV maps to target locations for QA performance point measurements.** This option uses RICM-MV georeferenced maps to identify "weak" areas on which to focus QA point measurements. Proper QC measures (e.g., controlling moisture content, lift thickness, and so on) should be followed during compaction. The contractor should provide the IC-MV map to the field inspector for selection of QA test locations. Judgment is involved in selecting the number of tests and test locations. Acceptance is based on achievement of target QA point measurement values in roller identified "weak" areas. If in situ QA test criteria are not met, additional compaction passes should be performed, or QC operations should be adjusted (e.g., moisture, lift thickness, etc.) and retested for QA.
2. **Calibration of IC-MVs to QA performance point measurements.** This option requires calibration of RICM-MVs to QA point measurements from a representative calibration test strip before production QA testing is performed. The measurement value–target value (MV-TV) is established from project QA criteria through regression analysis and application of prediction intervals. For modulus/strength measurements, simple linear regression analysis is generally suitable; for correlation to dry unit weight or relative compaction measurements, multiple regression analyses including moisture content as a variable may be needed. If underlying layer support conditions are heterogeneous, relationships are likely improved by the performance of multiple regression analyses with RICM-MV or point measurement data from underlying layers. Acceptance of the production area is based on achievement of MV-TV at the selected prediction interval (80% is suggested) and achievement of target QA point measurement values in the areas with MVs less than MV-TV.

Ground Improvement Technologies. Several existing and emerging geotechnical technologies have the potential to promote the goals of rapid renewal; they are often overlooked because they entail the use of proprietary systems or lack a standardized analysis and design procedure. The SHRP 2 R02 project, Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform, addresses several of these technologies. The R02 project developed a selection tool to help users identify appropriate technologies for a given set of project conditions.

To help promote the use of some of these technologies, guide performance specifications have been developed for the following application areas:

- Vertical support elements (technological solutions could include aggregate columns, micropiles, jet grouting, etc.); and
- Subsurface improvements for existing pavements (technological solutions could include injection of expanding foam, pressure grounding with cementitious materials, etc.).

By incorporating high-level performance requirements (e.g., settlement, bearing capacity, pavement smoothness, and so on), the specifications allow agencies to consider proposals for several competing technologies at once. In that way they avoid the possibility of creating a proprietary specification and allow contractors to select the technology that will best serve the project's needs.

Demonstration Project

As part of the development of the geotechnical performance specification for earthworks, a field project was conducted in partnership with Missouri DOT in 2010 and 2011 on the Route 141 project in Chesterfield, Missouri. The project involved working with the Missouri DOT, the contractor (Fred Weber, Inc.), and an equipment provider (Caterpillar Inc.) to demonstrate earthwork QC/QA performance measurement technologies, including roller-integrated compaction monitoring (RICM) technology in combination with mechanistic-related QA testing methods (plate load tests, dynamic cone penetration tests, and borehole shear tests). Specific goals of the pilot project were as follows:

- Identify suitable QA/QC testing technologies to improve test frequency and construction process control;

- Develop effective reporting, analysis, and evaluation protocols;
- Link the design approach with construction monitoring and the proposed statistical analysis framework, and develop performance models that include a long-term performance aspect;
- Study the effect of the contract delivery mechanism on the responsibilities and actions of parties involved;
- Assess the cost and benefit of implementing the performance specification; and
- Improve the proposed earthwork and proof mapping performance specifications.

The results of the field-testing phase of the project were used to evaluate the proposed earthwork performance and proof mapping specifications. One of the important attributes of the proposed specifications was the use of mechanistic-based performance measurements and the geospatially referenced RICM data. This approach eliminates traditional moisture/density testing with a nuclear gauge and requires the contractor to field control the operation around performance design values.

According to William Stone of the Missouri DOT's (MoDOT) Organizational Performance Administration,

> MoDOT is looking for a technology that both MoDOT and the construction industry can utilize during QC/QA that can provide information with more uniform coverage of compaction data than traditional methods with an outcome being the elimination of nuclear density testing. Intelligent compaction appears to fit that role of providing number of passes and stiffness of material over the entire project area rather than a few point locations and will give information that is more closely linked with current design methods with mechanistic properties of the aggregate, soil and pavement. (W. Stone, personal communication, 2011).

RICM technology provided 100% coverage of the project. That is a major advancement over traditional testing, which tests less than 1% of the project area.

Some important findings from the research work on the Missouri DOT project include the following:

- Traditional nuclear density testing results are not necessarily repeatable between the QC and QA agents. Further, the RICM MVs are not well correlated to the percentage of relative compaction or moisture content.
- Alternative in situ testing methods—including plate load testing, light weight deflectometer testing, and dynamic cone penetration testing—provide quality measurements of support conditions.
- Final acceptable procedures based on proof rolling with a loaded dump truck can be replaced with RICM proof mapping. Using RICM eliminates the need to use loaded trucks, provides integrated measurements, and is faster with greater coverage.
- Obstacles to implementation of RICM and alternative testing methods remain because of lack of training and accepted specifications.

Exit interviews from the project provided positive input in favor of the technologies and general performance parameters used.

According to Dave Dwiggins (815 operator for contractor Fred Weber, Inc.):

> I like the technology. It helps me know where to focus where more compaction work is needed as well as knowing when it is good. Also, it could speed up operations by not having to guess on what is going to pass.

Ross Adams (roadway superintendent for Fred Weber, Inc.) stated:

> I like the concept if the results correlate with the acceptance criteria and it could eliminate nuclear tests on the contractor QC plan.

Nancy Leroney (project inspector for Missouri DOT) noted:

> It could save time and money by knowing when the soil passes. I would love to eliminate the nuclear testing.

Lashonda Neal (QC inspector for ABNA Engineering) stated:

> Great learning experience with the new technology and approaches. I liked being part of the whole experience. It could save time. With the nuclear test you actually test a very small area versus the larger area with the new tests being demonstrated.

Work Zone Traffic Control

Current Status

Transportation agency officials and contractors express growing concern that traditional owner-developed, method-based specifications for work zone traffic control (WZTC) do not provide an efficient and cost-effective means of managing the work zone. Nonetheless, the majority of related specifications in use today are generally prescriptive, dictating to the contractor a set of clear, specific steps for work zone management. This system provides the contractor minimal latitude and no motivation to implement innovative and potentially more efficient traffic control measures.

Some agencies have begun to include performance specifications for WZTC, particularly on DB projects; but many of these are "performance" in title only. Although such specifications identify some performance goals (e.g., "provide a safe travel corridor"), they generally do not tie objectives to a quantitative measurement strategy (e.g., "limit work zone crashes to two per month").

One example of a mature set of WZTC performance criteria was prepared by Michigan DOT under the Highways for LIFE initiative (Michigan DOT 2007). Michigan DOT incorporated clear methods of measurement and explicit contractor incentives and disincentives for WZTC into a special provision prepared for a Highways for LIFE demonstration project.

Many state agencies have been more successful in implementing innovative contracting techniques than strict performance-based traffic control specifications as a means to accelerate construction duration and minimize traffic disruption. These techniques include A+B bidding (cost plus time bidding), lane rental, active management payment mechanism, and lump-sum traffic control.

Guide Specification

To draft the guide work zone specification, the team gathered available work zone performance specifications developed by various states, including Maryland, Utah, and Oregon, as examples. The resulting guide specification presents a menu of possible performance requirements that an agency can customize to fit a particular project's goals, jurisdiction, locale, and environment. The performance parameters within the specification focus on minimizing delay (travel time, queue length, traffic volume), minimizing construction duration, maintaining access/mobility, and maximizing public safety. Within the goals of rapid renewal, the specification is intended to help promote high-speed construction by allowing the contractor to develop a traffic management plan and construction sequence that will be most beneficial to its operations and resources, while also allowing for minimal disruption by setting performance goals around minimizing disruption to the public.

Potential gaps may limit the possibility of immediately implementing all portions of the specification. For example, the use of a trip time reliability parameter appears promising but may be difficult to implement in the near term without having the necessary network infrastructure in place. Technology, though continuing to improve, may not yet be ready to provide reliable data on a consistent basis. Reliability is essential if an agency wants to tie payment to the data. New technologies that use detector and video cameras to count vehicles are evolving and may address this issue.

Demonstration Project

In attempting to demonstrate a WZTC specification, the team engaged in discussions with Arizona DOT, Utah DOT, and South Carolina DOT. Even though no demonstration was conducted, as a result of these discussions, the team gained valuable insight into the challenges related to implementing a performance-based WZTC specification.

Agency Concerns. In general, the discussions revealed some agency reluctance to implement a WZTC performance specification. Agency concerns with implementing a WZTC performance specification varied but can be summarized as follows:

- Concerns that the construction project would cost more because of the use of incentive payments or contractors placing a high premium on WZTC during the bidding process;
- Reluctance to relinquish control over traffic control operations because of the potential negative effects on traffic and undesirable publicity that would go along;
- Lack of awareness of the benefits of a WZTC performance specification and how it could provide a better product;
- Concerns about the risk associated with a performance specification and concerns that a quality construction project might be jeopardized;
- The effort required by the agency to verify performance results of the contractor versus the potential risk if the agency relied solely on the contractor's reported data;
- Concerns related to potential safety issues during construction;
- Questions about the dispute resolution process if the agency's independent verification does not match the results of the contractor's monitoring; and
- Concern that the use of the performance specification might reduce the bidding pool.

Challenges with Implementing a WZTC Specification. Given the concerns voiced by the agencies, implementing a performance-based WZTC specification presents some challenges. They include the following:

- Conveying the message that the project may cost more in terms of construction cost, but when considering the real cost, including both the construction cost and the user (delay) cost, the project will cost less than if done according to a traditional method-based specification;
- Finding the right project on which to apply the performance specification, which is not applicable to all projects and project types;
- Helping contractors understand what they are bidding on to ensure that bids are not artificially inflated;
- Having realistic expectations about costs and scheduling before the project is bid;
- Understanding the reliability of technology that is used to measure performance; and

- Defining requirements for nighttime versus daytime work if both will be permitted.

Importance of Selecting the Correct Performance Requirement for a Project. A key to successfully implementing a performance specification for WZTC is selecting the appropriate performance requirement for the project. There is no one-size-fits-all performance parameter for WZTC. The agency needs to establish the most important performance criteria for the project and align them with the performance requirements. In addition, the following recommendations should be taken into account:

- Select the performance requirements carefully. Inappropriate requirements will likely affect the project schedule, particularly if additional phases of construction are needed.
- Match the performance requirement to the project type and location. The type of facility will play a role in what the performance requirement should be.
- Avoid selecting conflicting performance measures. For example, use only one performance requirement to measure “minimizing delay” on a project.

Best Application of the WZTC Specification. A work zone performance specification can be used on a variety of applications, but certain project types lend themselves to a performance specification better than others. Specifically, the following should be considered:

- Select projects that allow the contractor to be innovative in staging the project. This would be typical of a DB project delivery method.
- Avoid projects that can be performed using short-term traffic control. The performance specification will not work as well on mill and overlay type maintenance projects which can be done using standard special provisions along with liquidated damages clauses.
- More complex projects call for increased creativity and innovation and will likely yield more value in saving construction time and user-delay cost.
- A performance specification will be a viable option on projects in which the reduced capacity of the work zone produces speed reductions or delay increases.

Value of Performance Specifications

Literature Review

Literature quantifying the value added and/or lost by implementing performance specifications in highway construction projects is rather limited. Nevertheless, research and practice, particularly from outside the U.S. highway industry, generally supports the perception that performance specifications can provide several advantages. The advantages include the ability to introduce new technologies, decrease overall life-cycle costs, reduce inspections, and improve quality and customer satisfaction.

One of the most significant perceived benefits reported in the literature is the ability of performance specifications to promote construction innovation. Performance specifications allow contractors flexibility in choosing the materials, methods, and equipment that best match their resources and expertise. This flexibility not only facilitates innovation in project execution but also allows for reductions in overall project budgets and schedules leading to an enhanced competitive ability (Whiteley et al. 2005).

Experience Outside the U.S. Highway Industry

Several highway agencies in Europe and Latin America have been gradually increasing private-sector involvement in highway construction through alternative or integrated contracts containing design, construction, maintenance, and operational responsibilities. In doing so, several of these agencies have moved away from their traditional method specifications to more performance-oriented contracts and specifications that include functional requirements intended to capitalize on the expertise of the private sector (Scott and Konrath 2007).

For example, recognizing that the earlier involvement of the contractor could increase opportunities for innovation, improve risk management, improve constructability, and reduce impacts during construction, the United Kingdom’s Highways Agency created a new generation of design-build contracts that provided for earlier contractor involvement (Matthews 2001). Under these early contractor involvement (ECI) contracts, the contractor is selected, largely on the basis of qualifications, shortly after the identification of the preferred route and well before any statutory planning stages that involve public hearings. After contractor selection, additional design and planning is performed with input from the entire delivery team to establish a target price for the project from that point forward. Various mechanisms are incorporated throughout the design and construction process for the contractor to share in savings and participate in any losses realized when actual costs are compared with the target price. This scheme is intended to encourage additional innovation and continual improvement throughout the development of the project by the design builder.

In the United States, similar performance-based contracting (PBC) arrangements are more common in nontransportation sectors of the federal government. The Office of Federal Procurement Policy (OFPP) produced an extensive report on the results and findings of a governmentwide pilot project to implement performance-based service contracting (PBSC) methods on contracts for recurring services (OFPP 1998b). Even though the entities involved in the study are not involved in road construction projects, their experiences and findings do provide an indication of the value of using performance specifications.

The OFPP research project started in October 1994 when executives from 27 government agencies agreed to implement PBSC and measure its effects. Four industry associations representing more than 1,000 companies endorsed the project. The research team on the PBSC study evaluated the before and after effects of adopting PBSC. They considered variables such as contract price, agency satisfaction with contractor performance, type of work performed, type of contract, competition, procurement lead-time, and audit workload.

The report concludes that the results strongly validate PBSC and support its use as a preferred acquisition methodology. Furthermore, the resulting data showed that PBSC, when fully and properly applied, enables agencies to obtain improved performance at significantly reduced prices. The agencies involved reported an average 15% reduction in contract price in nominal dollars and increased customer satisfaction. The report noted that some agencies reported an initially higher up-front investment; however, the resultant savings through the use of performance-based services acquisition (PBSA) quickly offset the initial up-front investment. As a result of this study, a number of the agencies involved have moved toward adopting performance-based service contracting (PBSC) as their preferred approach to contracting (OFPP 1998b).

One of the agencies adopting PBSA as a standard delivery approach, the Department of Defense (DoD), produced a guidebook for PBSA. The guidebook explains that by describing requirements in terms of performance outcomes, agencies can help achieve the following objectives (DoD 2000):

- **Maximize performance.** Allow contractors to deliver the required service by following their own best practices. Because the prime focus is on the end result, contractors can adjust their processes, as appropriate, through the life of the contract without the burden of contract modifications, provided that the delivered service (outcome) remains in accordance with the contract. The use of incentives further motivates contractors to furnish the best performance they are capable of delivering.
- **Maximize competition and innovation.** Encourage innovation from the supplier base by using performance requirements to maximize opportunities for competitive alternatives in lieu of government-directed solutions. Because PBSA allows for greater innovation, it has the potential to attract a broader industry base.
- **Shift risk.** Shift much of the risk from the government to industry as contractors become responsible for achieving the objectives in the work statement through the use of their own best practices and processes. Agencies should consider this reality in determining the appropriate acquisition incentives.
- **Achieve savings.** Use performance requirements, as experience in both government and industry has demonstrated they result in cost savings.

Experience in the U.S. Highway Industry

Attempts in the U.S. highway industry to assess the value of performance specifications have focused primarily on warranty provisions. Some examples follow.

Wisconsin. In 1996, the Wisconsin DOT developed a comprehensive warranty specification for asphaltic concrete pavements. The study was performed jointly with the Wisconsin Asphalt Pavement Association and FHWA. The anticipated benefits from implementing the warranty specification included reducing the Wisconsin DOT's project delivery costs, lowering total project construction costs, increasing the chances of contractors using innovative construction methods and materials, and maintaining or increasing construction quality. The report published by the research team (Shober et al. 1996) outlines the unique features of the warranty specification, including the warranty period, bonding requirements, pavement performance characteristics, performance thresholds, pavement evaluation methods, required pavement remedial actions, and the use of a conflict-resolution team.

The Wisconsin DOT published a 5-year progress report on its asphaltic pavement warranties in June 2001. The agency acknowledged that the limited amount of performance data available made assessing long-term trends difficult, but it offered a glimpse of comparative performance data by capturing comparative cost data between warranty and nonwarranty contracts over a 5-year period (Brokaw et al. 2001).

Costs evaluated under standard contracts over 5 years included mix bid prices, asphalt bid prices, tack coat bid prices, quality management bid prices, state delivery costs, and state maintenance costs. Costs evaluated under 5-year warranty contracts included warranted asphalt pavement bid prices and state delivery costs. The results of the cost comparison were broken into two categories, on the basis of the year the project was let. Projects let in 2000 were broken out because of the addition of ancillary pavements to the warranty provision and the large increase in asphalt price which occurred that year. The evaluation showed that warranty projects averaged $24.34 per ton compared with $27.72 per ton for standard projects from 1995 to 1999; and warranty projects averaged $29.34 per ton compared to $31.25 per ton for standard projects let in 2000. In both cases, the warranted projects appeared to cost less overall compared with nonwarranted projects. This cost comparison concluded that even when an initial cost was up to 7% greater, warranty pavements were still more cost effective than standard pavements.

The report also examined the comparative performance data on the warranty and nonwarranted projects over the 5-year period. The average IRI values of the warranted pavements over 5 years were better compared with the average state IRI values. The pavement distressed index (PDI) values were also significantly better than average state PDI values for nonwarranted pavements (Brokaw et al. 2001).

The Wisconsin DOT conducted follow-up studies that compared the cost and performance outcomes of warranted HMA pavements with the cost and benefits of nonwarranted pavements. Thirty-eight warranted and 37 nonwarranted pavements were analyzed from around the state between 2002 and 2006, with warranties expiring between 2007 and 2011. The agency found that the total cost, pavement distress, and anticipated rehabilitation schedule of both nonwarranted and warranted hot-mix asphalt pavements were approximately equal. The cost of staff time was greater for warranted projects and the ride quality was found to be better for warranted pavements. Wisconsin DOT recommends that both warranted and nonwarranted pavements be monitored so that any similarities between their service lives may be determined.

Though Wisconsin DOT continues to support the use of warranties (it issued a solicitation in 2012 for a consultant to assist in pavement warranty program oversight), it issued a moratorium on the use of warranties in June 2012 until it can revise the current specification to address concerns from industry and FHWA. Wisconsin DOT had made revisions to the original specification in 2011 to tighten the warranty requirements, and industry representatives have expressed concerns about their ability to meet the revised specification. In addition, FHWA has requested several changes to the Wisconsin DOT specification.

Colorado. The Colorado DOT research branch conducted a study to evaluate the cost benefits of short-term warranties for hot-mix asphalt pavements. The Colorado DOT study compared 10 pairs of warranty and control projects to assess their relative costs and benefits as of January 1, 2007. The projects were 3-year and 5-year warranty projects constructed between 1998 and 2003. The projects' current performance life was between 3 and 8 years. To minimize bias, the researchers paired projects carefully on the basis of similar characteristics: preoverlay repair work, functional class, design life, and other features (Aschenbrener and Goldbaum 2007).

The research team on the study reported that on the basis of 3 to 8 years of performance information, the 3-year to 5-year short-term warranty pavements had slightly less rutting and were slightly smoother than the control projects. However, the cost to maintain warranty pavements was much greater. The warranty projects resulted in a shift in risk and responsibility; however, up to the time the report was published, no tangible benefits were identified by the research team. The research team concluded that, on the basis of the evaluation of these pavements, the implementation of short-term warranties of HMA was not a cost-effective tool for the Colorado DOT (Aschenbrener and Goldbaum 2007).

Minnesota. The Minnesota DOT has been implementing warranties in highway projects since the mid-1990s. Since that time, the agency has gained valuable experience in developing and implementing warranties on both DB and DBB projects. The results of Minnesota DOT's experience with warranties are documented in the report, *Innovative Contracting Summary*, for the period between 2000 and 2005. The report was prepared and published by the Minnesota DOT Office of Construction and Innovative Contracting. According to the report, some of the benefits in applying specifications and warranties in highway construction projects include increased product quality (lower life-cycle costs), reduced agency staffing during construction, decreased owner risk from shifting responsibility to the contractor, and better opportunities for using innovative construction techniques and methods to improve quality (Minnesota DOT 2005).

Minnesota DOT also identified several drawbacks and limitations concerning the implementation of warranties. For example, the report states that under the warranty system, bonding and insurance requirements may eliminate smaller companies from bidding. Furthermore, some paving contractors are uncomfortable with warranty issues when another contractor constructs the subgrade. Minnesota DOT also voiced the concern that enforcing warranties over longer periods of time may prove difficult. The report explained how Minnesota DOT had to monitor the project in greater detail during the warranty period. In addition, when implementing warranties, contract time could increase if contractors spend more time addressing minor issues that may affect the performance of the warranty item. Despite such disadvantages, Minnesota DOT appears to favor continuing this system and applying it on different projects (Minnesota DOT 2005).

Survey and Workshop Findings

This section summarizes the more qualitative observations and conclusions that can be drawn from workshop discussions with agency and industry representatives. Complete details on the Delphi analysis and workshop are provided in Appendix E. In general, both the literature and expert assessments support the conclusion that using performance specifications will add value to a project. However, the value added is contingent on project objectives, project characteristics (e.g., degree of flexibility to meet objectives), and the type of project delivery system used. Table 3.8 summarizes the associated benefits and

Table 3.8. Perceived Benefits and Risks of Performance Specifications

Perceived Benefits	
Owners	***Industry***
• Increased private-sector accountability for performance • Accelerated delivery • Potential for higher construction quality, lower life-cycle costs, and increased customer satisfaction • Potential for reducing construction inspection and administrative resources	• More flexibility • Ability to be more competitive • Potential for higher rate of return through innovation and incentive contracts • Opportunity to apply innovative materials and methods to improve efficiency and meet performance requirements at lowest life-cycle costs • Opportunity to realize competitive advantage on best-value procurements
Perceived Risks	
Owners	***Industry***
• Difficulty in setting appropriate thresholds and incentives/disincentives, especially at handback • Quality and safety sacrificed to meet or beat time and budget constraints (primarily for design-build-nonwarranty projects) • Loss of control of over highway asset (DBOM)	• Overly stringent requirements and thresholds • Inflation/escalation costs (for long-term maintenance agreements)

risks of using performance specifications from the perspective of both owners and industry.

According to the literature and input from practitioners, performance specifications have the potential to improve quality and long-term durability. From this perspective, they better align design requirements with construction acceptance criteria, focusing on parameters that more directly influence performance and promoting an improved understanding of performance by all parties. This improved understanding of performance has further promoted the development and use of rational performance-based payment adjustment systems, replacing pass–fail decisions and judgment calls.

The earlier the contractor becomes involved in a project, the greater the opportunity to realize added value. The benefit (money saved) attributable to the use of performance specifications is driven by the degree of design control and flexibility extended to the contractor. Value is also affected by the duration of the contractor's responsibility for performance, with savings more pronounced for larger, longer-duration projects.

Performance specifications should be considered when the actual or perceived savings resulting from their use exceed their added premium. This more often occurs when the projects are large and when contractors have enough time in the contract to capitalize on efficient budgeting.

However, an agency may decide to use a performance specification on a smaller, less complex project to minimize risk, especially when implementing the performance specification for the first time on a pilot or demonstration project. This conclusion was also supported by the team's interactions with agencies interested in collaborating on demonstration projects. The agencies felt that smaller, less complicated projects were a more appropriate platform for implementing performance specifications for the first time because the owner and contractor risks were more manageable than would be the case on a larger, high-profile project. This observation contrasts with the workshop conclusion that larger, complex projects provide the greatest value when using performance specifications. However, when using a performance specification for the first time, agencies should factor the risks and learning curve into the decision.

A final conclusion regarding the implementation of performance specifications was that agencies and the industry can better manage any changes in business practices required by the new specifications in steps or increments. For example, the California Department of Transportation (Caltrans) indicated that it was implementing its performance-based long-life asphalt concrete specification for its I-710 projects in stages to allow the industry to adapt to changes in roles and responsibilities.

Risks Associated with Performance Specifications

The literature revealed several different risk areas related to the use of performance specifications. The team factored this information into its performance specification development framework, as described in Chapter 2 of the specification writers guide. In summary,

- **Risk associated with measurement technology and sampling.** Depending on the accuracy and reliability of the extent to which the measurements reflect the real conditions, some agency risk, also called "buyer's risk," is inherent in any transaction based on performance specifications. A small probability always exists that the agency may be paying for rejectable work. The opposite result, or the “seller’s risk,” may also be realized: the contractor may not be receiving due compensation for acceptable work (Buttlar and Hausman 2000).

- **Risk associated with use of predictive models.** Predictive models assess future performance or predict an end result on the basis of facility characteristics soon after construction, using parameters such as in-place density, asphalt content, and waterproofing ability. Predictive models are viewed as a “black box,” and their long-term reliability is often untested—especially if conditions such as traffic loads are different from those assumed in the design. They often require revisions or replacement.
- **Risk associated with warranty exclusions.** Warranty specifications present a different set of risks because actual performance is measured for certain parameters (rutting, cracking, etc.) over time during the warranty period, and the contractor is required to fix defects only for discrete items of the work directly under its control. These specifications typically define exclusions related to features of the work not covered under the warranty. The agency risk is that it may be responsible for correcting failures for items not specifically covered by the warranty.
- **Procurement risk.** If significant contractor investment or resources are needed to meet performance requirements, some contractors may be unwilling to assume the risks associated with performance specifications. The result could be reduced competition.
- **Risk associated with empirical modeling.** Empirical models for predicting performance over the service life are ineffective because innovative products and techniques are out of the bounds of the applicability of empirical knowledge (van der Zwan 2003).
- **Risk of defining performance parameters using qualitative measures.** Qualitative measurements (e.g., “conduct work in a manner that ensures minimal interference with traffic”) are difficult to enforce or test for.
- **Risk of combining performance and prescriptive requirements.** Combining performance and prescriptive requirements may restrict innovation or require contractors to assume responsibility for performance when they have not fully controlled the design.
- **Risk associated with verification.** The availability, economics, and speed of measurement and verification strategies may not be able to support the goals of rapid renewal.
- **Risk of internal agency resistance to changed roles and responsibilities.** The use of performance specifications shifts greater control to the contractor, changing the traditional agency roles and responsibilities. Agency staff may attempt to retain control using traditional administration practices, reducing the effectiveness of the performance specifications and causing the agency to retain the performance risk.

When to Use Performance Specifications

Although literature addressing the selection of method versus performance specifications is limited, a number of studies report systematic processes for selecting alternative contracting methods. For example, FHWA’s Highways for LIFE performance-based contracting framework provides a decision tree for choosing contract type but does not address levels of performance specifying (SAIC 2006).

Anderson and Damnjanovic (2008) report that several states have systematic processes to select alternative delivery methods. Minnesota, Utah, Ohio, California, and Pennsylvania offer some level of guidance in selecting alternative contracting methods or warranty contracts. Minnesota DOT uses a document titled *Innovative Contracting Guidelines,* which highlights the pros and cons of different innovative contracting methods, including performance warranties, and provides selection guidelines. Utah DOT has a similar document that addresses the benefits and drawbacks of different contracting methods and provides selection criteria. Ohio DOT uses the *Innovative Contracting Manual* to select alternative contracting methods. Caltrans has a similar document titled *Innovative Procurement Practices* to address issues related to selecting alternative contracting methods. Caltrans also maintains a guidance document for selecting warranty projects on the basis of project scope and characteristics. Several other departments of transportation (Wisconsin, Michigan, Colorado, and Ohio) use similar screening criteria for warranties. Lastly, Pennsylvania DOT has an “Innovative Bidding Toolkit,” which divides contracting methods into three categories: (1) time-based, (2) quality based, and (3) others. For each method, the toolkit provides a variety of information, including definitions, benefits and risks, and typical project profiles.

Outside the transportation industry, the *Guidebook for Performance-Based Services Acquisition (PBSA)* maintained by the U.S. Department of Defense includes screening criteria for when to use performance contracts (DoD 2000).

Using these selection and screening tools as a guide as well as feedback from workshop participants, the team developed a two-part decision process for determining when to use method versus performance specifications. This process is presented in Chapter 5 of the executive guide.

CHAPTER 4

Summary and Conclusions

A review of the information gathered during the R07 research effort—including findings from the literature review, practitioner input, and analysis of case studies and demonstration projects—shows that performance specifications can increase quality, encourage innovation, promote the use of new materials and technology, and reduce an agency's quality assurance burden during construction. To achieve these benefits, performance specifications should emphasize desired outcomes (either through as-constructed end-result requirements or target levels of service over some defined period of performance) while eliminating unnecessary constraints on materials selection and construction methods. The successful implementation of performance specifications requires careful project selection and institutional support. Success also depends on following systematic approach to specification development.

Research Products

The R07 team recognized that guidance is needed for decision makers and project managers to properly implement performance specifications at the program or project level, and for engineers and specifiers to develop performance specifications for any type of application. Therefore, the team developed guide performance specifications and associated implementation guidelines to help support the application of performance specifications across a wide range of work and projects.

Guide Performance Specifications

To help agencies develop and implement performance specifications, the R07 team drafted a set of AASHTO-formatted guide specifications to be used by engineers and specifiers as a template from which to develop project-specific performance specifications for various topic areas. Guide performance specifications are provided in the areas of HMA and PCC pavement, concrete bridge decks, geotechnical application areas, work zone traffic control, and quality management.

The specifications include commentary to help specifiers select performance parameters and performance measurement strategies (test methods, sampling plans, target values, pay adjustment mechanisms) that best align with the project's goals and the capabilities of the agency and local industry. Emphasis is placed on the use—to the extent possible—of new and emerging nondestructive testing (NDT) techniques which facilitate rapid renewal and performance parameters that validate mechanistic models used for design.

As applicable, the guide specifications have been tailored to specific delivery approaches (design-bid-build, design-build, warranty, and design-build-operate-maintain). The chosen approach can significantly affect how much performance risk can be placed on the private sector. Thus the team factored in both possible changes to traditional roles and responsibilities with respect to design, quality management, and postconstruction maintenance, and the level at which performance parameters may be set.

If properly implemented, the guide specifications will provide agencies with a useful tool to motivate and empower the private sector to offer innovative solutions to save time, minimize disruption, and achieve long life in the interest of rapid renewal for these specific applications.

The audience for the guide specifications includes design, construction, materials, and maintenance personnel from within a state or local highway agency, and industry partners including consultants, researchers, industry advisory members, and reference standard organizations.

Implementation Guidelines

To accompany the guide specifications, the team also prepared a two-volume set of implementation guidelines.

Strategies for Implementing Performance Specifications: Guide for Executives and Project Managers provides a broad overview of the benefits and challenges associated with implementing performance specifications. Recommendations address project selection criteria, procurement and project delivery options, industry and legal considerations, and the various cultural and organizational changes needed to support the implementation of performance specifications.

The audience for the strategies guidelines includes mid-level to senior managers and project engineers within state or local highway agencies and industry partners such as contractors, subcontractors, and material suppliers. The anticipated benefits of the strategies guide are as follows:

- Improved decision making by executives and project managers leading to more effective implementation of performance specifications and a more performance-oriented business model; and
- Improved understanding of the changes in risk allocation and contract administration associated with different project delivery methods.

Framework for Developing Performance Specifications: Guide for Specification Writers presents a flexible framework for assessing whether performance specifying is a viable option for a particular project or project element. When applicable, this volume explains how performance specifications can be developed and used to achieve project-specific goals and satisfy user needs. The guidance is intended to be accessible to both experienced and novice members of a project team, as well as adaptable to any project element and delivery method.

In addition to providing a step-by-step "how-to" guide for developing performance specifications, the document also contains guidance on specific application areas (e.g., pavements, bridge decks, earthworks, and work zone) found to have the greatest need or potential for performance specifying.

Demonstration Projects

An important step in implementing performance specifications is to demonstrate their viability on actual projects, by collecting data to measure and evaluate performance against traditional specifications and using the lessons learned to make improvements and support continued implementation. For example, an important objective is to move beyond the use of specification acceptance properties that act only as surrogates for performance to the use of measures that more directly correlate with performance and the assumptions in the design process. Demonstrating the new specifications provides a means to begin the move toward more performance-oriented requirements. The team completed two projects, the Missouri DOT Route 141 Roadway Improvement Project, demonstrating the use of roller-integrated compaction monitoring (RICM) technology for improved compaction of the roadway foundation, and the Virginia DOT Lake Anna Bridge Rehabilitation Project, demonstrating the use of acceptance properties that place more emphasis on durability.

Missouri DOT Route 141 Roadway Improvement Project—Geotechnical Performance Specifications

As part of the development of the geotechnical performance specification for earthworks, a field project was conducted in partnership with Missouri DOT in the fall of 2010 and 2011 on Route 141 in Chesterfield, Missouri. The project involved working with Missouri DOT, the contractor (Fred Weber, Inc.), and an equipment provider (Caterpillar Inc.) to demonstrate earthwork QC/QA performance measurement technologies, including RICM technology, in combination with mechanistic-related QA testing methods (plate load tests, dynamic cone penetration tests, and borehole shear tests).

The results of the field-testing phase of the project were used to evaluate the proposed earthwork performance and proof mapping specifications, which are included in Appendix C. One of the key attributes of the proposed specifications was the use of mechanistic-based performance measurements and the geospatially referenced RICM data. This approach eliminates traditional moisture/density testing with a nuclear gauge and requires the contractor to field control the operation around performance design values.

Some of the important findings from the research work on the Missouri DOT project include the following:

- Traditional nuclear density testing results are not necessarily repeatable between the QC and QA agents. Further, the RICM MVs are not well correlated to percent relative compaction or moisture content.
- Alternative in situ testing methods—including plate load testing, light weight deflectometer testing, and dynamic cone penetration testing—provide quality measurements of support conditions.
- Final acceptable procedures based on proof rolling with a loaded dump truck can be replaced with RICM proof mapping. Using RICM eliminates the need to use loaded trucks, provides integrated measurements, and is faster with greater coverage.
- Challenges remain with implementation of RICM and alternative testing methods because of the lack of training and accepted test methods and standards.

Virginia DOT Route 208 Lake Anna Bridge Rehabilitation Project

The Virginia DOT project demonstrated a performance shadow specification for a hydraulic cement concrete bridge deck using construction parameters that relate to performance (e.g., PCC deck permeability, cracking, joint condition, skid, smoothness, and thickness and cover depth). A PWL was developed for construction parameters (e.g., cover depth, thickness, strength, and permeability), and pass–fail criteria were used for other parameters (e.g., cracking, joint condition, and cross-slope). The performance specification was shadowed to compare results with Virginia DOT's end-result specification, which incorporates a PWL with pay adjustments for strength and permeability.

Compared with the Virginia DOT specification, the pay factors for the R07 performance specification would have resulted in a more severe penalty for certain parameters (e.g., cover depth and thickness) and a higher bonus for others (e.g., strength and air content). An important consideration is that agencies will need to carefully set limits for parameters and use pay adjustment formulas that balance targeted performance with what industry can reasonably achieve.

Another important lesson learned from this demonstration project was that workmanship issues can have a large effect on performance outcomes, and such issues may not necessarily be addressed or identified through the use of performance parameters measured through end-result testing. Given this result, the team developed a checklist, included in Appendix F, for use as a companion document with the guide specification. The checklist addresses inspector certification, transportation and handling, preplacement and placement inspection, and postplacement inspection.

Louisiana DOTD US-90 Frontage Roads

The team advised LTRC on the development of a research plan and draft specifications to evaluate the use of nondestructive roller-integrated compaction monitoring (RICM) and mechanistic-based in situ point measurements on a new pavement section, including subgrade, stabilized subgrade, base course, and HMA layers.

The Louisiana DOTD and LTRC are moving forward with a demonstration project with the following goals:

- Demonstrate the value of real-time quality control of compaction operations to accelerate construction, reduce rework, and improve uniformity;
- Improve the value of field data and reduce the frequency of traditional sampling through improved construction process control;
- Evaluate the reliability and potential use of RICM data for acceptance and measurements of in situ stiffness of the constructed earth materials, and link properties that relate more directly to design (e.g., modulus) and in-service performance;
- Establish the value of using RICM and mechanistic-based point measurement technologies for rapid renewal projects by benchmarking against sections built using standard construction techniques; and
- Establish long-term monitoring sections and monitoring protocols/assessments for LTRC to document the value of implementing this specification approach and technologies.

LTRC began collecting performance data for the earthwork operations in December 2012. Additionally, North Carolina State University, under FHWA Project DTFH61-08-H-00005, plans to collect HMA materials from this project during construction and characterize them with the mechanistic-based tests (e.g., S-VECD) being developed under the FHWA contract. Louisiana DOTD and LTRC are also planning to test the materials and perform long-term monitoring of the project. This supplemental work will enhance the future validation of performance specifications as advances are made in testing.

Recommendations for Future Activities and Implementation

The team has identified a number of potential follow-on activities that would help move the products of this research effort into practice. These activities can be classified into four general areas: future demonstration projects, continued specification development, training and outreach, and development of automated tools for specification development.

Demonstration Projects

Demonstration projects are a proven tool for validating and fine-tuning new procedures, specifications, and contracting practices resulting from research. The validation process typically involves benchmarking by comparing the outcomes of projects using traditional procedures with the performance of projects using the new practices to determine the relative success.

The team reached out to a number of agencies during the project to explore the possibility of conducting demonstrations. Agencies expressed a high level of interest in demonstrating performance specifications. For example, 10 agencies (Caltrans, Missouri DOT, Louisiana DOTD, Virginia DOT, Pennsylvania DOT, Florida DOT, South Carolina DOT, Wisconsin DOT, Utah DOT, and Delaware DOT) explored with the team the potential for implementing performance specifications on a suitable demonstration project. Given the R07 budget and schedule, the team decided to move forward with three demonstration projects (Missouri DOT, Virginia DOT, and Louisiana DOTD). However, the team believes that significant opportunities for additional demonstrations exist.

Performance specifications could be further validated by conducting long-term, postconstruction performance monitoring to assess their relative value. Particularly useful would be demonstrations of the long-term performance outcomes for warranty and DBOM specifications using postconstruction performance parameters. Suitable project types for this scenario would likely involve pavement applications but could also include bridge or structural elements for which long-term performance evaluations (i.e., health monitoring) would be necessary to assess value.

Continued Performance Specification Development and Implementation

Before initiating the SHRP 2 R07 project, FHWA convened an expert technical group (ETG) with representatives from AASHTO, industry, and academia to provide guidance and support for the continued development of performance specifications, with particular focus on PRS for rigid and flexible pavements. With the issuance of draft performance guide specifications and implementation guidelines under SHRP 2 R07, the team sees a need to reestablish a performance specification ETG to provide continued support and guidance for implementation of the performance specifications developed under the R07 project and to identify additional performance specifications to test and implement. The ETG's activities could potentially cover several areas.

The ETG's primary activity would be to assist with the adoption of selected R07 specifications as AASHTO guide specifications by providing additional vetting of the specifications and acting as liaisons to the relevant AASHTO subcommittees. The ETG could also help build the business case and institutional support for the use of performance specifications. That would involve fostering a performance-based culture within owner organizations, handling legal issues, addressing industry concerns (i.e., risk management, insurance and bonding, and subcontractor relationships), and also addressing project delivery and procurement considerations.

In the area of pavements, the ETG could further develop and demonstrate test methods and acceptance criteria using NDT that more directly relate to performance (e.g., mechanistic-based properties) and could support PRS demonstrations (e.g., FHWA-sponsored research and demonstrations using PaveSpec for PCC and HMA predictive models). For bridges, the ETG could develop performance specifications for additional elements (e.g., piers, beams, or whole bridge performance), develop performance criteria for field acceptance of modular bridge components or innovative bridge technology (e.g., fiber-reinforced polymer composite bridges), and monitor systems for long-term performance of technological advancements and data management.

For geotechnical applications, the ETG could develop additional performance specifications for ground improvement and pavement foundations, develop and test acceptance criteria for RICM on the basis of mechanistic properties (e.g., modulus), and integrate geotechnical and pavement performance specifications. In the area of work zone traffic control, the ETG could support the advancement of tools for monitoring performance, the standardization of methods for calculating incentives and disincentives, and the management of data and independent verification of data. The ETG could also take the lead on development of performance specifications for other highway construction elements (e.g., lighting, signals, signage, pavement markings, guardrails, and landscaping). And finally, the ETG could provide training and outreach to stakeholders at AASHTO, FHWA, local agencies, and industry partners.

Training and Outreach

As part of a short-term implementation strategy, the products of this research effort can be effectively broadcast to stakeholders through a series of webinars, supplemented by articles and presentations at highway industry forums. For example, a potential topic area for project managers may include "Deciding When to Use Performance Specifications," which could address project selection criteria, delivery and procurement considerations, risk allocation, contract administration, and other management considerations related to the use of performance specifications. A potential webinar for specification writers could address the step-by-step process for drafting performance specifications, which could be further tailored to a specific project type or element (e.g., pavement, bridge deck replacement, work zone traffic).

Longer-term outreach activities could entail developing materials for 1-day or 2-day workshops or more formalized training programs sponsored by the National Highway Institute, the FHWA Resource Center, state highway agencies, university-affiliated transportation institutes, or other forums. For example, the National Highway Institute presents a construction course titled, "Principles of Writing Highway Construction Specifications." Module 4 of the course addresses approaches to writing end-result specifications. This module could be updated to include the SHRP 2 R07 guidance for drafting performance specifications. Additional topics for formal training could include specific PRS training for pavements.

Web-Based Specification Development Tool

The team believes that the development of an electronic tool to help specifiers write performance specifications for specific applications would have significant value. This approach is consistent with current agency trends toward developing and maintaining web-based specifications. The tool would generally be based on the guide for specification writers and could be database-driven with standard language and templates for different types of product specifications. The tool would guide the specification writer through steps or decision points with various options to consider depending on the project scope and characteristics. On a very high level, these steps may include the following:

1. Identifying project scope and characteristics;
2. Defining project goals;
3. Assessing whether goals can best be achieved through use of performance or method specifications;
4. Selecting the appropriate project delivery approach aligned with project goals and risk allocation;
5. Assessing which performance parameters to use and how to measure and test them to manage performance;
6. Selecting appropriate template language from a database or e-library of performance guide specifications on the basis of delivery method; and
7. Adapting the specification to the specific project on the basis of guidance and options for roles and responsibilities, testing, verification and acceptance, and payment system.

The level of effort needed to develop this tool would depend in part on the product areas and types of performance specifications considered in the tool. One possible approach would be to develop the tool incrementally, focusing on a specific product area (e.g., pavements) and developing a beta version for testing. The beta version should also be compatible or work in conjunction with other web-based specification development tools, for example, SpecRisk Quality Assurance Specification Development and PaveSpec software tools.

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APPENDIX A

Workshop and Demonstration Project Participants

The R07 research team is indebted to the following individuals who gave their time to participate in workshops and meetings to share their expertise, vet the performance specifications and implementation guidelines, and help advance the demonstration projects.

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APPENDIX B

Definitions

Specification Types

method specifications. Also called recipe or prescriptive specifications, these specifications require the contractor to use specified materials in definite proportions and specific types of equipment and methods to place the material. [TRC E-C074]

performance specifications. Can be used as an umbrella term incorporating end-result specifications, performance-related specifications (PRS), performance-based specifications (PBS), and performance warranties and maintenance provisions. In the broadest terms, a performance specification defines the performance characteristics of the final product and links them to construction, materials, and other items under the contractor control. [PS Strategic Roadmap 2004]

end-result specifications. Require the contractor to take the entire responsibility for supplying a product or an item of construction in exchange for receiving flexibility in the selection of materials, techniques, and procedures. The agency's responsibility is to either accept or reject the final product or to apply a pay adjustment to account for the degree of compliance with the specified performance criteria, as established through sampling and testing of the final in-place product. [TRC E-C074]

quality assurance (QA) specifications. Require contractor quality management and agency acceptance activities throughout the production and placement of a product. Final acceptance of the product is usually based on a random, statistical sampling of the measured quality level on a lot-by-lot basis for key quality characteristics. Price adjustments are generally determined on the basis of a mathematical assessment of the measured variability of the product. [TRC E-C074]

performance-related specifications (PRS). QA specifications that

- Base acceptance on key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that can be used to predict subsequent product performance;
- Use mathematical models to quantify the relationship between key materials and construction characteristics that lend themselves to acceptance testing at the time of construction; and
- Provide rational pay adjustments based on the difference between the as-designed and as-constructed life-cycle cost.

Thus far, PRS have been piloted only for concrete pavement.

performance-based specifications (PBS) are QA specifications that describe the desired levels of fundamental engineering properties (e.g., resilient modulus, creep properties, and fatigue properties) that are predictors of performance and appear in primary prediction relationships (i.e., models that can be used to predict stress, distress, or performance from combinations of predictors that represent traffic, environmental, roadbed, and structural conditions). [TRC E-C074] PBS differ from PRS in that they specify the desired levels of actual fundamental engineering properties (as opposed to key quality characteristics) as predictors of performance. Further development and validation of predictive models and performance-based test methods are needed to advance PBS, which have thus far not been implemented on highway construction projects.

performance-based maintenance provisions. Incorporate performance indicators and thresholds similar to those found in warranties. However, unlike typical short-term warranties, postconstruction operational and maintenance provisions that extend for at least the design life of the facility (i.e., as found on design-build-operate-maintain or public-private partnership projects) are a way to transfer whole-life performance risk to the contractor. They provide maximum flexibility with regard to design, construction means and methods, and the repair and rehabilitation measures that will be necessary over the contract term.

warranties. Hold the contractor responsible for product performance over a prescribed postconstruction period, thereby protecting the agency against defective work and premature failure. Warranty provisions incorporate performance indicators and thresholds for monitoring the actual performance or condition of the product over time (e.g., performance indicators for an asphalt pavement may include rutting and cracking). While the scope of warranted work and performance indicators may not capture all of the factors contributing to performance, they provide a tool to transfer responsibility for performance to the private sector and ensure that the products of construction meet targeted performance thresholds for part of the life cycle of that product or component. Although warranty provisions of sufficient duration to address long-term performance can be developed, bonding issues may limit the practicality of implementing such a specification.

Project Delivery Methods

design-bid-build. The traditional delivery system for the public sector in which the owner contracts separately with a designer and contractor. [NHI Course No. 134058]

design-build. A project delivery system in which an entity provides both design and construction services under a single contract. [NHI Course No. 134058]

performance-based maintenance agreement. A type of contract in which payments for the management and maintenance of road assets are linked to the contractor successfully meeting or exceeding clearly defined performance indicators. [World Bank TN-27]

public-private-partnership/concessionaire. A project delivery system in which an entity or developer invests in a project and provides financing and integrated services to design, construct, operate, and maintain a roadway or transportation facility in return for tolls or some other compensation under the operating or concession agreement.

APPENDIX C

Performance Specifications for Earthwork/Pavement Foundation

Recent developments and improvements to in situ testing devices and integrated machine sensors (e.g., intelligent compaction rollers with accelerometer-based measurements of ground stiffness) have provided opportunities to develop more performance-oriented specifications in the areas of embankment and pavement subgrade/subbase construction.

Two specifications related to pavement foundation systems were prepared under the SHRP 2 R07 project. The first, and perhaps easiest to implement, entails replacing traditional forms of proof rolling with roller-integrated compaction monitoring (RICM) proof mapping to verify that pavement subgrade support conditions are satisfactory. Compared with traditional proof rolling, proof mapping can provide

- Geospatially referenced documentation of an RICM measurement value (MV);
- Real-time information to the contractor during the construction process; and
- Results that can be correlated to subgrade support values, such as bearing capacity and stiffness.

The second specification represents a more comprehensive attempt to specify the construction of embankment and pavement foundation materials in terms of performance measures and quality statements. Key features of this specification include the following:

- Use of RICM technology to provide 100% sampling coverage to identify areas needing further work;
- Acceptance and verification testing using performance measures and parameters—such as elastic modulus testing, shear strength, and permeability—that relate to design assumptions;
- Protocols for establishing target values for acceptance;
- Quality statements and assessment methods that require achievement of at least some overall minimal value during construction, and achievement of a minimum level of spatial uniformity in a given lot area; and
- Protocols for data analysis and reporting such that the construction process is field controlled in an efficient manner to ensure the final product meets design assumptions.

This second specification may not be ready for immediate implementation on a construction project because of training needs and limitations in technology, data analysis/software, and endorsed test methods/standards. Nevertheless, it presents an approach for establishing target values for acceptance based on engineering parameters that relate to design assumptions.

Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Performance Specification for Subgrade

Commentary: The goal of this guide specification is to describe a new construction quality control (QC) and quality assurance (QA) approach to verify that pavement subgrade support conditions are satisfactory. The specification includes a provision to replace traditional forms of proof rolling with roller-integrated compaction monitoring (RICM) proof mapping.

Compared with proof rolling, proof mapping has the advantages of (1) providing geospatially referenced documentation of an RICM measurement value (MV), (2) providing real-time information to the contractor during the construction process, and (3) being correlated to subgrade support values such as bearing capacity and stiffness. By incorporating proof mapping capability into rollers, the results can be used as part of the contractor's process control operations.

Through agency verification performance testing, the RICM measurement records are intended to be used in the agency's acceptance decision. For practical reasons, the verification test results in this situation cannot be independent RICM measurements; so it is recommended that verification tests involve in situ testing conducted by the agency and correlated to the RICM MV (e.g., LWD, DCP, PLT).

This specification was drafted as part of the SHRP 2 R07 research effort to develop guide performance specifications for rapid highway renewal. The Missouri Department of Transportation (MoDOT) provided guidance in the development and field testing of this guide specification. An example of the proof mapping output is provided with this document. The MoDOT field results demonstrate an effective application of RICM proof mapping as an alternative to traditional proof rolling via a loaded, tandem-axle dump truck.

Implementation of this specification is not envisioned in the short term because of limitations in technology, data analysis/software, endorsed test/method standards (e.g., AASHTO), and training. A well-planned program will need to be developed to overcome these obstacles. As part of this research, a demonstration project was organized to provide field data to validate parts of this specification. The project report summarizes key findings from the demonstration project.

1 DESCRIPTION

This work shall consist of testing the support conditions of the prepared roadbed subgrade by proof mapping with a roller-integrated compaction monitoring (RICM)–equipped compactor before paving. Perform RICM proof mapping on all prepared subgrade, including main line, outer roadways, ramps, and all side streets. The department will establish target values for proof mapping through on-site RICM verification testing.

Record and document all RICM measurements obtained as part of compaction process control operations. Submit process control results to the department on request. Submit RICM proof mapping passes intended for inclusion in the department's acceptance decision on completion of mapping operations. RICM deliverables shall be current for each payment period.

Commentary: As an alternative to traditional nuclear moisture density testing and moisture content testing, drive core sampling (ASTM 2937), dynamic cone penetration testing (ASTM 6951), plate load testing (ASTM D1196), light weight deflectometer testing (ASTM E2583 or ASTM E2835), and other tests can be considered. A description of target value determination for these alternative methods is beyond the scope of this guide specification. Motivations to use alternatives to nuclear gauges include elimination of the nuclear compliancy and safety training issues and the understanding that current RICM measurements are better correlated to strength and stiffness measurements than to volumetric/gravimetric measurements.

2 TERMS AND DEFINITIONS

For the purpose of this specification, the following definitions shall apply.

A. **Roller-integrated compaction monitoring (RICM):** RICM for earthwork and pavement foundation materials is defined as the generic gathering of data from roller systems involved with the measurement and recording of roller position, date/time, speed, vibration frequency, vibration amplitude, pass count, travel direction, and a compaction measurement value (MV). The RICM system is supplied by either the roller manufacturer or a third party. The RICM monitoring system shall include calibration records of the sensor systems.

B. **Measurement value (MV):** Measurement values are calculated from calibrated sensors integrated into rollers that provide information on machine-ground interaction(s). Machine-ground interaction measurements are typically derived from vibration analysis of accelerometers, sensor systems that monitor machine drive power inputs, or direct measures of sinkage/rutting.

C. **Target value (TV):** Target values are the established minimum MVs based on in situ correlation analysis to in situ performance point measurements. Correlation analysis requires statistical analysis of geospatially paired independent point measurement values (PMVs) linked to MVs using global navigation satellite system (GNSS) positioning information.

D. **Subgrade bearing capacity** is the plate load test contact pressure required to induce 1 in. of plate deflection (25.4 mm) for a 12-in. (300-mm) diameter plate.

E. **Real-time kinematic (RTK)–based GNSS** with base station corrections is used for determining the position of the roller and correlation spot tests. Results from the RICM shall be displayed to the roller operator on a color-coded computer screen in real time during roller operations, and the data shall be saved for transfer and viewing by the engineer.

Commentary: Additional terms and definitions may be needed for modified versions of this specification. The focus on subgrade bearing capacity for this specification is based on MoDOT's current proof rolling specification. Also note that the incorporation of moisture content measurement into the suite of RICM measurements is not commercially available; but it is an ongoing area of research and industry development, and it is expected to be incorporated in the near term.

3 EQUIPMENT/TEST CAPABILITIES

A. Provide RICM-equipped compactor(s) that have the capability to near continuously measure and record a roller-ground interaction measurement value (MV) that correlates to the subgrade bearing capacity as determined from a static plate load test performed in accordance with ASTM 1196.

Commentary: The RICM system requirement of "near continuous measurement" is intended to provide a requirement for reporting the measurement value. Reporting an RICM MV in distance increments ≤12 in. (300 mm) traveled is desirable but is not a set requirement at this point.

An alternative to defining subgrade bearing capacity based on 1 in. of plate deflection is to use a target minimum modulus of subgrade reaction (e.g., k-value used for pavement design purposes) at a defined plate contact stress. In brief, modulus of subgrade reaction is defined as the plate contact stress divided by the average plate deflection (see ASTM D1196 or AASHTO T222). Common plate contact stress values used to define modulus of subgrade reaction are 10 pounds per square inch (psi) (69 kPa) for subgrade and 30 psi (207 kPa) for stabilized subgrade and aggregate base. Although a 12-in. diameter plate is listed above, a plate diameter of 30 in. is normally the reference standard. For plate diameters smaller than 30 in. (762 mm), perimeter to surface area corrections are typically required so that the reported values are equivalent to the standard 30-in. diameter plate.

B. Provide an RTK GNSS to acquire northing, easting, and elevation data for mapping of RICM measurements. Ensure the system has the capability to collect data in an established project coordinate system. Furnish a local base station for broadcasting differential correction data to the rollers with a tolerance less than 0.1 ft in the vertical and horizontal.

Commentary: If a lower accuracy system is substituted for RTK GNSS, the quality of correlation analysis from verification testing is reduced and may require increased in situ testing frequencies and/or high minimum RICM target values to account for position induced measurement error. RTK GNSS position information is recommended.

C. The RICM system shall have the capability to immediately display and provide a permanent electronic record of the proof mapping results and data as follows:
   1. Integrated, color-coded, real-time computer display viewable by roller operator showing RICM measurement value (MV), RICM MV with reference to RICM target value (TV), and roller pass coverage. Provide displayed results to the engineer for review on request.
   2. Electronic data file in American Standard Code for Information Interchange (ASCII) format with time stamp, RTK global positioning system (GPS) position in state DOT standard coordinate system, roller operation parameters (speed, gear, and travel direction), the RICM measurement value (MV), and target value (TV).

4 CONSTRUCTION REQUIREMENTS

4.1 RICM Work Plan

Submit to the engineer an RICM work plan at the time of the preconstruction conference.

A. Describe in the RICM work plan the following:
   - Roller vendor,
   - Roller model,
   - Roller dimensions and weights,
   - Description of RICM measurement system(s),
   - Past independent verification of RICM correlations to in situ engineering measurements,
   - Roller data collection methods including sampling rates and intervals,
   - RTK GPS capabilities,
   - Minimum parameters for GPS calibration (required daily),
   - Validation process of RICM equipment and results (required daily),
   - Documentation system and data file types,
   - Software,
   - Roller operations per manufacturer recommendations, and
   - Proposed rolling patterns for each lift.

B. Describe the process for RICM operations during the agency's testing to establish RICM target values.

C. Address quality management of the pavement foundation layers, including testing to be performed and coordination with the department's efforts to verify that the contractor is meeting the minimum and/or maximum engineering parameter values.

Commentary: Agencies are encouraged to consider requirements for RICM operating training/certification when the data will be used as part of the acceptance decision.

D. Describe how data will be acquired and transferred to the engineer, including method, timing, and personnel responsible. Data transfer shall occur at a minimum once per day or as directed by the engineer. Provide and export the following data in a comma, colon, or space delimited ASCII file format:
   - Machine model, type, and serial/machine number;
   - Roller drum dimensions (width and diameter);
   - Roller and drum weights;
   - File name;
   - Date stamp;
   - Time stamp;

- RTK-based GPS measurements showing northing, easting, and elevation (e.g., in local project coordinate system);
- Roller travel direction (e.g., forward or reverse);
- Roller speed;
- Vibration setting (i.e., on or off);
- Vibration amplitude;
- Vibration frequency;
- RICM MV; and
- Pass count.

4.2 RICM Target Value Determination and Correlation Analysis

A. For RICM verification and correlation analysis to establish RICM target value, the department (or an independent third-party inspection firm) will conduct in situ testing. Perform RICM roller operations for correlation analysis in the presence of the engineer, unless approved otherwise. The engineer will review all results to set the RICM TV.

B. The department (or its third-party inspection firm) will prepare reports containing the results of the plate bearing testing and assessment of the RICM TV determination within 24 hours of testing. The test report will include the following:
   - Test identification number,
   - Dates of testing,
   - Names of QC/QA field personnel conducting tests,
   - Description of tests,
   - Tables presenting all data,
   - Plots of plate bearing test results,
   - Summary of calculated engineering values,
   - Plot of RICM MV versus independent measurements, and
   - Plots of RICM proof maps.

4.3 Proof Mapping Roller Operation

To allow comparison of successive roller passes, the roller operations should be consistent between passes. For static (e.g., nonvibratory) rolling operations, maintain relatively constant speed and operate within the manufacturers slope and pitch limits. For vibratory rolling operations, maintain relatively constant vibration frequency and amplitude during roller operations. Permitted variation in vibration frequency is ±2 Hz. Maintain rolling speed to provide a minimum of 10 impacts per linear foot and within ±0.5 mph during measurement passes. Record roller operations in forward and reverse directions. Check and validate, if necessary, RICM equipment at the beginning of each workday. Make GNSS calibration checks on a daily basis.

Commentary: Changes in frequency and amplitude can influence RICM MVs. However, the limits for vibration frequency and speed variation can be adjusted if the RICM technology is documented as providing reliable and repeatable measurements outside the noted ranges. Speed fluctuations can also influence the RICM MVs and should not be allowed outside of the specified range during measurement passes. It is anticipated that RICM MVs will be affected by rolling direction, and therefore the output data fields shall indicate rolling direction.

A. RICM proof mapping shall include two complete passes per lane and one complete pass in shoulder areas. Perform each pass so that a 0% to 10% overlap occurs between passes in the coverage area. The roller operations and rolling patterns for each lift shall be in accordance with the manufacturer guidelines and as proposed in the RICM work plan, subject to approval by the engineer.

B. Protect completed work before the placement of the subsequent layers and until final acceptance of the project. At any time during construction of aggregate base pavement materials, the engineer may require the contractor to perform RICM proof mapping according to this specification in areas on the project where unstable subgrade is observed. Make corrections to the subgrade even if the engineer previously accepted the areas before they became unstable.

C. Provide the results of RICM proof mapping to the engineer in printed and electronic form on request or within at least 24 hours of measurement. On approval of the RICM proof mapping, place the subbase, base course, or initial pavement course within 48 hours. If the subbase, base coarse, or initial pavement course is not placed within 48 hours or the condition of the subgrade changes because of weather or other conditions, perform proof mapping and corrective work at the discretion of the engineer and at no expense to the department.

5 PERFORMANCE REQUIREMENTS

The department will consider the roadbed to be unstable if the RICM measurement value is less than the established requirements for the mapping area based on the RICM target value (TV). To establish the RICM TV, the department will perform correlation analysis of the RICM MV to the subgrade bearing capacity, as defined in Section 2. The department will use simple linear regression analysis to establish a correlation between the RICM MV and plate load test values. The department will use a minimum of eight plate load tests to establish the correlation. The department will set the RICM TV as the RICM MV that correlates to a 1-in. plate deflection at a contact pressure of 90 psi (10,178 lbf for 12-in. diameter plate).

Commentary: Simple linear regression analysis involves developing a relationship between independent and dependent variables using an intercept and slope coefficient. This analysis is simple enough to be performed on a hand calculator. For each linear, univariate regression model, the coefficient of determination R2 provides a measure of how well the regression model describes the data. In this specification the correlation is considered acceptable if R2 ≥ 0.5. The regression relationships will be developed by considering the "true" independent variables (in this specification, plate bearing test measurements or modulus of subgrade reaction) and the RICM MV as the dependent variable using the model shown in Equation 1.

$$\text{RICM MV} = b_0 + b_1 \cdot \alpha \qquad (1)$$

where b_0 = intercept, b_1 = slope, and α = independent variable.

As an alternative to on-site calibration using simple linear regression analysis, suitable evidence of RICM MV correlations with the selected in situ point measurements (e.g., plate load tests) may be used. Suitable evidence would be unbiased third-party measurements describing and verifying the statistical significance of the determined correlations. The correlations would need to be derived from the same roller machine configuration, operating conditions, and similar soil types.

Note: Relationships between RICM to in situ point measurements can be nonlinear, in which case simple linear regression is not recommended. There are many nonlinear models that can be used to develop correlations. An example of a hyperbolic relationship is provided in Figure C.1.

6 ACCEPTANCE REQUIREMENTS

The department will base acceptance of the RICM proof mapping area on achievement of the RICM TV in the proof mapping area with a minimum of 80% of the RICM MV ≥ TV and no contiguous, isolated areas that are larger than 25 ft in length. When proof mapping identifies unacceptable areas in the roadbed, the contractor shall rework the area by scarifying and moisture conditioning the soils as necessary. Reshape and compact the disturbed areas. The engineer may not require retesting of that area by RICM proof mapping if the engineer is satisfied that the corrective actions taken have eliminated the cause of the instability as evidenced by testing and/or visual inspection.

Commentary: The 80% minimum criterion is a suggested value and is expected to vary from about 70% to 90% depending on the desired quality conditions and uniformity. Further, the 25-ft maximum for unstable areas may be adjusted from 3 ft to 50 ft contiguous length. An alternative to the maximum continuous length is to use a maximum area such as the roller footprint (about 150 ft^2). Currently, limited information is available to fully understand the impacts of the size of nonconforming areas, and the engineer should use judgment in setting these limits. Areas requiring corrective work, as determined from proof mapping, because of unforeseen conditions may require extra work, in which case the engineer may need to identify the needed remediation. Proof mapping areas are generally on the order of the project width by 200 ft to 1,000 ft in length, but that will depend on the project conditions.

In addition to the RICM mapping described, it may be desirable for the agency to conduct quality assurance plate bearing tests. The number of tests and test locations will be based on assessment of the RICM MVs. In areas of high RICM variability (e.g., coefficient of variation, COV >20%), the test frequency will be about one test per 500 ft. In areas of low RICM variability (e.g., COV <20%), the test frequency will be about one test every 1,000 ft. The test locations could be randomly selected or by inspection of the RICM proof map to identify soft spots. The target numbers for quality assurance testing and RICM variability are related to the materials being tested and the type of RICM measurement technology. Engineering judgment should be used when selecting these limits. Typical values are presented in NCHRP Report 676.

7 BASIS OF PAYMENT

All RICM proof mapping operations are considered incidental to the grading and earthwork. No direct payment will be made to the contractor for RICM proof mapping or corrective work required as a result of the proof mapping.

Commentary: An alternative basis of payment language is as follows: Payment for RICM will be the lump sum contract price. Payment is full compensation for all work associated with providing RICM equipped rollers, transmission of electronic data files, two copies of RICM roller manufacturer software, and training. Delays resulting from GPS satellite reception of signals to operate the RICM equipment or RICM roller breakdowns will not be considered justification for contract modifications or contract extensions. In the event of RICM roller breakdowns, system malfunctions, or GPS problems, the contractor may operate with conventional rolling operations; but RICM proof mapping shall be provided for a minimum 90% of the project surface.

If, because of unforeseen ground conditions and as determined from proof mapping, the engineer determines that corrective construction work is necessary, such corrective work could be paid at the applicable contract unit price or as extra work.

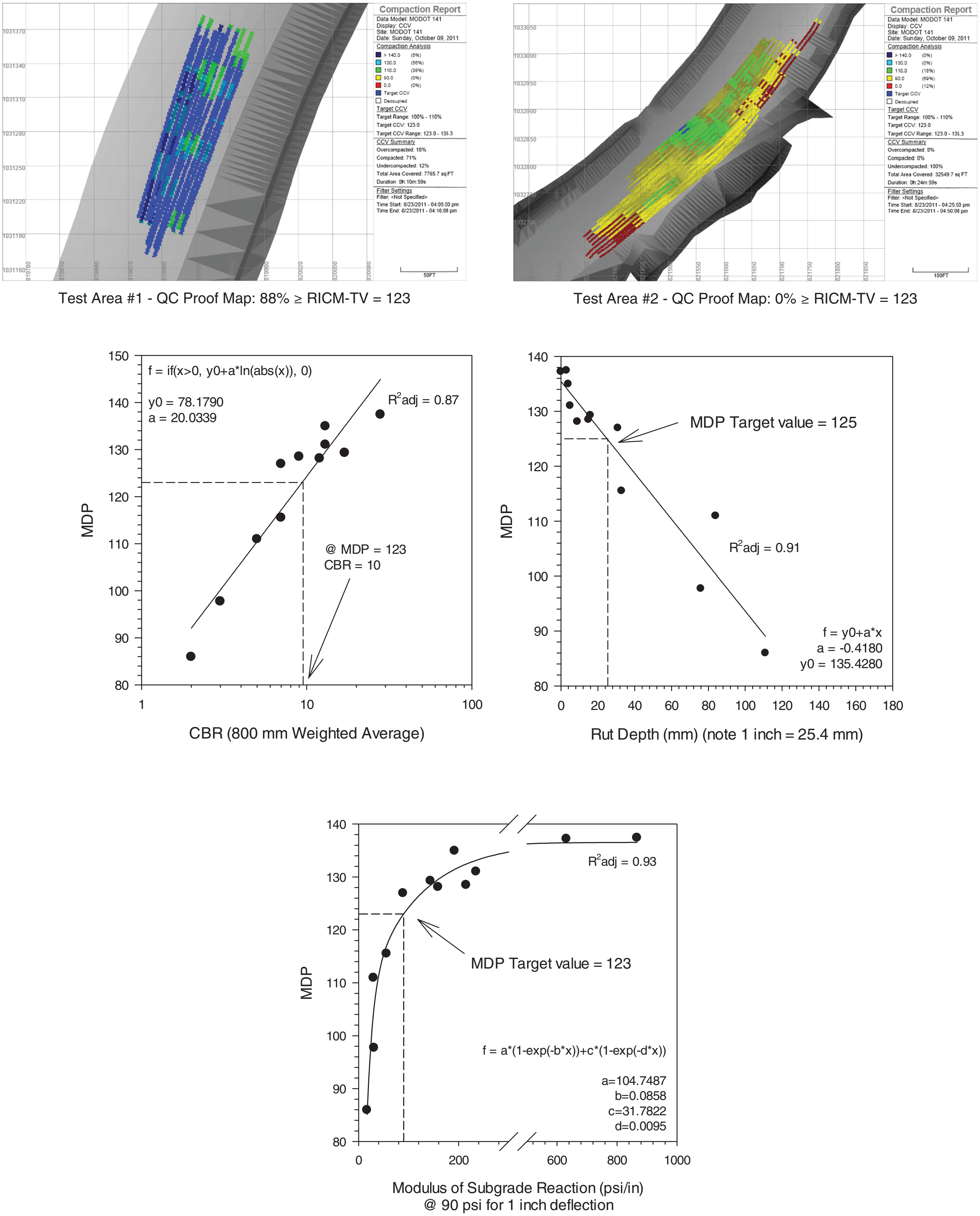

Figure C.1. Example RICM proof maps and calibration plots.

Performance Specification for Embankment and Pavement Foundation Construction

Commentary: This guide specification, developed under the SHRP 2 R07 project, provides a template from which a state highway agency can develop a detailed performance specification for quality control (QC) and quality assurance (QA) of embankment and pavement foundation materials. Implementation of this specification will require investment in new technologies, training, and data management solutions. Traditionally, earthwork specifications are prescriptive, require relatively low test frequency, and/or do not use acceptance testing methods that directly evaluate performance characteristics during construction. To overcome these limitations, this guide specification includes the following key features:

- Acceptance and verification testing using performance measures and parameters—such as elastic modulus testing, modulus of subgrade reaction, and shear strength—that relate to design assumptions;
- Use of real-time roller-integrated compaction monitoring (RICM) technology [i.e., intelligent compaction (IC), continuous compaction control (CCC), compaction documentation system (CDS)] or instrumented proof rolling technology to provide nearly 100% coverage to identify areas needing further work, geospatially referenced data for uniformity analysis, and information to select verification testing locations;
- Protocols for establishing target values for acceptance based on the required engineering parameter values consistent with the design methodology used for the project;
- Quality statements and assessment methods that require achievement of at least some overall minimal value during construction, achievement of a minimum level of uniformity, and identification of contiguous areas of noncompliance that exceed the maximum allowable;
- Protocols for data analysis and reporting such that the construction process is field controlled in an efficient manner to ensure the final product meets design assumptions;
- Assignments of responsibility for field QC/QA, data reporting, and verification testing, and guidance on data interpretation and remediation; and
- A few options for pay adjustments that provide incentives/disincentives to promote achievement of the specific performance criteria and maximize coverage of the performance verification assessment.

A distinguishing factor for this guide specification, compared with other components of civil infrastructure, is the subterranean nature of the earthworks and pavement foundation projects. If such projects are not built to achieve the intended performance criteria to begin with, maintenance and repair can be costly and difficult, if not impossible. The need to provide technologies and specification guidelines to improve process control and verify as-constructed conditions remains high. A companion performance guide specification was developed separately from this document and titled, Roller-Integrated Compaction Monitoring (RICM) Proof Mapping Performance Specification for Subgrade. The proof mapping guide specification is a simpler alternative to this specification and achieves many of the key performance criteria.

Implementation of this specification is not envisioned in the short term because of limitations in technology, data analysis/software, endorsed test/method standards (e.g., AASHTO), and training. A well-planned program needs to be developed to overcome these obstacles. As part of this research, demonstration projects were organized to provide field data to validate parts of this specification. A project report summarizes key findings from the demonstration.

1 GENERAL

This specification presents details on how to evaluate and accept the placement of embankment and pavement foundation materials in terms of performance measures and performance quality statements.

A. **Materials:** This specification is applicable to a range of unbound granular and nongranular earth materials, including general embankment fill materials, pavement subgrade materials, unbound aggregate base materials, and chemically and mechanically stabilized materials.

B. **Technologies:** Testing technologies that provide rapid measures for increased test frequency are required for quality control (QC) and quality assurance (QA) testing. Many of these technologies are standardized with existing test protocols while some are not standardized and require special protocols for their use as described in this specification.

C. **Performance criteria and assessment:** The goal of the specification is to provide a mechanism to ensure that the compacted materials are satisfactory for the intended design purpose. Performance quality assessment is based on achievement of the following quality criteria:
   1. Critical design property value(s) over the entire site achieves the specified minimum value;
   2. Nonuniformity of the critical design property value(s) over the entire site are no more than the specified maximum amount;
   3. Contiguous noncompliance areas are not larger than the specified maximum value; and
   4. Moisture contents are greater than the specified minimum values to eliminate postconstruction saturation induced volume and stiffness changes to the acceptable level.

Commentary: Traditional end-result earthwork specifications normally address item (1) through infrequent random point measurements. The point measurements have traditionally been moisture content and density determined from nuclear density tests. The test frequency is such that less than 0.1% of the soil volume is typically tested, making statistical analysis of the data difficult. Geospatially referenced RICM and proof rolling technologies provide the opportunity to address items (2) and (3). Options for enforcing these quality criteria are presented in this guide specification. Generally, moisture control is critical for effective and efficient soil compaction. The specification options address the influence of moisture control through an option to include moisture content as a significant variable in the correlation analysis with stiffness and strength performance criteria and by requiring laboratory testing to select minimum moisture contents to limit post-construction wetting-induced design property changes to within acceptable limits.

D. **Responsibilities and reporting:** As part of this specification, the contractor shall develop, implement, and maintain a quality management plan (QMP). The plan shall address selection of the measurement technologies, methods for test strip construction to establish site- and material-specific target values, and electronic data collection and transfer.

2 TERMS AND DEFINITIONS

For the purpose of this specification, the following definitions shall apply:

A. **Roller-integrated compaction monitoring (RICM):** RICM for earthwork and pavement foundation materials is defined as the generic gathering of data from roller systems involved with the measurement and recording of roller position, date/time, speed, vibration frequency, vibration amplitude, pass count, travel direction, and a compaction measurement value (MV). The RICM system is supplied by either the roller manufacturer or a third party. The RICM monitoring system shall include calibration records of the sensor systems.
B. **Measurement value (MV):** Measurement values are calculated from calibrated sensors integrated into rollers that provide information on machine-ground interaction(s). Machine-ground interaction measurements are typically derived from vibration analysis of accelerometers, sensor systems that monitor machine drive power inputs, or direct measures of sinkage/rutting.
C. **Target value (TV):** Target values are the established minimum MVs based on in situ correlation analysis to in situ performance point measurements. Correlation analysis requires statistical analysis of geospatially paired independent point measurement values (PMV) linked to MVs using global navigation satellite system (GNSS) positioning information.
D. **In situ performance point measurement value (PMV):** Point measurement values are in situ measurements used to set TVs for RICM MVs. PMVs suitable for performance measurements include measures of strength and stiffness.
E. **Real-time kinematic (RTK)–based GNSS** with base station corrections is used for determining the position of the roller and correlation spot tests. Results from the RICM shall be displayed to the roller operator on a color-coded computer screen in real-time during roller operations, and the data shall be saved for transfer and viewing by the engineer.
F. **RICM repeatability** refers to variation observed in the measurement values (also referred to as measurement error) obtained over a test area from consecutive passes under identical operating conditions (i.e., using same operator, amplitude, speed, direction of travel, etc.).
G. **RICM reproducibility** refers to the variation in measurements obtained from consecutive passes under changing conditions. The changing conditions may be due to different measurement methods, machines used, operators, or speed and amplitude settings.

3 TEST EQUIPMENT AND METHODS

Commentary: This section should list and describe suitable test equipment and methods to be used in the performance quality assessments. Some of the test methods may not have established AASHTO or ASTM standards and will require listing of state agency standards and/or reference to accepted user manuals. There are many details here, including special focus on RICM and proof rolling/mapping equipment as it is relatively new and not well described in current specifications. The devices for which AASHTO/ASTM standards exist are not described.

3.1 Roller

Provide RICM rollers that comply with the standard specifications for self-propelled vibratory rollers, static rollers, or pneumatic roller. Ensure that RICM equipment can measure roller position, date/time, speed, vibration frequency, vibration amplitude, pass count, travel direction, and a compaction measurement value (MV) with known repeatability and reproducibility. Provide a computer screen in the roller cab for viewing measured results. Ensure that results are stored for transfer to the engineer for viewing on a laptop computer. Provide the engineer with a copy of the RICM data analysis software for viewing results. Ensure that results are displayed as color-coded spatial maps based on GNSS coordinates.

3.1.1 Data Collection, Export, and Onboard Display

Provide and export the following data in a comma, colon, or space delimited ASCII file format:

1. Machine model, type, and serial/machine number;
2. Roller drum dimensions (width and diameter);
3. Roller and drum weights;
4. File name;
5. Date stamp;
6. Time stamp;
7. RTK-based global positioning system (GPS) measurements showing northing, easting, and elevation [±76 mm in the horizontal and vertical directions (RTK GPS)];
8. Roller travel direction (e.g., forward or reverse);
9. Roller speed (±0.5 km/h);
10. Vibration setting (i.e., on or off);
11. Machine gear;
12. Vibration amplitude (±0.2 mm);
13. Vibration frequency (±2 Hz);
14. Compaction measurement value (MV); and
15. Pass count.

Ensure that the roller onboard display will furnish color-coded GNSS-based mapping showing number of roller passes, vibration frequency, vibration amplitude, and the MV on a computer screen in the roller operator's cab. Provide displayed results to the engineer for review upon request.

3.1.2 Local GNSS Base Station

Provide an RTK GNSS to acquire northing, easting, and elevation data for use in mapping of RICM measurements. Ensure the system has the capability to collect data in an established project coordinate system. Furnish a local base station for broadcasting differential correction data to the rollers with a tolerance less than 25 mm in the vertical and horizontal.

Commentary: If a less accurate system is substituted for RTK GNSS, the quality of correlation analysis from verification testing is reduced and may require increases in the number of in situ tests and/or a higher minimum RICM target value to account for position-induced measurement error. RTK-GNSS position information is recommended to minimize this error.

3.1.3 Roller Operations

Conduct roller operations according to the manufacturer's recommendations to provide reliable and repeatable RICM measurements. To allow comparison of successive roller passes, the roller operations should be consistent between passes. For static (e.g., nonvibratory) rolling operations, maintain relatively constant speed and operate within the manufacturer's slope and pitch limits. For vibratory rolling operations, maintain relatively constant vibration frequency and amplitude during roller operations. Permitted variation in vibration frequency is ±2 Hz. Maintain rolling speed to provide a minimum of 10 impacts per linear foot and within ±0.5 mph during measurement passes. Record roller operations in forward and reverse directions. If necessary, check and validate RICM equipment at the beginning of each workday. Make GNSS calibration checks on a daily basis.

Commentary: Changes in frequency and amplitude can influence RICM MVs. However, the limits for vibration frequency and speed variation can be adjusted if the RICM technology is documented as providing reliable and repeatable measurements outside the noted ranges. Speed fluctuations can also influence the RICM MVs and should not be allowed outside of the specified range during measurement passes. RICM MVs will likely be affected by rolling direction, and therefore the output data fields shall indicate rolling direction.

3.1.4 Repeatability and Reproducibility Analysis

RICM measurements determined from repeated passes must exhibit reproducible and repeatable results for well-compacted materials. If the results are not repeatable, a test section should be constructed to evaluate the influence of roller operating and changing ground conditions. The procedure for calculating reproducibility and repeatability errors is presented in Attachment A: Repeatability and Reproducibility Analysis Using Two-Way Analysis of Variance (ANOVA).

Commentary: Currently, there are no published acceptable limits of measurement error for roller MVs. However, it is an important element of this specification for evaluating the usefulness of a machine before its use or even periodically during the course of project; this will help build confidence in the measurements. As with any quality assessment device, the measurement values should be both repeatable and reproducible. Variability in roller MVs is one source of scatter in relationships compared with in situ point measurements. The measurement variability is quantified in this specification in a repeatability and reproducibility context. Repeatability refers to variation observed in the measurement values (also referred to as measurement error) obtained over a test area from consecutive passes under identical operating conditions (i.e., using same operator, amplitude, speed, direction of travel, etc.). Reproducibility refers to the variation in measurements obtained from consecutive passes under changing conditions. The changing conditions may result from different measurement methods, machines used, operators, or speed and amplitude settings. The repeatability and reproducibility analysis procedure described is applicable for any RICM technology, although the magnitude of measurement error (for the range of MVs) is expected to be different for different RICM technologies. This is important from a specification standpoint as it affects the regression relationships, minimum TVs, and anticipated variability in MVs.

3.2 Test Devices for In Situ Performance Point Measurement Values

The department will establish target values (TVs) for RICM MVs based on material and RICM machine-specific parameters. Select appropriate in situ PMVs from Table C.1.

Maintain current records of calibration and inspection records for the in situ test devices. Submit records to the engineer, on request, before initiating testing.

Commentary: The in situ test technologies listed were selected with the goal of linking design with the as-constructed conditions. Ideally, these measurement technologies will (1) measure characteristics that significantly affect performance, (2) assess quality compaction characteristics that are under the direct control of the contractor, and (3) provide a measurement at or near the time of construction. In some cases no suitable testing technology is available to measure the various

Table C.1. In Situ Point Measurements Property

Measurement	Test Methods/References	Measurement Parameter
Modulus of subgrade reaction (k-value)	AASHTO T222: Nonrepetitive Static Plate Load Test of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements	k-value
Dynamic modulus	ASTM E2583: Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD); ASTM WK25932: New Test Method for Measuring Deflections Using a Portable Impulse Plate Load Test Device	E_{LWD}
Dynamic cone penetration (DCP) resistance	ASTM D6951: Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications	DCP Index, California bearing ratio (CBR)
Falling weight deflectometer (FWD) modulus	ASTM D4694–09: Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device	E_{FWD}
Clegg impact hammer (CIH) value	ASTM D 5874: Standard Test Method for Determination of the Impact Value (IV) of a Soil	Clegg impact value (CIV)
Rolling wheel deflectometer (RWD) value	ARA. 2005. *Rolling Wheel Deflectometer.* Brochure. Applied Research Associates, Inc., Albuquerque, N.M. http://www.ara.com/Projects/RWD_brochure.pdf. Accessed November 9, 2009.	δ
Seismic pavement analyzer (SPA) value	Nazarian, S., M. Baker, and K. Crain. 1995. Use of Seismic Pavement Analyzer in Pavement Evaluation. In *Transportation Research Record 1505,* TRB, National Research Council, Washington, D.C., pp. 1–8.	E_{SPA}
Borehole shear test (BST) shear strength parameters	Handy, R. L. 2002. *Borehole Shear Test Instruction Manual.* Handy Geotechnical Instruments, Inc., Madrid, Iowa.	c', ϕ'
Vane shear test (VST) peak and residual shear strength	ASTM D2573: Standard Test Method for Field Vane Shear Test in Cohesive Soil	S_u, $S_{u\text{-}r}$
Moisture content	Numerous devices can be used to determine moisture content.	w%
Other*	To be determined*	To be determined*

Note: *Other test devices may provide desired performance assessments that are not listed here, and many new technologies are being developed that will serve this purpose.

functional design properties (e.g., measures that reflect long-term repetitive loading conditions). In addition to these current technology gaps, analysis gaps exist for which there is no known way to collect and process the desired information. Many recent studies (e.g., NCHRP 626) have focused on identifying improved measurement technologies.

4 DESIGN AND PERFORMANCE CRITERIA

Design parameter values for the materials subject to performance quality assessment in this specification were developed on the basis of the procedures identified in Table C.2. The design values establish the performance quality target values to be evaluated in the quality control and quality assessment testing. Table C.2 also lists the project-specific performance criteria.

Commentary: This section lists the project design procedure(s) and elements of the geotechnical system and engineering parameters and mechanisms that control performance attributes. By providing this information, the link is established between the design phase and construction quality assessment phase of the project. The performance parameters determined from laboratory measurements and the field investigation should be provided.

5 CONSTRUCTION REQUIREMENTS

Commentary: In exchange for providing the contractor flexibility with regard to construction operations to meet the design and performance criteria for embankment and foundation construction, the agency should require the contractor to describe in its QMP how it intends to perform the work and meet the performance requirements. A well-developed plan should help assure the agency that the contractor understands how its own actions (e.g., scheduling, hauling, spreading, finishing, and compaction) will affect the in-place properties and performance of the work and that the contractor has planned the work and allocated its resources accordingly.

6 QUALITY MANAGEMENT

Commentary: The requirements included in this section assume the contract includes a separate provision related to development and implementation of a quality management plan (QMP) that defines general requirements related to the

Table C.2. Example Design and Performance Criteria

Material Components	Design Procedure[1]	Example Performance Criteria[2]
Embankment fill (>3 ft below bottom of pavement layer)	Limit equilibrium slope instability analysis at (failure surface) FS ≥ 1.5	Effective cohesion, c' = 500 psf Effective friction angle, ϕ' = 25 degrees (accounting for geometric factors and ground water table, etc.)
	Total settlement criteria ≤ 2% of fill height	k-value ≥ 200 pci
	Differential settlement criteria ≤ 1 in.	w% ≥ strain softening condition for post-saturation and ≤ required to achieve strength/stiffness criteria
Pavement foundation layers (subgrade, stabilized subgrade, unbound base and fill ≤3 ft below bottom of pavement layer)	1993 AASHTO Guide for Design of Pavement Structures/*MEPDG*	Subgrade k-value = 160 pci Stabilized subgrade, k-value = 300 pci or achievement of 50 psi unconfined compressive strength
	Determine resilient modulus (M_r) per AASHTO T307 and estimate k-value = M_r/19.4	Unbound k-value = 400 pci (composite k-value based on 30-in. diameter plate load test)
		In situ M_r = 30,000 psi
		w% ≥ strain softening condition for post-saturation and ≤ required to achieve strength/stiffness criteria
Fill materials at identified critical areas (e.g., structural foundations, box culverts)	Total settlement criteria ≤ 1% of fill height	k-value = 500 pci
	Differential settlement criteria ≤ 0.5 in.	w% ≥ strain softening condition for post-saturation and ≤ required to achieve strength/stiffness criteria

[1] Agency to update design references with applicable FHWA design or agency procedures.

[2] Parameters and values provided as examples only. Actual values are project specific and based on the project design requirements.

contractor's quality management personnel and organizational structure, documentation and reporting requirements, and procedures related to nonconforming work, corrective action, and similar matters. In case such requirements are not otherwise addressed in the contract's general conditions, a sample general provision addressing quality management is included among the guide specifications developed under the SHRP 2 R07 project.

6.1 Contractor's Quality Management Plan (QMP)

Develop and submit a project-specific QMP at the time of the preconstruction meeting that addresses

- Quality control of the compaction materials, including RICM equipment, operations, and coordination with the department's on-site calibration testing. QC may be based on assessment of the RICM MVs according to Section 6 of this specification.
- Process for performing compaction operations during the agency's verification testing to establish RICM target values.
- Data acquisition methods and methods of transmitting data to the engineer.
- Corrective actions to bring areas of noncompliance into compliance per the performance assessment criteria described in Section 6 of this guide specification.
- Development of daily quality compaction report submittals to the engineer.

6.2 RICM Repeatability/Reproducibility Analysis

Perform a repeatability/reproducibility analysis according to the procedures described in Attachment A. Conduct repeatability/reproducibility analyses at the beginning of the project and thereafter as directed by the engineer.

6.3 Correlation Analysis

For correlation analysis, the agency will conduct the in situ PMV testing. Perform RICM roller operations for calibration testing in the presence of the engineer, unless approved otherwise. Conduct roller operations to ensure the results are repeatable and reproducible.

The engineer will evaluate all MV and PMV results to set the RICM TV. The analysis details for correlation analysis are described in Attachment B: Correlation Analysis Between RICM Measurement Values and QA/QC Point Measurements. A test report will be prepared within 24 hours of completing the testing and will include the following:

- Test identification number;
- Dates of testing;
- Names of QC field personnel conducting tests;
- Description of tests;
- Tables presenting all data;
- Plots of test results;
- Summary of calculated engineering values;
- Plot of RICM MV versus in situ PMV measurements; and
- Geospatially referenced plots of RICM results (see Attachment C: Geospatial Uniformity Analysis).

7 PERFORMANCE EVALUATION AND ACCEPTANCE CRITERIA

The department will base performance compaction acceptance on four primary quality factors for compacted materials and Type I or Type II performance compaction quality assessment options.

7.1 Primary Quality Factors

The four primary quality factors for compacted materials are as follows:

1. The RICM TV (in correlation with the PMV) over the entire site is achieved to at least some specified minimal value during construction (e.g., 80% of the lot area).
2. The variability of the RICM MV (in correlation with the PMV) over the entire site is no more than some specified maximum amount [e.g., the coefficient of variation (COV) <30%, distribution of 90% of 90% RICM TV, or geospatial statistical analysis parameters].
3. Contiguous areas ("blobs") not achieving the RICM TV (in correlation with the PMV) are no larger than some maximum specified value (e.g., 25 yd^2 of area, depending on the severity of noncompliance).
4. The moisture content is not less that the critical moisture content to ensure postsaturation placement volumetric stability (e.g., prevent collapse/swell, strain softening).

Assessment of these factors is described in Section 7.2, Quality Compaction Performance Acceptance Options.

Commentary: The quality assessment program should provide the ability to measure the design parameters in the field to assess compliance with the design, and to facilitate the setting of suitable target values for in situ measurements that will provide assurance of the quality and performance of the final product. The four primary quality factors in Section 7.1 form the basis of requirements for testing to establish the target values and define responsibilities for the contractor's process control and the agency's verification and acceptance testing. The specification should require that the contractor report the QC from RICM MVs while the agency (or independent agent) performs the in situ performance QA testing. The RICM MVs will be part of the overall data used to inform the agency's acceptance decision.

7.2 Quality Compaction Performance Acceptance Options

The department will assess the four primary quality factors using one of the two options described in the following:

> ***Commentary:*** Refer to Figure C.2 and Table C.3 for additional explanation of the two options.

Performance compaction Type I: For this option, the department will use the calibrated RICM-MV maps to target locations for QA PMV testing. The department will use the RICM-MV proof maps to identify areas of possible noncompliance (e.g., too dry/wet, undercompacted, low stabilizer content) to focus QA point measurements.

Use the compaction history of the RICM MVs to control the compaction process. Follow and document proper QC procedures (e.g., controlling moisture content, lift thickness) during compaction operations. Provide the RICM-MV proof maps to the engineer for evaluation and selection of QA test locations. The proof maps are to be assessed in terms of the four primary quality factors described in Section 7.1.

The engineer (or the department's independent QA agent) will select the number of tests and test locations on the basis of the RICM proof maps. The department will base acceptance on achievement of the RICM-TV requirements and in situ PMVs. If quality criteria are not met, perform additional compaction passes and/or adjust construction operations (e.g., moisture, lift thickness), after which the engineer will retest the area.

Performance compaction Type II: The department will establish RICM TVs from on-site calibration of RICM MVs to QA point measurements. This specification option requires detailed calibration of RICM MVs to in situ QA PMVs from a representative calibration test strip before performing production QA testing. The department will establish the RICM TV from project QA criteria through regression analysis and application of prediction intervals. Correlation test strip construction and testing for this option are discussed in Attachment B: Correlation Analysis Between RICM Measurement Values and QC/QA Point Measurements.

The department will base acceptance of the production area on achievement of MV-TV at the selected prediction interval (e.g., 80%) and achievement of target QA PMVs in the areas with MVs < MV-TV. If quality criteria are not met, perform additional compaction passes and/or adjust construction operations (e.g., moisture, lift thickness), after which the engineer will retest the area.

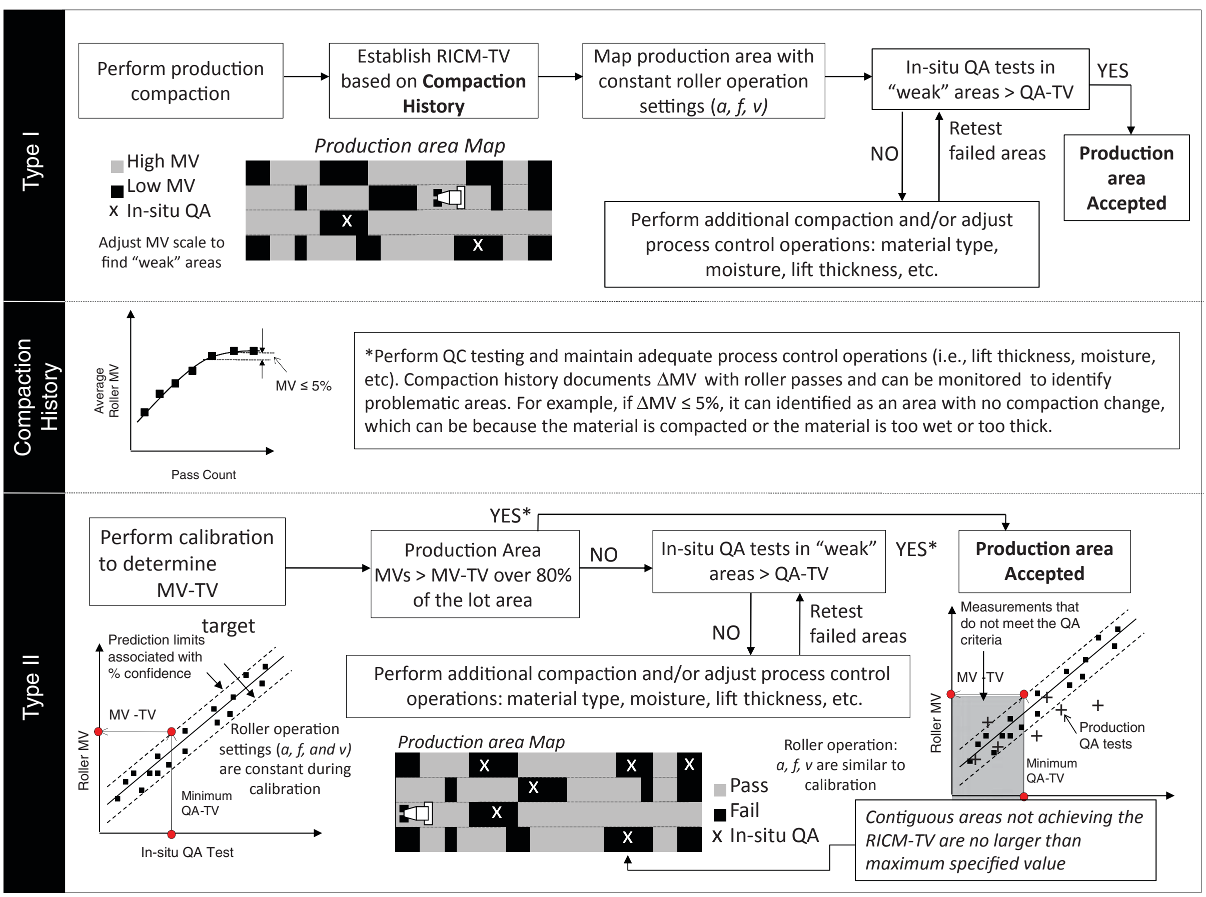

Figure C.2. Illustrations of the specification process for performance compaction Types I and II.

Table C.3. QC/QA Test Guidelines for Performance Compaction Types I and II

Description		Type I	Type II
Subgrade, subbase/base layers, stabilized layers $\leq$ 3ft below the bottom of the pavement			
Acceptance criteria	**QC**	RICM TV is achieved in at least 90% of the lot area; QC TV is achieved in RICM-identified "weak" areas; COV < 30%, or 90% of RICM values fall within 90% of RICM TV or of meeting geostatistical target parameters; and RICM noncompliance areas ("blobs") not achieving the RICM-TV are no larger than 15m^2.	
	QA	QA TV is achieved in RICM-identified weak areas.	
RICM-TV determination		RICM TV is established by contractor, on the basis of machine-soil specific operations and monitoring compaction curves (e.g., $\Delta MV \leq 5\%$).	RICM TV is established from calibration test strips on the basis of a QA-TV point measurement and a desired percentage prediction interval (e.g., 80%).
Testing frequency	**QC**	RICM-MV Quality Compaction Reports: Lift thickness, roller pass count, RICM compaction curves	
	QA	1 per 4000 yd^2/layer	1 per 8000 yd^2/layer
QA/QC test methods	**QC**	RICM MV	
	QA	Plate load test (PLT), DCP (for nongranular soils), LWD (for granular and stabilized soils), FWD	
Embankment fill > 3 ft below the bottom of the pavement			
Acceptance criteria	**QC**	RICM TV is achieved in at least 80% of the test area; QC TV is achieved in RICM-identified weak areas; COV < 40%, or 80% of RICM values fall within 90% of RICM-TV or of meeting geostatistical target parameters; and RICM contiguous noncompliance areas ("blobs") not achieving the RICM TV are no larger than 25m^2.	
	QA	QA TV(s) are achieved in RICM-identified weak areas.	
RICM-TV determination		RICM TV is established by contractor, on the basis of machine-soil specific operations and monitoring compaction curves (e.g., $\Delta MV \leq 5\%$).	RICM TV is established from calibration test strips on the basis of a QA-TV point measurement and a desired percentage prediction interval (e.g., 80%).
Testing frequency	**QC**	RICM-MV Quality Compaction Reports: Lift thickness, roller pass count, RICM compaction curves	
	QA	1 per 5000 yd^3 (1 per 2000 yd^3 in designated critical areas)	1 per 10,000 yd^3 (1 per 5000 yd^3 in designated critical areas)
QA/QC test methods	**QC**	RICM MV	
	QA	PLT, DCP (for nongranular soils), LWD (for granular and stabilized soils), BST, VST	

Commentary: For modulus/strength measurements simple linear regression analysis is generally suitable, while for correlation to dry unit weight/relative compaction measurements, multiple regression analysis including moisture content as a variable may be needed. If underlying layer support conditions are heterogeneous, relationships are likely improved by performing multiple regression analysis with RICM MV or point measurement data from underlying layers. Details of regression analysis are described in Attachment B: Correlation Analysis Between RICM Measurement Values and QC/QA Point Measurements.

Assessment of the required moisture content on the basis of performance parameters values (e.g., strength, stiffness, volumetric stability) has been described in the literature and continues to be part of ongoing research efforts. An example of a method to adjust plate load test k-values is described in AASHTO T222. In that test standard, a saturation correction factor is developed on the basis of the ratio of the deformation of a test specimen at the natural moisture content to the deformation in a saturated specimen under loading. Two specimens of the undisturbed material are placed in a consolidometer or triaxial chamber. One specimen is tested at the in situ moisture content and the other is saturated after the seating load has been applied. Each specimen is then subjected to the same seating load that was used for the field test (or to account for the desired embankment loading). The seating load is allowed to remain on the in situ moisture content specimen until all deformation occurs, at which time a zero reading is taken on the vertical deformation dial. Without releasing the seating load, additional load is applied to the specimen and allowed to remain until all deformation has occurred. A final reading is then taken on the vertical deformation dial. The other specimen is allowed to soak in the consolidometer or trial cell under the seating load. After the specimen is saturated, a zero dial reading is obtained; then without releasing the seating load, an additional load is applied. The load is allowed to remain on the specimen until all vertical deformation has occurred, and after that a final reading on the dial is obtained. A correction for saturation is then applied.

Determine the target stiffness values as described in ASTM D5874: Standard Test Method for Determination of the Impact Value (IV) of a Soil. The test method involves preparation of test specimens and selected moisture contents and compaction energies. Tests are then performed to establish the CIV versus moisture content. In this standard test method a target value for the CIV is determined from the correlation curve at the point at which an increase in water content results in a corresponding loss of strength. Similar procedures can be used to set strength and stiffness–based target values.

8 METHOD OF MEASUREMENT

Measurement for embankment materials furnished and placed in accepted portions of work will be in cubic yards of placed material. Measurement for subgrade materials, stabilized materials, and unbound base material furnished and placed in accepted portions of work will be in square yards for the specified design thickness. The measured area will be based on plan dimensions for the finished surface but will exclude fillets. The department will verify design thickness of the placed materials with spot checks of the grade.

9 BASIS OF PAYMENT AND PAYMENT ADJUSTMENTS

This section describes relationships between payment, pay factors, and performance measurement values.

A. **Option 1:** The contractor will be paid the contract unit price per square yard for each specified design thickness of subgrade materials, stabilized materials, and unbound base as measured above. This payment shall be full compensation for furnishing all materials, water, preparation of subgrade, and for doing all work necessary to complete the material placement in compliance with the contract documents.

B. **Option 2:** Payment for RICM will be the lump sum contract price. Payment is full compensation for all work associated with providing RICM-equipped rollers, transmission of electronic data files, two copies of RICM roller manufacturer software, and training. Delays resulting from GPS satellite reception of signals to operate the RICM equipment or RICM roller breakdowns will not be considered justification for contract modifications or contract extensions. In the event of RICM roller breakdowns or system malfunctions/GPS problems, the contractor may operate with conventional rolling operations; but RICM proof mapping shall be provided for a minimum 90% of the project surface. If corrective construction work is necessary, as determined from proof mapping, because of unforeseen ground conditions, the department may pay for the corrective work required at the applicable contract unit price or as extra work.

C. **Option 3:** The contractor will be paid according to a pay adjustment to the final quantities on the basis of the final proof map RICM MVs according to the following relationships:

Range of RICM MV ≥ TV	Pay Factor
80	1.00
85	1.04
95	1.08
100	1.10

Attachment A: Repeatability and Reproducibility Analysis Using Two-Way Analysis of Variance (ANOVA)

Requirements for Reproducibility and Repeatability Analysis: Currently, there are no published acceptable limits of measurement error for the roller measurement values. However, it is an important element of this specification for evaluating the usefulness of a machine before its use or even periodically during the course of the project, and it will help build confidence in the measurements. Variability in RICM MVs is one source of scatter in relationships with in situ point measurements. The measurement variability is quantified in this specification in a repeatability and reproducibility context. Repeatability refers to variation observed in the measurement values (also referred to as measurement error) obtained over a test area from consecutive passes under identical operating conditions (i.e., using same operator, amplitude, speed, direction of travel). Reproducibility refers to the variation in measurements obtained from consecutive passes under changing conditions. The changing conditions may result from different measurement methods, machines used, operators, or speed and amplitude settings. The repeatability and reproducibility analysis procedure described is applicable for any IC technology, although the magnitude of measurement error (for the range of RICM MVs) is expected to be different for different RICM technologies. This is of consequence in a specification context as it affects the regression relationships and anticipated variability in MVs.

The procedure for calculating reproducibility and repeatability errors is presented in the attachment. Generally, a 250-ft long well-compacted test section representative of the production area is suitable for conducting the repeatability testing. At least four roller passes are recommended for a given roller operation parameter (speed, theoretical vibration amplitude, vibration frequency, and travel direction). The roller passes should be performed to capture the planned operating conditions on the project. The total number of passes can be determined as follows:

> Number of passes = 4 × machine operation variables to be used during production (e.g., amplitude, speed, direction, frequency). For example, the total number of passes required to evaluate just the influence of speed at two different settings, then the total number of passes required = 4 × 2 = 8 passes. It should be noted that the measurement error should be expected to increase with an increasing number of variables in the analysis. Variants of this process can also provide acceptable results and depend on the desired roller operating conditions. As discussed later, the RICM roller measurement error is an input parameter that is required as part of statistical QA/QC assessment.

Analysis Methodology: Consider a data set consisting of *m* repeated measurements at a test location at *I* different locations under each condition of operation *J*.

For roller measurement values

m: number of passes on a test strip;
I: number of data points across the test strip; and
J: change in operator, amplitude, speed, direction, etc.

For LWD measurement values

m: number of measurements at a location;
I: number of test locations; and
J: change in operator, device, material tested, etc.

The two-way random effects model and the three quantities of interest are provided here:

$$y_{ijk} = \mu + \alpha_i + \gamma_j + \alpha\gamma_{ij} + \varepsilon_{ijk}$$

$$\sigma_{repeatability} = \sigma$$

$$\sigma_{reproducibility} = \sqrt{\sigma_{\gamma}^2 + \sigma_{\alpha\gamma}^2}$$

$$\sigma_{R\&R} = \sqrt{\sigma_{reproducibility}^2 + \sigma_{repeatability}^2}$$

Estimates of these from two-way ANOVA results are shown here, and the parameters of the equations are shown in Table C.A.1 with ANOVA results.

$$\sigma_{repeatability} = \sigma = \sqrt{MSE}$$

For LWD measurements, $\sigma_{\text{repeatability}}$ is simply the standard deviation of repeated measurements obtained at a given location. To calculate, $\sigma_{R\&R}$ and $\sigma_{\text{reproducibility}}$, Condition (i.e., operator, device, material tested, etc.) variables are considered as nominal variables in two-way ANOVA. A typical ANOVA table is provided (Table C.A.1).

For roller measurements, $\sigma_{\text{repeatability}}$ is computed by considering Pass and Location as nominal variables in two-way ANOVA—accounting for the systematic pass effect. To calculate, $\sigma_{R\&R}$ and $\sigma_{\text{reproducibility}}$, Condition (i.e., amplitude, speed, direction, etc.), and Location variables are considered as nominal variables in two-way ANOVA. A typical ANOVA table is provided (Table C.A.1). Pass effect on the measurement values in this case should be statistically insignificant (as assessed by student's *t*-ratio and *p*-value). (As a rule-of-thumb, in a simple linear regression analysis between pass and roller measurement values, if *t*-ratio is < -2 or > 2 and *p*-value is < 0.05, the effect of pass can be considered statistically significant.) To conclude that there is no effect of change in Condition or Location, the reproducibility standard deviation should be similar or less than the repeatability standard deviation.

Table C.A.1. Typical Two-Way ANOVA Table

Source	SS (sum of square)	DOF (degree of freedom)	MS (mean square)
Location (I)	SS_A	$I - 1$	$MS_A = SS_A/(I - 1)$
Operating condition (J)	SS_C	$J - 1$	$MS_C = SS_A/(J - 1)$
$I \times J$ (interaction term)	SS_{AC}	$(I - 1)(J - 1)$	$MS_{AC} = SS_{AC}/(I - 1)(J - 1)$
Error	SS_C	$IJ(m - 1)$	$MS_E = SS_E/IJ(m - 1)$
Total	SS_{Tot}	$IJm - 1$	—

$$\sigma_{reproducibility} = \sqrt{\max\left(0, \frac{MSC}{ml} + \frac{(I-1)MSAC}{ml} - \frac{MSE}{m}\right)}$$

$$\sigma_{R\&R} = \sqrt{\sigma^2_{reproducibility} + \sigma^2_{repeatability}}$$

A two-way ANOVA Table such as indicated in Table C.A.1 can be generated using any standard statistical analysis software (e.g., JMP, SPSS) or using add-ins in Excel. An example step-by-step procedure of repeatability and reproducibility analysis using JMP statistical analysis software for roller and E_{LWD} measurement values follows.

Example Calculation of Repeatability and Reproducibility Analysis for Roller Measurements [Outputs from JMP Statistical Analysis Software]: The following analysis is for roller measurements (MDP*) obtained over a 50-m long compacted test strip with variable stiffness in two different speeds (nominal 3.2 km/h and 6.4 km/h) at a constant amplitude setting (a = 0.9 mm). The data is analyzed for repeatability of MDP* at constant speed settings and reproducibility of MDP* with change in speed.

- For this data set
  - *m:* number of passes on the test strip in each setting = 5;
  - *I:* number of data points across the test strip = 164; and
  - *J:* total number of speed settings = 2.
- First, the repeatability ($\sigma_{repeatability}$) of MDP* at each speed setting is computed. As explained earlier, number of Passes and Location are considered as nominal variables and a two-way ANOVA is performed, accounting for any systematic pass effect, to compute $\sigma_{repeatability}$. The data must be organized into columns of Pass, Location [location represents data points across the test strip], and Measurement Values as shown in Figure C.A.1. One challenge with organizing the Location column is that the data points obtained from different passes are not collected at the exact same location. To overcome this problem, the data should be processed in such a way that an average data is assigned to a preset grid point (e.g., 0.3 m as used in this report) along the roller path. The grid point along the roller path represents an average of RICM MVs that falls within a window of size that is half the size of the grid length (in this case it is 0.15 m) in forward and backward directions.
- The Pass and Location columns have to be selected as Nominal (highlighted as histograms, see Figure C.A.1) while the measurement values (in this case MDP*) have to be selected as Continuous (highlighted as the triangle, see Figure C.A.1) variables.
- Then select "Fit Model" as shown in Figure C.A.2 which opens a "Model Specification" window. Select the measurement value as "Y", and add Pass and Location number as "Construct Model Effects" as shown in Figure C.A.4. Then select "Run Model." The two-way ANOVA table and $\sqrt{MSE} = \sigma_{repeatability}$ results are shown in Figure C.A.2.
- For reproducibility analysis, select at least three passes data that have statistically negligible effect of pass. Organize the data in columns of Pass, Location, Measurement Value (in this case MDP*), and Speed. The Pass, Location, and Speed columns have to be selected as Nominal, while the Measurement Value column has to be selected as Continuous (see Figure C.A.3).
- Then select "Fit Model" and select the measurement value as "Y", and add Location (I), Speed (J), and Location * Speed (I*J) interaction terms as "Construct Model Effects" as shown in Figure C.A.4. Then select "Run Model."
- The two-way ANOVA Table and $\sqrt{MSE} = \sigma_{reproducibility}$ results are shown in Figure C.A.3. Using the SSC, SSAC, and corresponding degree of freedom numbers calculate

$$\sigma_{reproducibility} = \sqrt{\max\left(0, \frac{MSC}{mI} + \frac{(I-1)MSAC}{mI} - \frac{MSE}{m}\right)}$$

$$\sigma_{R\&R} = \sqrt{\sigma^2_{reproducibility} + \sigma^2_{repeatability}}$$

- Using data in Figure C.A.3 and the above equations (for MDP*), the $\sigma_{repeatability}$ = 5.9, $\sigma_{reproducibility}$ = 18.2 mm, and $\sigma_{R\&R}$ = 19.1 mm.
- Results indicate that the contribution of $\sigma_{reproducibility}$ to the overall variability $\sigma_{R\&R}$ is greater than the contribution of $\sigma_{repeatability}$. For this data set, the impact of change in speed on MDP* is considered statistically significant.

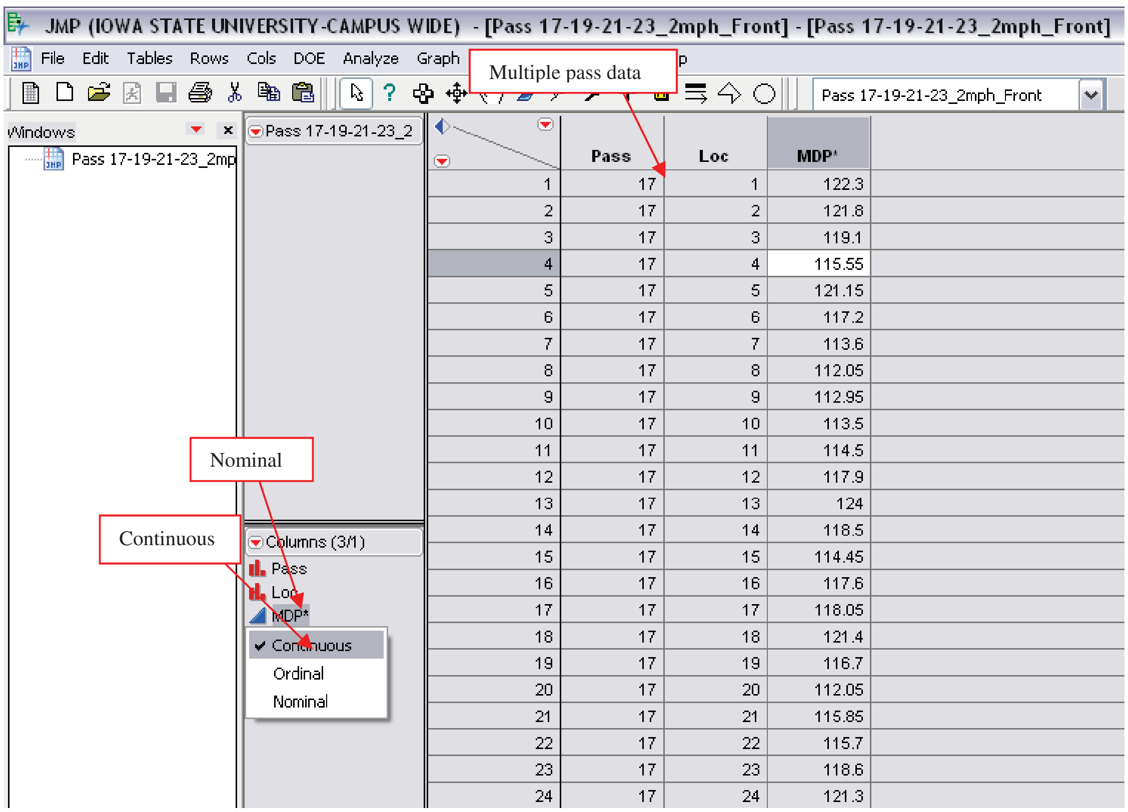

Figure C.A.1. Data organization in JMP for repeatability analysis of roller measurement values.

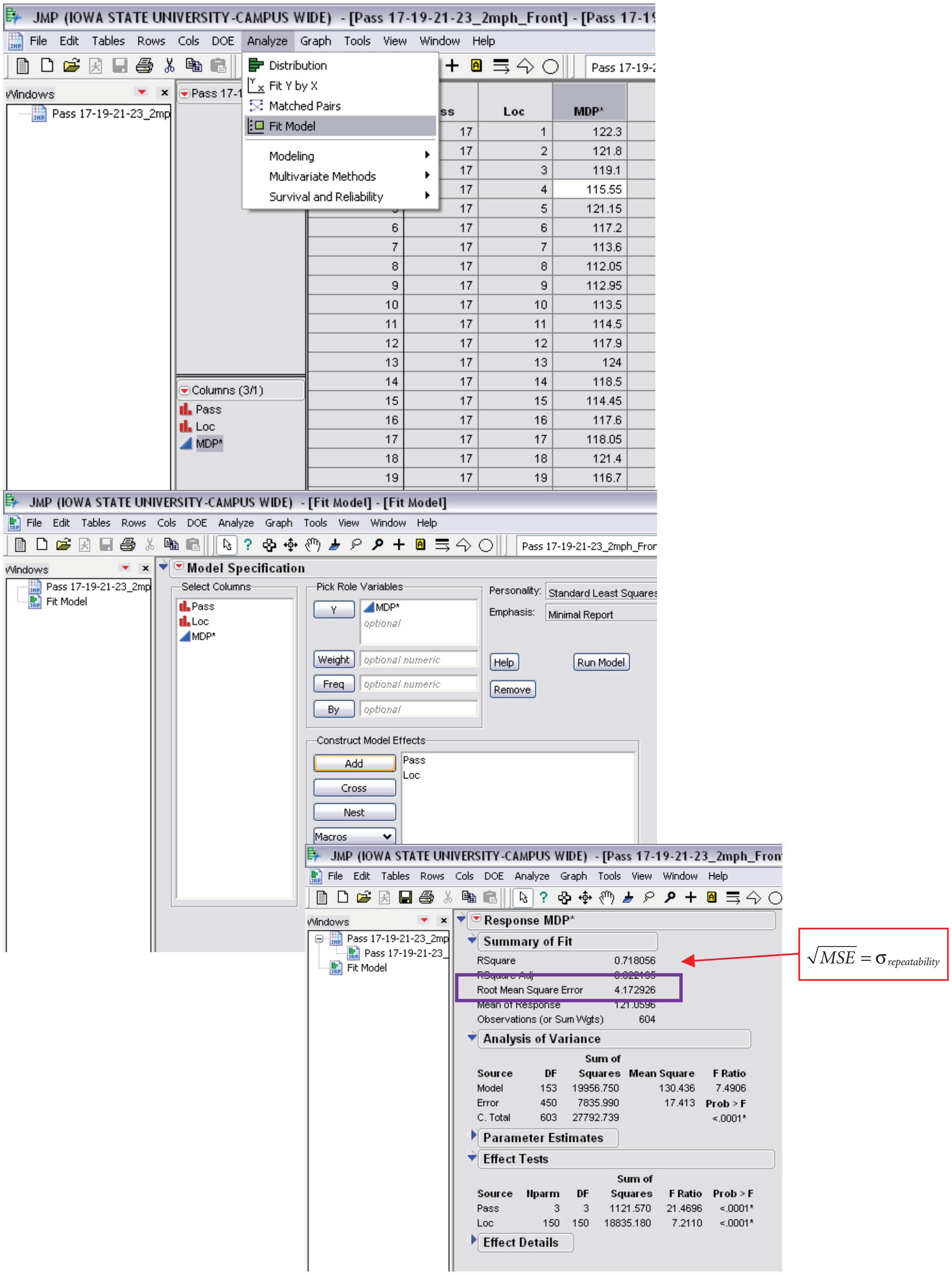

Figure C.A.2. Repeatability analysis procedure in JMP.

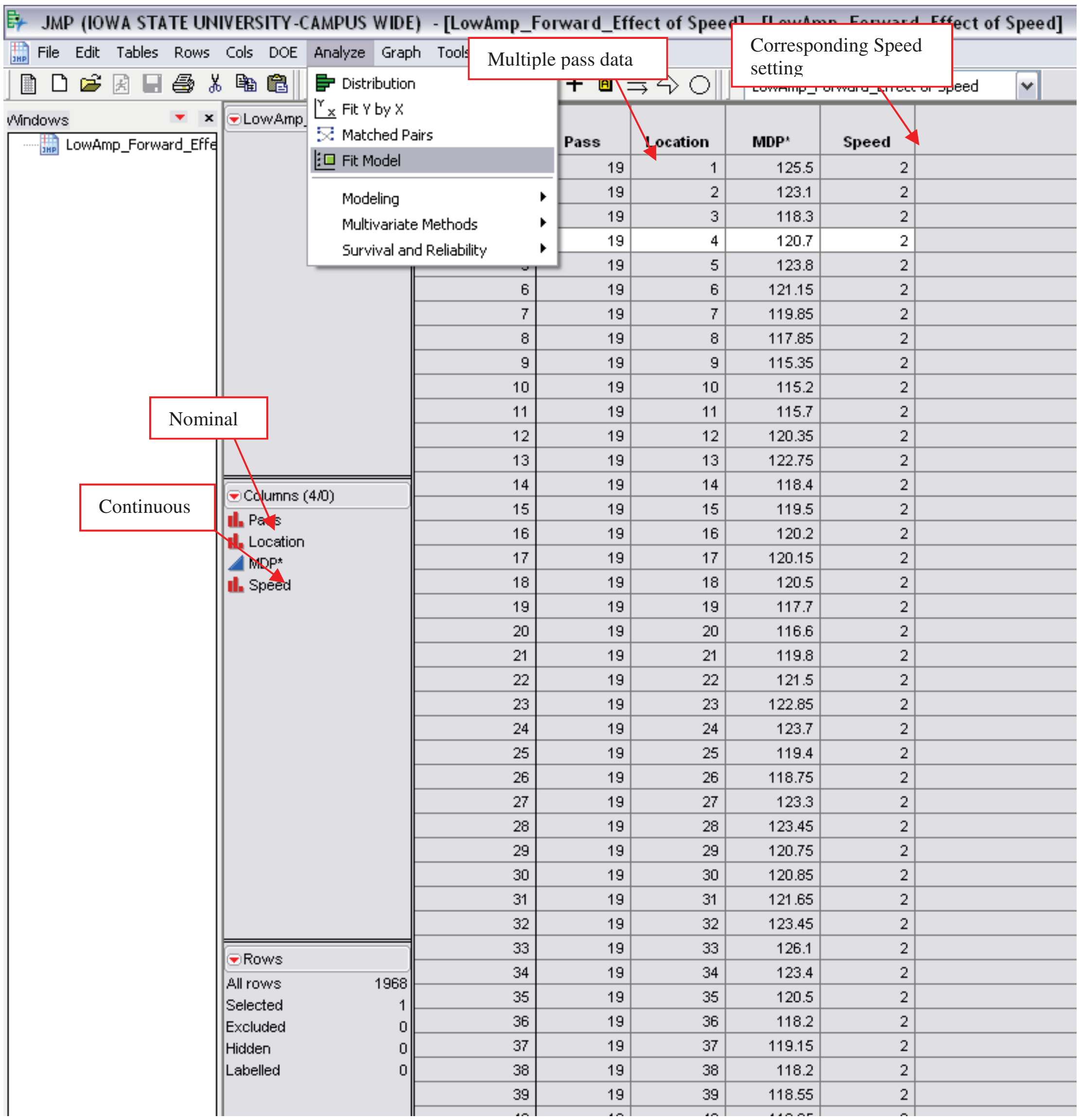

Figure C.A.3. Data organization in JMP for reproducibility analysis.

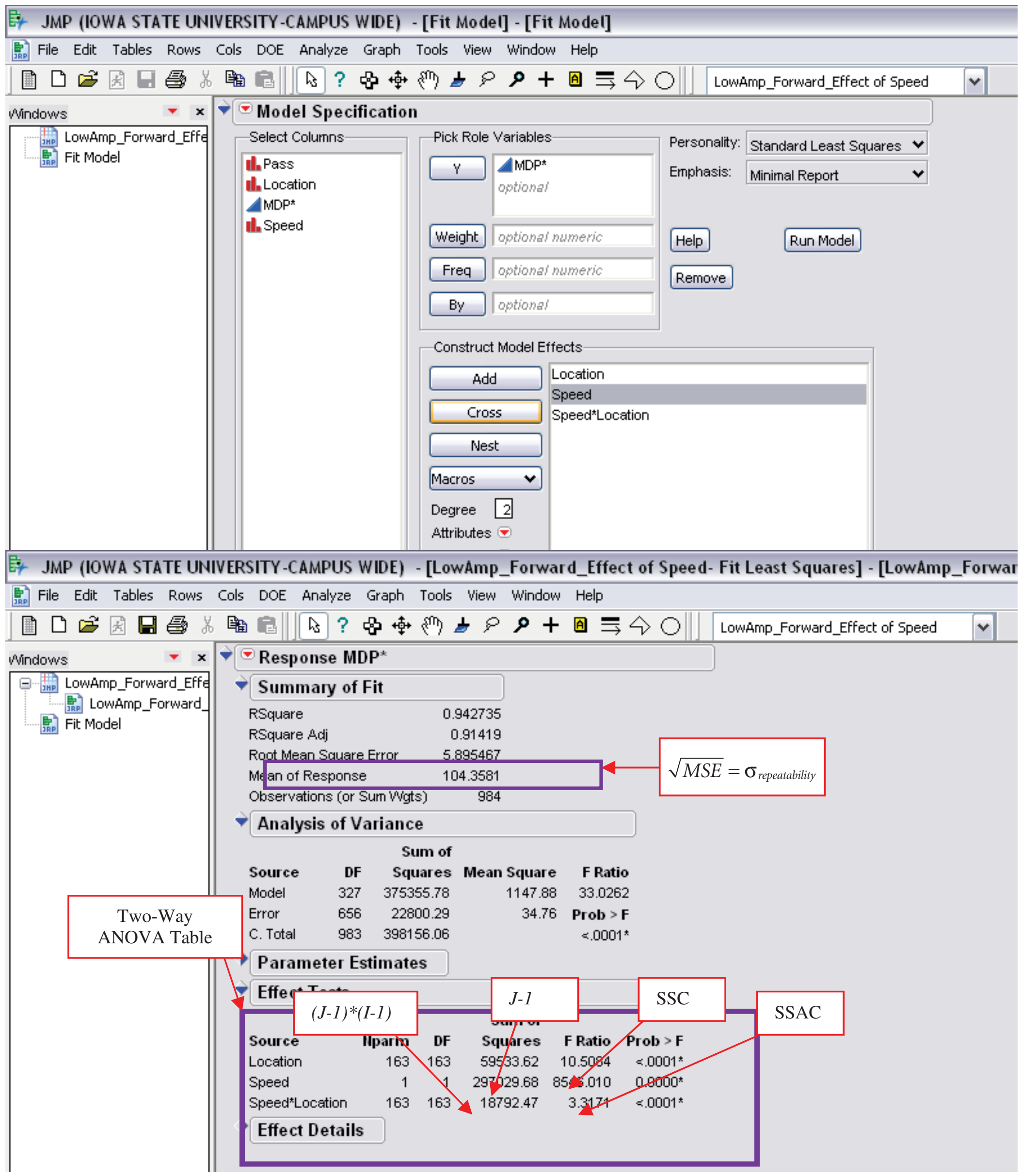

Figure C.A.4. Results of two-way ANOVA for roller measurement reproducibility analysis.

Attachment B: Correlation Analysis between RICM Measurement Values and QC/QA Point Measurements

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Implementation of RICM technologies into earthwork specifications requires an understanding of relationships between roller MVs and soil compaction measurements. Simple linear correlations between MVs and compaction layer in situ point measurements are possible for a compaction layer underlain by relatively homogenous and stiff/stable supporting layer. Heterogeneous conditions in the underlying layers, however, can adversely affect the relationships. In some cases regression coefficients can be improved using multiple regression analysis that includes parameter values to represent underlying layer conditions when statistically significant, to improve the correlations. E_{LWD}, E_{V1}, E_{V2}, and E_{FWD} measurements generally capture the variation in roller MVs better than dry unit weight measurements. DCP tests are effective in detecting deeper weak areas (at depths > 300 mm) which are commonly identified by the roller MVs and not by compaction layer point measurements. High variability in soil properties across the drum width and soil moisture content contribute to scatter in relationships. Averaging measurements across the drum width and incorporating moisture content into multiple regression analysis, when statistically significant, can help mitigate the scatter to some extent. Relatively constant machine operation settings are critical for calibration strips (i.e., constant amplitude, frequency, and speed), and correlations are generally better for low amplitude settings (e.g., 0.7 mm to 1.1 mm) for vibratory rollers. A field testing protocol to obtain reliable correlations during implementation/roller calibration testing and establishing target values from simple and multiple regression relationships is described in this attachment.

Requirements for Correlation Test Strips Construction and In Situ Testing: The calibration test area should be prepared and constructed with the same methods and conditions (e.g., material type, moisture conditioning, and lift thickness) as in the production area. Roller MVs are influenced by lift thickness, material type, moisture content, and the underlying layer support conditions. Plan dimensions required for the calibration area depend on the spatial heterogeneity of the support conditions and variability in moisture content of the material. As a guide, for areas with relatively homogenous support conditions and uniform moisture content, a representative calibration test area with minimum dimensions of 5 m wide by 50 m long should be identified. The test area should be relatively consistent in structure (e.g., cut/fill section) to a depth of about 1 m. If heterogeneous support conditions are evident over the production area, the plan dimensions should be increased up to 7.5 m wide by 100 m long. A roller MV map of the underlying layer and/or MV map of the first roller pass over the production area are helpful in selection of an appropriate area for calibration. Judgment is involved in selecting the location and size of the calibration test area. The 50 to 75 percentile variation can be used to target the size and location of the calibration area on the basis of MVs from an initial roller pass of the area.

Compaction operations in the calibration area should be performed at constant amplitude (if not static), frequency, and speed. A low amplitude vibration setting (~0.7 mm to 1.1 mm) is preferred for vibratory operations. High amplitude settings can cause "jumping" as compaction increases, which affects some roller MVs and reduces correlations to QA point measurements. Point test measurements as required by the project QA criteria (e.g., target dry unit weight, E_{LWD}) should be performed in parallel with roller compaction operations. At each test location, at least three test measurements should be obtained across the drum width and averaged to generate one regression point. Regression relationships improve by averaging measurements across the drum width. Test measurements should be obtained at several locations across the calibration area, for at least three intermediate passes (e.g., 1, 2, 4, 8, or 12) until target compaction is achieved. As the range of regression data increases, the correlations are improved and likely more representative of variability in the production areas. For a 50-m long test strip, five test points per pass along the centerline of the roller lane would be the minimum, and 10 test points per pass with three measurements across the drum width at each test point would be about the maximum. The contractor and/or owner will benefit from investing in more testing up front as part of the calibration to improve reliability of the correlations and selected MV-TVs. Calibration analysis of roller MVs to in situ point measurements is described later in the attachment.

Simple linear regression relationships are developed from calibration analysis with prediction intervals using in situ point measurements averaged over the width of the drum(s) and roller MV data corresponding to the spatially nearest point. Generally, the least-square regression relationship should achieve an R^2 value of at least 0.50. Typically, the R^2 values do not exceed 0.80. Obtaining reliable correlations between compaction layer point measurements (e.g., dry unit weight) and roller MVs with soft and heterogeneous support conditions (especially in the case of a soft underlying layer) can be difficult. Variation in roller MVs are generally better captured by stiffness/modulus measurements compared with dry unit weight measurements, especially with heterogeneous support conditions at shallow depths (<300 mm). In situ point measurements (e.g., DCP, PLT, E_{FWD}/E_{LWD}) that provide information deeper than the compaction layer can help improve confidence in correlations for such conditions. Regardless, scatter in regression relationships is to be expected. Major factors that influence the regression relationships include (a) differences in measurement influence depths, (b) range over which measurements were obtained, (c) influence of moisture content on point measurements, (d) intrinsic measurement errors associated with the roller MVs and in situ point test measurements, (e) position error from pairing point test measurements and roller MV data, and (f) soil variability.

Multiple regression analysis can be performed by incorporating underlying layer properties (i.e., roller MVs or in situ point measurements of the underlying layer) for heterogeneous support conditions to obtain improved correlations with compaction layer point measurements. Selection of target values using multiple regression relationships should be based on applying prediction intervals to the predicted roller MV and mean squared error of the estimate. Moisture content can also be included in multiple regression analysis to better relate dry unit weight to roller MVs. MV TVs for that case should be based on multiple regression relationships. Regression analysis between roller MVs and in situ stiffness based point measurements (e.g., E_{LWD}, E_{FWD}) generally do not require multiple regression analysis with moisture as a variable.

Simple Linear Regression Analysis: Simple linear regression analysis involves developing a relationship between independent and dependent variables using an intercept and slope coefficient. This analysis has the advantage of being simple enough to perform on a hand calculator. For each linear, univariate regression model the coefficient of determination R^2 provides a measure of how well the regression model describes the data. For reference, correlations considered acceptable per the European specification options meet the requirement of $R^2 \geq 0.5$. Although simple linear regression analysis is relatively straightforward, many factors can affect the quality of the correlation between MVs and the various point measurement values. A list of these factors is provided in this section to aid the reader in interpretation of the results. Multiple regression analysis was identified as one approach to overcome some of the factors that affect the simple liner regression relationships and is discussed later.

Analysis Approach: Simple linear regression relationships were developed by considering in situ point measurements as "true" independent variables and roller MVs as dependent variables using the model shown in Equation C.B.1. Statistical significance of the independent variable was assessed based on *p*- and *t*-values. The selected criteria for identifying the significance of a parameter included p-value < 0.05 = significant, p-value < 0.10 = possibly significant, p-value > 0.10 = not significant, and t-value < -2 or $> +2$ = significant.

$$Roller\ MV = b_0 + b_1 \cdot \alpha \qquad \text{(C.B.1)}$$

where b_0 = intercept, b_1 = slope, and α = point measurement value.

Calibration analysis of roller MVs to in situ point measurements is performed using the inverse regression method (Ott and Longnecker 2001) to establish an MV TV for a target QA measurement value (QA TV). This procedure is illustrated in Figure C.B.1 with MV as a dependent variable (y) and the in situ point measurement as an independent true measurement variable (x). As a measure of uncertainty in the regression relationship, prediction limits at the selected percent confidence can be applied to estimate the limits of in situ test measurement values for an observed roller MV (prediction limits should not be confused with confidence intervals).

From this procedure, roller MV TV to achieve a minimum QA TV corresponding to a percent confidence can be established using the upper prediction limits as shown in Figure C.B.1. The greater the percent confidence needed in the predictions, the higher the MV TV.

Factors Affecting Quality of Regression Relationships: As with any regression analysis, it is important to identify factors that affect the quality of the regressions. Factors affecting regression relationships are broadly identified in Table C.B.1 for the purpose of linking some of these factors to various test bed (TB) conditions. This list was derived from linking TB conditions with correlation analysis but also from experiences gained from field tests as part of this study. Five examples described in the next section illustrate some of the TB conditions that led to development of Table C.B.1. Heterogeneity in support conditions of layers underlying the compaction layer is one of the major factors that affect correlations between MVs and point measurements. This is largely due to differences in measurement depths between the roller and the point measurements. Roller MVs from 11- to 15-ton vibratory rollers can be representative of conditions to depths of 1.0 to 1.2 m (3.3 to 3.9 ft). Use of underlying layer MVs and use of point measurements with comparable measurement influence depths are ways to overcome this obstacle. This approach is discussed in detail in the multiple regression analysis section.

Multiple Linear Regression Analysis: Use of multiple regression analysis to statistically assess the influence of variability in underlying layer soil conditions and variability in machine operation conditions is presented in this section. Multiple regression analysis is performed by incorporating variables of interest as independent variables into a general multiple

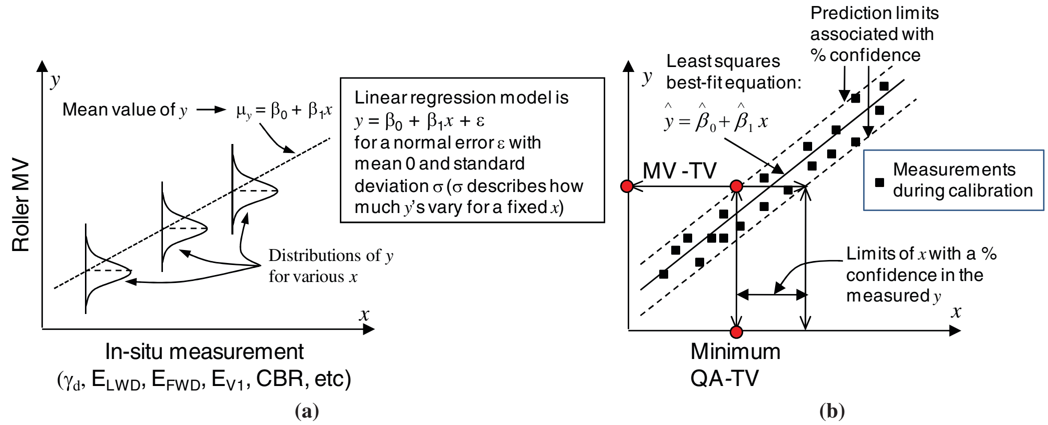

Figure C.B.1. (a) Illustration of inverse regression method and (b) application of prediction limits to establish roller MV target values.

linear regression model, as shown in Equation C.B.2. The statistical significance of each variable is assessed based on *p*- and *t*-values. The selected criteria for identifying the significance of a parameter included *p*-value < 0.05 = significant, < 0.10 = possibly significant, > 0.10 = not significant, and *t*-value < −2 or > +2 = significant. The *p*-value indicates the significance of a parameter, and the *t*-ratio value indicates the relative importance (i.e., the higher the absolute value, the greater the significance).

$$Roller\ MV = b_0 + b_1 \cdot \alpha + b_2 \cdot w + b_3 \cdot A + b_4 \cdot \beta + b_5 \cdot \gamma + b_6 \cdot w^2 + b_7 \cdot f + b_8 \cdot v \qquad \text{(C.B.2)}$$

Table C.B.1. Summary of Factors Affecting Correlations Between MVs and In Situ Point Measurements

No.	Factors Affecting Correlations
1	Heterogeneity in underlying layer support conditions
2	High moisture content variation
3	Narrow range of measurements
4	Machine operation setting variation (e.g., amplitude, frequency, speed) and roller "jumping"
5	Nonuniform drum/soil contact conditions
6	Uncertainty in spatial pairing of point measurements and roller MVs
7	Limited number of measurements
8	Not enough information to interpret the results
9	Intrinsic measurement errors associated with the roller MVs and in situ point test measurements

Source: NCHRP 2009b.

where b_0 = intercept; b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8 = regression coefficients, A = amplitude (mm), α = point measurement value (γ_d, E_{LWD}, etc.); β = underlying layer roller MV or point measurement; γ = lift thickness (mm); f = vibration frequency (Hz); and v = velocity (km/h).

For the multiple regression analysis, the reported R^2 values have been adjusted for the number of regression parameters, as shown in Equation C.B.3, where n = the number of data points and p = the number of regression parameters. The adjusted coefficient of determination R^2_{adj} from multiple regression analysis may be compared with R^2 from simple linear regression analysis to assess which regression model best captures variation in the data.

$$R^2(adjusted) = 1 - (1 - R^2)\frac{n-1}{n-p} \qquad \text{(C.B.3)}$$

Complications with collinearity should be avoided when performing multiple regression analysis. Collinearity refers to inclusion of two or more strongly related independent variables into a model to predict a dependent variable, which may result in misleading R^2_{adj} values (Ott and Longnecker 2001). This is possible in the above-described model if, for example, underlying layer MV and point measurement values are included together. Collinearity in a model can be detected using variance inflation factors (VIF). VIF of *i*th independent variable is defined as $1/(1 - R_i^2)$, where R_i^2 is the coefficient of determination for the regression of the *i*th independent variable on all other independent variables. Although there are no formal criteria on the acceptable magnitude of VIF, a common rule of thumb is that if VIF of the *i*th independent variable is $< 1/(1 - R^2)$, where R^2 is the coefficient of determination of the univariate model), then it can be concluded that the variable is not contributing to collinearity (Freund et al. 2003).

Attachment C: Geospatial Uniformity Analysis

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Uniformity Criteria

Uniformity is recognized as an important component of quality compaction (e.g., Davis 1953; Sherman et al. 1966). Results from numerical studies indicate that considering average values in design may not capture actual performance (e.g., White et al. 2004; Griffiths et al. 2006). With the ability of real-time viewing of compaction data, roller-integrated measurement technology offers an opportunity to construct more uniform earthwork layers. Current CCC specifications address uniformity using percentage limits based on an MV-TV. The International Society of Soil Mechanics and Geotechnical Engineers (ISSMGE 2005)/Austrian CCC earthwork specifications, for example, require that roller MVs in the production area should fall within 0.8 to 1.5 MIN-TV with a coefficient of variation < 20% (MIN-TV corresponds to the MV at 0.95 QA-TV established from calibration). Using a slightly different approach, the Minnesota Department of Transportation (MnDOT) implemented a predetermined target percentage limits distribution criterion (MnDOT 2007) on a full-scale earthwork project in the state (White et al. 2007, 2008a, 2008b). The acceptance requirement was that 90% of roller MV data in the production area should fall within 90% to 120% of the MV-TV; none should be below 80% of the MV-TV; and if any are above 120%, a new MV-TV should be established.

If uniformity criteria are desired as part of the specification, the ISSMGE and MnDOT approaches described above can be implemented [for some specification options]. However, it must be realized that these approaches are limited to conditions where *Evaluation Sections* have similar spatial heterogeneity in compaction layer properties and support conditions to the *Calibration Area.* If not, achieving these uniformity targets is challenging. For such cases, information of underlying support conditions may help in evaluating compaction layer data and selecting representative *Calibration Areas.* Further, these approaches do not address uniformity from a spatial standpoint. More research is needed in relating uniformity to performance for a better understanding of the level of uniformity desired and how field operations can be improved to control nonuniformity.

An alternate approach to quantify uniformity is to use spatial statistics in combination with univariate statistics (mean and standard deviation; Brandl 2001; Vennapusa et al. 2010; Facas et al. 2010). Using spatial statistics requires developing semivariogram models using spatially referenced GPS coordinate measurements, which describe the spatial relationship in the measured roller MVs. The three main characteristics by which a semivariogram is often summarized are range, sill, and nugget (Isaaks and Srivastava 1989). Comparatively, a semivariogram with a lower *sill* and longer *range* represents reduced nonuniformity and improved spatial continuity. Vennapusa et al. (2009) describe an approach for using spatial statistics to target areas for compaction that results in improved spatial continuity and reduced nonuniformity.

Geostatistical Analysis

The Geostatistics section of this attachment is reprinted from Vennapusa et al. 2010, with permission from the American Society of Civil Engineers.

Geostatistics characterize and quantify spatial variability. The semivariogram $\gamma(h)$ is a common analysis tool to describe spatial relationships in many earth science applications and is defined as one-half of the average squared differences between data values that are separated at a distance h (Isaaks and Srivastava 1989). If this calculation is repeated for as many different values of h as the sample data will support, the result can be graphically presented as shown in Figure C.C.1 (shown as circles), which constitutes the experimental semivariogram plot. The mathematical expression to estimate the experimental semivariogram is

$$\hat{\gamma}(h)=\frac{1}{2n(h)}\sum_{i=1}^{n(h)}[z(x_i+h)-z(x_i)]^2 \qquad \text{(C.C.1)}$$

where $z(x_i)$ = a measurement taken at location x_i; $n(h)$ = the number of data pairs h units apart in the direction of the vector, and $\hat{\gamma}$ = an experimental estimate of the underlying variogram function γ (Olea 2006).

The three main characteristics by which a semivariogram plot is often summarized include the following (Isaaks and Srivastava 1989):

Range (a): As the separation distance between pairs increases, the corresponding semivariogram value will also generally increase. Eventually, however, an increase in the distance no longer causes a corresponding increase in the semivariogram, and the semivariogram reaches a plateau. The distance at which the semivariogram reaches this plateau is called the range. Longer range values suggest greater spatial continuity or relatively larger (more spatially coherent) "hot spots";

Sill ($C_0 + C$): The plateau that the semivariogram reaches at the range is called the sill. A semivariogram (which is one-half of the variogram) generally has a sill that is approximately equal to the variance of the data (Srivastava 1996); and

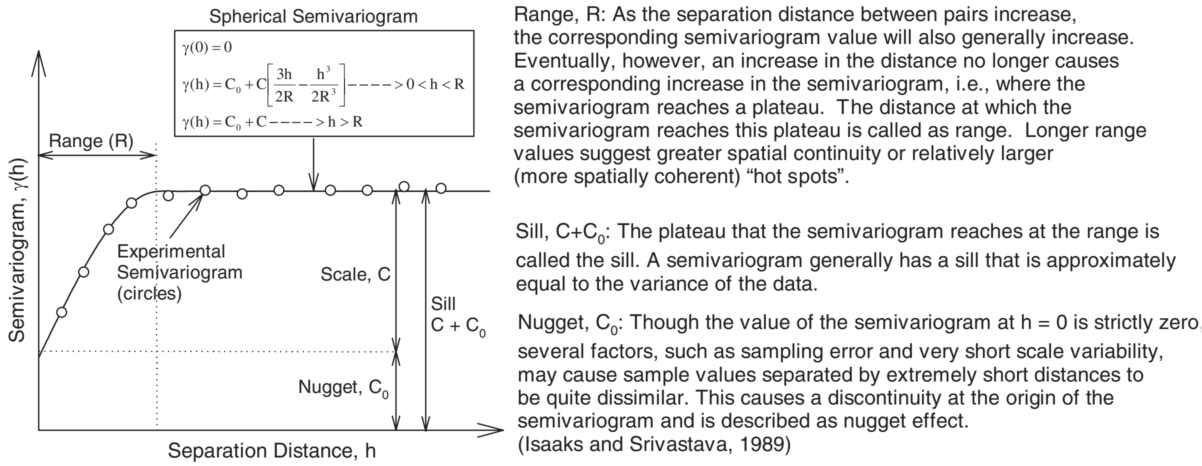

Figure C.C.1. Description of a typical experimental and spherical semivariogram and its parameters.

Nugget effect (C_0): Though the value of the semivariogram at $h = 0$ is strictly zero, several factors, such as sampling error and very short scale variability, may cause sample values separated by extremely short distances to be quite dissimilar. This causes a discontinuity at the origin of the semivariogram called the nugget effect.

Some important points to note are that a semivariogram model is stable only if the measurement values are stationary over an aerial extent. If the data values are nonstationary, spatial variability should be modeled only after appropriate transformation of the data (Clark and Harper 2002). If the values show a systematic trend, the trend must be modeled and removed prior to modeling a semivariogram (Gringarten and Deutsch 2001).

In addition to quantifying spatial variability, geostatistics can be used as a spatial prediction technique, i.e., for predicting a value at unsampled locations based on values at sampled locations. Kriging is a stochastic interpolation procedure (Krige 1951) by which the variance of the difference between the predicted and “true” values is minimized using a semivariogram model. Kriging was used to create “smoothed” contour maps of RICM point data for analysis of non-uniformity and comparison to maps of different in situ spot test measurement values.

Fitting a Theoretical Model

The major purpose of fitting a theoretical model to the experimental semivariogram is to give an algebraic formula for the relationship between values at specified distances. There are many possible models to fit an experimental semivariogram. Some commonly used models include linear, spherical, exponential, and Gaussian models. Mathematical expressions for these models are presented in Table C.C.1. Detailed descriptions of these theoretical models can be found elsewhere in the literature (e.g., Isaaks and Srivastava 1989; Clark and Harper 2002).

The range in a spherical model is well defined because it has a definitive sill. This is not true for exponential or Gaussian models that have asymptotic sills. The approximate range for those models is three to five times larger than the range values obtained for closely matched spherical models (Clark and Harper 2002). Some researchers have used 3*a* as an effective range for the exponential semivariogram (e.g., Erickson et al. 2005).

Table C.C.1. Commonly Used Theoretical Semivariogram Models

Model Name	Mathematical Expression
Linear	$\gamma(0) = 0$ $\gamma(h) = nC_0 + ph,$ when $h > 0$
Spherical	$\gamma(0) = 0$ $\gamma(h) = C_0 + C\left[\frac{3h}{2a} - \frac{h^3}{2a^3}\right]$ when $0 < h < a$ $\gamma(h) = \gamma(h) = C_0 + C$ when $h > a$
Exponential	$\gamma(0) = 0$ $\gamma(h) = C_0 + C\left[1 - \exp\left(-\frac{h}{a}\right)\right]$ when $h > 0$
Gaussian	$\gamma(0) = 0$ $\gamma(h) = C_0 + C\left[1 - exp\left(-\frac{h^2}{a^2}\right)\right]$ when h > 0

Note: p = slope of the line, a = range, C_0 = nugget effect, and $C + C_0$ = sill.

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White, D. J., T. Rupnow, and H. Ceylan. 2004. Influence of Subgrade/Subbase Nonuniformity on Pavement Performance. *Proc., GeoTrans 2004—Geotechnical Engineering for Transportation Projects,* Geotechnical Special Publication No. 126, ASCE, pp. 1058–1065.

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APPENDIX D

Annotated Bibliography

Bridges

Badie, S. S., K. T. Maher, and A. F. Girgis. *NCHRP Report 584: Full-Depth, Precast-Concrete Bridge Deck Panel Systems* (NCHRP Project 12-65). Transportation Research Board of the National Academies, Washington, D.C., 2006.
This report provides recommended guidelines and specifications for the design, fabrication, and construction of full-depth, precast-concrete bridge deck panel systems. The general outcome criteria imbedded in these prescriptive specifications can serve as a basis for the development of performance specifications.

Bickley, J., R. D. Hooton, and K. C. Hover. *Preparation of a Performance-Based Specification for Cast-in-Place Concrete.* Ready Mixed Concrete (RMC) Research Foundation, Silver Spring, Md., 2006. http://www.nrmca.org/P2P/. Accessed Dec. 3, 2007.
This report was commissioned by the National Ready Mixed Concrete Association to review the state-of-the-art for performance-based specifications for concrete. It provides a historical and international review of performance specifications for concrete, including discussion of the other concrete materials specifications included in this bibliography. The report lists all the prevailing quality tests for concrete and discusses their suitability for administering a true performance specification of concrete materials.

FHWA. *Prefabricated Bridge Elements and Systems in Japan and Europe.* International Technology Exchange Program, Federal Highway Administration, U.S. Department of Transportation, 2005. http://international.fhwa.dot.gov/prefab_bridges/index.htm. Accessed Dec. 3, 2007.
This resource describes a scanning tour of five countries in April 2004, which identified nine technologies including two superstructure systems, four deck systems, one substructure system, and two bridge movement systems. The tour found that bridge replacement using self-propelled mobile technology (SPMT) to move prefabricated bridges into position has been done overseas, as well as in Florida, Rhode Island, and New Jersey. SPMT for bridge or bridge component replacement appears especially relevant to rapid renewal projects. Use of SPMT is being documented in draft versions of guidelines being developed by FHWA. The guidelines are expected to produce performance criteria for rapid-replacement systems.

Hughes, C. S., and C. Ozyildirim. *End-Result Specification for Hydraulic Cement Concrete* (VTRC 05-R29). Virginia Transportation Research Council, Charlottesville, 2005.
This report discusses an end-result specification for accepting and paying for hydraulic cement concrete (for use in bridges and pavements). It addresses the selection of quality characteristics, sampling and testing criteria, specification limits, and pay adjustments. The selected quality characteristics represent some of the most contemporary surrogates for long-term performance.

Missouri Department of Transportation. Safe and Sound Bridge Improvement Program. Missouri DOT, Jefferson City. http://www.modot.org/safeandsound/. Accessed Nov. 29, 2007.
If successful, the Missouri DOT Safe and Sound Bridge Improvement Program will outsource the rehabilitation and maintenance of approximately 800 highway bridges for a period of 25 years. The program establishes objectives for the original rehabilitation/reconstruction phase of the work, as well as performance expectations for the 25-year period of maintenance. Most of these detailed performance requirements are built around the Structure Inventory and Appraisal standards (SI&A) of the National Bridge Inspection Standards (NBIS). The program proposes to make the performing contractor responsible for delivering performance (through rehabilitation and/or maintenance) but to retain the DOT's responsibility for determining whether performance expectations are met (via the routine bridge inspection program).

Ramirez, J. A., J. Olek, A. Lu, and R. J. Frosch. *Performance Related Specifications for Concrete Bridge Superstructures: A Four Volume Report.* FHWA/IN/JTRP-2001/8. Division of Research, Indiana Department of Transportation, West Lafayette, 2002.
This research is among the very few to address performance specifications for entire concrete superstructures (the deck and major structural concrete elements). This work moves beyond materials issues to discuss performance in a larger structural context. Specific limit conditions (or performance criteria) in this research address corrosion-related deterioration, excessive crack width, flexural failure, and excessive deflections.

Sprinkel, M. M. *Performance Specification for High Performance Concrete Overlays on Bridges.* VTRC 05-R2. Virginia Transportation Research Council, Charlottesville, 2004.
This report describes the Virginia Department of Transportation's first experience with a performance specification for concrete overlays of bridges. The specification accepts and pays for the overlay on the basis of air content, compressive strength, and permeability of the overlay material (concrete), as well as the strength of the bond to the original deck material. The research demonstrates how the new specification delivered an improved product.

Tadros, M. K., and M. C. Baishya. *NCHRP Report 407: Rapid Replacement of Bridge Decks.* TRB, National Research Council, Washington, D.C., 1998.
NCHRP Report 407 provides a number of techniques that facilitate rapid deck replacement and includes proposed special provisions for the removal of the deck, which is one of the most time consuming aspects of the replacement process. The report recommends the use of performance specifications. Also, the report includes details of a precast, partial-depth deck panel system that can be used to accelerate the replacement of the deck. Information from this project can serve as a basis for the development of performance specifications for rapid deck replacement.

Geotechnical Infrastructure Systems

Bennert, T., and A. Maher. *The Development of a Performance Specification for Granular Base and Subbase Materials.* FHWA-NJ-2005-003. New Jersey Department of Transportation, Trenton, 2005.
Performance testing, selected to simulate or evaluate aggregate materials from a pavement system, was conducted to evaluate the influence of aggregate gradation. The results provided guidance for the potential modification of the New Jersey DOT specifications for base and subbase aggregates used in the construction of pavements.

Brown, D., R. Thompson, and S. Nichols. Performance Specifications for Drilled Piles. *Proc., 10th International Conference on Deep Foundations,* Amsterdam, Netherlands, 2006. http://danbrownandassociates.com/wp-content/uploads/2006/06/Performance%20Specs%20for%20CFA.pdf. Accessed Nov. 12, 2007.
This paper discusses the use of a performance specification in which the contractor can choose the most appropriate foundation system and also has greater responsibility for the performance of the completed foundation. Deep foundation contracting for transportation projects in the United States has typically followed the design-bid-build model in which contractors bid on a specific work product according to relatively inflexible prescriptive specifications. With new proprietary drilled displacement auger piling, there may be advantages to contracting according to the performance-based specification model, including opportunities to encourage innovation. There are also challenges for implementation in public works projects, notably the selection of qualified contractors and the verification of performance requirements on production foundations. This paper describes a number of features characteristic of performance specifications; in particular, it emphasizes the need for quality assurance (QA) and quality control (QC) using automated monitoring systems and the need for an appropriate testing program to assure the owners that the performance criteria are met.

Edwards, P., N. Thom, P. Fleming, and J. Williams. Testing of Unbound Materials in the Nottingham Asphalt Tester Springbox. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1913,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 32–40.
The current trend in mechanistic (analytical) pavement design is to use the mechanistic properties of pavement materials to optimize design. This is compatible with the move toward performance-based specifications and away from traditional, empirically based design methods and recipe specifications. The performance parameters assessed, over a range of moisture and soaking conditions, are resistance to permanent deformation and resilient stiffness. The apparatus used during the unbound mixture assessments is the newly developed Springbox, which uses the standard Nottingham Asphalt Tester loading frame and software.

Ellis, S., M. Nunn, and D. Weston. Development and Perceived Benefits of Performance Specifications in the UK. World Road Association, PIARC, Paris, July 2002, pp. 68–78.
This article discusses the features of the United Kingdom performance specifications for surfacing and base layers of pavements. The benefits determined from UK experiences and conditions are discussed. A performance-related specification for asphalt materials was implemented in the UK in 1996. The clause was primarily implemented to ensure materials reach the standard assumed in the pavement design, to allow more scope for contractors to produce the most economical mix design, and to ease the introduction of alternative materials.

Fleming, P., M. Frost, and J. Lambert. Geotechnical Specifications for Sustainable Transport Infrastructure. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1975,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 73–80.
The report pertains to the specification of materials and methods used in earthworks and foundations for highways, railways, and airfield runways that make best possible use of material properties. The functional requirements of a performance-based specification for UK highway foundations are described with the objective of a more sustainable use of resources. Reportedly, performance-based specifications better incorporate the principles of sustainable construction and require a fuller understanding of material behavior for their development and implementation. However, contractual issues and implications for construction need to be considered carefully to allow a full performance-based approach to be adopted successfully.

Fleming, P., J. Lambert, and M. Frost. In-Situ Assessment of Stiffness Modulus for Highway Foundations During Construction. *Ninth International Conference on Asphalt Pavements,* Copenhagen, Denmark, Aug. 2002.
This paper reviews in detail several portable field devices that measure stiffness modulus, including the German dynamic plate test (also known as the lightweight drop tester), the TRL foundation test, the prima, and the Humboldt soil stiffness gauge. Laboratory and field data are presented to explain the many important influences on the measured data and to demonstrate comparative performance with respect to the falling weight deflectometer. These field data show significant scatter and site-specific correlation.

Fleming, P., C. Rogers, N. Thom, and M. Frost. A Performance Specification for Pavement Foundations. *Transportation Geotechnics Proceedings,* Thomas Telford Publishing, London, 2003, pp. 161–176.
This paper describes how the taxation of virgin aggregates and the disposal of wastes in landfills are increasing the pressure to use novel, marginal, and recycled materials in earthworks and engineered fills that form the foundations of transport infrastructure. The paper details the performance required of pavement foundations and materials, discusses the philosophy of the performance specification that has been developed, and addresses the issues associated with its implementation. It concludes that a two-stage implementation of the specification should be adopted and that the specification could be extended to any application that requires construction of a platform/foundation to support a pavement, such as industrial paving, railway track-bed, or general fill.

Frost, M., J. Edwards, P. Fleming, and S. Arnold. Simplified Laboratory Assessment of Subgrade Performance Parameters for Mechanistic Design of Pavement Foundations. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1913,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 77–85.

With the increasing agenda for sustainability, the United Kingdom is attempting to move away from the empirical design of pavement foundations to develop a performance-specification approach that facilitates analytical design. The measurement of the subgrade performance parameters of resilient modulus and resistance to permanent deformation is required for analytical design.

Hefer, A., and T. Scullion. *Materials, Specifications, and Construction Techniques for Heavy-Duty Flexible Bases: Literature Review and Status Report on Experimental Sections.* Technical Report. Texas Department of Transportation, Austin, July 2005.
For the majority of Texas highways, the granular base layer is the main structural component of the pavement system. Base specifications and construction practices from eight U.S. departments of transportation (DOTs) and two overseas countries were compared with Texas DOT's current and proposed specifications. Currently, Texas DOT is the only agency that does not control the amount of fines (minus 200 fraction) in its bases. Research studies have indicated that high levels of minus 200 can severely affect both moisture susceptibility and cold weather performance. The newly proposed Texas DOT specifications, with limits on the fines content, are in line with the practices of other agencies in similar climates.

Iowa Department of Transportation. *Special Provision for Intermediate Foundation Improvements: Polk County, IM-NHS-235-2(498)11—03-77.* Iowa DOT, Ames, Aug. 2004.
This specification describes criteria for controlling settlement, bearing capacity, and stability for mechanically stabilized earth (MSE) walls by installation of an intermediate foundation system. Neither the methods of installation nor the product is specified; instead design parameters are given, including allowable bearing capacity, total settlement, and differential settlement. The basis for acceptance is ultimately visual inspection by the engineer, who will consider the results of all verification tests (load tests, soil borings, and in-ground instrumentation), as well as consistent use of procedures, methods, and construction performance rates.

Livneh, M., and Y. Goldberg. Quality Assessment During Road Formation and Foundation Construction: Use of Falling-Weight Deflectometer and Light Drop Weight. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1755,* Transportation Research Board of the National Academies, Washington, D.C., 2001, pp. 69–77.
Mechanistic, empirical-based specifications, which focus on the mechanical properties of materials, facilitate quantitative evaluations of alternative construction practices and materials such as reclaimed materials. To represent these mechanical properties, quality-control and quality-assurance testing are expected to include stiffness along with density measurements. In two case studies, a falling weight deflectometer (FWD) was used during the construction of two major interchanges in Israel. The possible use of the German light drop weight (LDW) device for measuring the mechanical properties of the formation of flexible pavements was also examined. Given its cost per test, rate of testing, and quality of the data, the German LDW is a cost-effective testing device for quality control and assurance during subgrade and capping-layer compaction.

Marr, A. Why Monitor Geotechnical Performance? Ohio River Valley Geotechnical Seminar, Feb. 2001.
The reasons for monitoring geotechnical performance are discussed to help engineers develop justifications for geotechnical instrumentation programs on their projects. A simplified method is presented for estimating the potential benefits of a geotechnical instrumentation program. The techniques taught in decision theory can help estimate the potential monetary benefits of a geotechnical instrumentation program. Application of these techniques can help estimate how much money can be justified for spending on a project to reduce potential risk costs from undesirable consequences. These techniques may show where to concentrate the focus of an instrumentation effort to have the most benefit.

Maryland State Highway Administration, *PS 304: Geotechnical Performance Specification,* Maryland SHA, Baltimore, 2007.
This document is a design requirement specification that stipulates criteria for the geotechnical subsurface exploration, geotechnical design, construction, and submittals. Performance criteria are provided for bearing capacity for shallow foundations (factor of safety = 3.0), settlements, external stability, (FS = 1.5 global, and FS = 2.0 sliding), axial and lateral load capacity for deep foundations, retaining walls, embankments, soil improvement, cuts, subgrades (minimum *k* and/or *Mr* to be verified by FWD). The actual design values are references to ASSHTO 17th Edition. Verification of performance is based on a variety of techniques including FWD (subgrade), wave equation analysis of piles (WEAP) + pile driver analyzer (PDA) (deep foundations), cross-hole sonic logging (CSL) (drilled shaft foundations), settlement plates (embankment settlement), and in-ground instrumentation.

McGuire, M., and G. Filz. *Specifications for Embankment and Subgrade Compaction, Technical Report.* Virginia Transportation Research Council, Virginia Department of Transportation, Richmond, May 2005.
Six approaches were developed for specifying embankment and subgrade compaction and/or verifying compaction quality on Virginia Department of Transportation (VDOT) construction projects. This study considered the use of a pay factor for embankment construction to motivate the contractor to deliver high-quality compaction. The pay factor developed for this project links the contractor's payment to the results of the field density tests. A shortcoming of this approach is that it increases the potential for disputes between the contractor and VDOT because every density test has the potential to influence the contractor's pay.

Minnesota Department of Transportation. *Specification 2111: Aggregate Base.* Minnesota DOT, St. Paul. http://www.mnroad.dot.state.mn.us/pavement/GradingandBase/G&BSpecs/2211_Sept_2003.pdf. Accessed Oct. 28, 2007.
A key element of this specification is the requirement that the aggregate meet minimum penetration index values based on dynamic cone penetration (DCP) testing, which provides a performance measurement of strength. The specification requires the full thickness of each layer to be compacted to achieve a penetration index value less than or equal to 10 mm (0.4 in.) per blow, as determined by a Minnesota DOT (MnDOT) standard DCP device. For test purposes, a layer is considered to be 75 mm (3 in.) in compacted thickness, but a testing layer can be increased in thickness to a maximum of 150 mm (6 in.) if compacted in one lift by a vibratory roller. At least two passing DCP tests should be conducted at selected sites within each 800 m^3 (1000 cubic yard) of constructed base course. If either of the tests fails to meet the specified requirements, the material represented by the test should be recompacted and retested for DCP index compliance.

Minnesota Department of Transportation. *Special Provision 5305-55, (2106) Excavation and Embankment—Quality Compaction by IC, LWD, & Test Rolling.* Minnesota DOT, St. Paul, 2007.
The pilot specification developed and implemented on this project was written to require use of intelligent compaction (IC) technology as the primary QC tool. In brief, the contractor was required to develop a QC procedure that incorporated IC measurement values gathered from control (or calibration) strips. After constructing the control strip, the contractor was required to detail how its QC procedure would be implemented on the remainder of the project (e.g., anticipated number, pattern and

speed of roller passes, potential corrective actions for noncompliant areas). The specification was written to ensure that grading materials were uniform and to confirm acceptable moisture contents. Following successful control strip construction and development of the QC procedures, proof layers (predetermined layers that required QC measurements by the contractor and QA by the engineer) were constructed. For proof layers, the engineer (1) observed the final IC recording pass; (2) reviewed and approved the QC data, documenting that acceptable compaction results were obtained; (3) performed companion and verification moisture content testing; and (4) observed test rolling results to ensure compliance (less than 50 mm rut under wheel of 650 kPa (95 lb/in.^{2}) tire pressure). IC target values (IC TV) for all proof layers were obtained on the 1.2-m (4.0-ft) layer of each control strip—unless the layer thickness was less than 0.75 m (2.5 ft). In that case, the IC TV was obtained on a 0.6-m (2.0-ft) layer of the strip. All segments were to be compacted so at least 90% of the IC measurement values were at least 90% of the IC TV before placing the next lift. If localized areas had IC measurement values of less than 80% of the IC TV, the areas were to be recompacted. If a significant portion of the grade was more than 30% in excess of the selected IC TV, the engineer reevaluated the IC TV.

Ohrn, G., and C. Schexnayder. Effect of Performance-Related Specification on Highway Construction. *Practice Periodical on Structural Design and Construction,* Vol. 2, No. 4, November 1997, pp. 172–176.
On the basis of interviews with interested parties, this paper documents advantages and disadvantages of performance-related specifications related to highway construction. The interviews were used to identify major roadblocks to implementation, including (1) performance specifications can be complex and (2) resistance to change comes from both transportation agencies and industry. Benefits to implementation include improved quality and not wasting effort on measuring parameters that are not meaningful to performance. Projects considered suitable for implementation include large highway projects but not small maintenance projects. Additional survey questions elicited discussion of the effect on change orders, safety, final quality, and construction claims. Recommendations include defining what quality characteristics should be measured, developing a consensus on pay factors (including positive pay factors if negative pay factors are used), and providing test methods for assessing quality characteristics during the construction process.

Ohrn, G., and C. Schexnayder. Performance-Related Specifications for Highway Construction. *Journal of Construction Engineering and Management,* Vol. 124, No. 1, January/February 1998, pp. 25–30.
This paper builds on the preceding paper and expands on it by differentiating between traditional and performance-based specifications, explaining an approach for developing a specification, summarizing previous research in this area, and presenting an example from New Jersey in which a pay factor was established for rigid pavement.

Petersen, D., M. Erickson, R. Roberson, and J. Siekmeier. Intelligent Soil Compaction: Geostatistical Data Analysis and Construction Specifications. Presented at 86th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2007.
The authors describe two projects in which intelligent compaction specifications adapted from standard earthwork and embankment specifications were implemented. Used together, intelligent compaction rollers, specifications, and geostatistics offer the promise of reducing maintenance costs and increasing pavement life by helping project personnel find and fix subgrade compaction problems before pavement placement.

Petersen, J., S. Romanoschi, M. Onyango, and M. Hossain. Evaluation of Prima Light Falling-Weight Deflectometer as Quality Control Tool for Compaction of Fine Grained Soils. Presented at 86th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2007.
Compaction of embankment soils is a key factor influencing premature pavement distresses. The authors investigated the use of the Prima 100 light falling weight deflectometer (L-FWD) to measure in situ soil stiffness and the feasibility of developing a stiffness-based specification for embankment soil compaction quality control that uses the L-FWD measured stiffness. They found that the predicted in situ resilient moduli did not correlate with the in situ measured moduli. Therefore, they could not develop a quality control scheme for embankment soil stiffness that employs stiffness requirements established on the basis of the results of laboratory resilient modulus tests. In addition, the testing proved that the in situ modulus of fine-grained soils has a high degree of spatial variability. This prevented the development of a quality control procedure based on stiffness measured on a control test strip.

Pinto, S. Proposal of Performance-Based Specifications for Selection and Placing of Natural Materials for Road Embankment Construction. *Proc., 22nd PIARC World Road Congress,* Durban, South Africa, 2004.
The paper proposes to abandon soil classification and to select soils for road construction according to a CBR-based procedure which chooses compaction energy and compaction water content range to achieve good mechanic and volume stability. This procedure should allow the use of almost every soil for embankment, avoiding the need to consider materials not compliant with specifications.

Rogers, C., P. Fleming, and M. Frost. A Philosophy for Performance Specification for Road Foundations. *Proceedings of the Institute of Civil Engineers,* Transport, Vol. 157, No. 3, Aug. 2004, pp. 143–151.
This paper focuses on development of performance specifications for pavement foundations. A flowchart summarizes the performance specification philosophy. To develop a specification, the types of in situ tests and test equipment need to be identified. Performance parameters needed for pavement design include resilient elastic modulus, shear strength, and resistance to permanent deformation. During the design stage, laboratory material properties are determined. Next, to assess the materials and construction equipment, a field trial can be conducted. Finally, an assessment is carried out during field construction to verify achievement of the specified parameters.

Schaefer, V., and D. White. Quality Control and Performance Criteria for Ground Modification Technologies. *Proc., Geotechnical Engineering for Transportation Projects,* Geotechnical Special Publication No. 126, ASCE, Los Angeles, Calif., 2006, pp. 1935–1942.
The paper describes a conceptual framework for linking QC and QA testing with performance-based criteria for ground modification techniques. The proposed method is general and can be applied to virtually any ground modification technology. The method provides a way to compare the relative merits of various ground modification strategies through a direct link to performance of the proposed system. The method has been demonstrated through examples of deep dynamic compaction and stone columns. Comparisons of QC and QA testing with performance results for additional case histories will be needed to verify the generality of the method to other ground modification techniques.

Utah Department of Transportation. *Geotechnical Performance Specification, Utah I-15 NOW Project.* Utah DOT, Salt Lake City, Dec. 9, 2006.
This document describes geotechnical investigations, analyses, and design for all components of the Utah DOT I-15 NOW project. A number of references are cited in the specification concerning design methodologies to be used. Design parameters included settlement bearing capacity, stability, and seismic performance criteria. Performance criteria were stated as

"(A) Perform analyses, prepare design, and construct the Project to limit the longitudinal and transverse settlement of the roadway, structures, embankments, and other Project facilities as specified in Part 9 Warranty Provisions; and (B) Mitigate and otherwise be responsible for all distress to structures and properties adjacent to the corridor that is caused by the Project (both directly and indirectly) as specified in the Part 9 Warranty Provisions. The Department will evaluate the Design Builder's compliance with these performance requirements based on the profilograph measurements, as required in the Pavement Performance Specification and the allowable settlement criteria specified in the Part 9 Warranty Provisions."

Walsh, K., W. Houston, and S. Houston. Field Implications of Current Compaction Specification Design Practices. *Journal of Construction Engineering and Management,* Vol. 123, No. 4, 1997, pp. 363–370.
Variations in both the field density and the laboratory-determined reference maximum dry density arise from numerous sources. A corresponding spatial variability of relative compaction should therefore be anticipated. This paper provides a comprehensive evaluation of potential problems in compaction control and addresses the sources of field variability in relative compaction.

White, D. J., K. L. Bergeson, and C. T. Jahren. *Embankment Quality: Phase III, Final Report.* Iowa DOT Project TR-401. Center for Transportation Research and Education, Ames, Iowa, June 2002.
Contractor QC and Iowa DOT QA special provisions were developed and tested by constructing a full-scale embankment project. Surficial density testing was shown not to be adequate for indicating the uniformity and stability of the embankment soils. The DCP test was able to detect nonuniformity and development of "Oreo cookie" effects requiring corrective action. One of the primary questions Phase III asked was, "Was the quality improved?" The project involved a "quality conscious" contractor, well-qualified and experienced Iowa DOT field personnel, a good QC consultant technician, and some of the best soils in the state. If the answer for this project was yes, the answer would unquestionably be yes for other projects as well. In the authors' opinion, the answer for this project was indeed yes: the quality was improved, as evidenced by the DCP test data and the amount of disking required to reduce the moisture content to within acceptable control limits.

Pavement

Portland Cement Concrete (PCC) Pavement

ARA, Inc. Design of New and Reconstructed Rigid Pavements. Chapter 4 in *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Final Report, Part 3: Design Analysis, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004.
This document is part of the final report for the new AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG). Chapter 4 covers the design of rigid (PCC) pavements. Although the MEPDG is a guide for design of new and reconstructed pavement, the models contained within the guide predict the performance of rigid pavements on the basis of project-specific inputs for design. Rather than relying solely on empirical performance models (as the PaveSpec software does), the MEPDG software includes mechanistic modeling and finite element analysis to predict pavement performance on the basis of site-specific inputs. The design process is described as follows:

> The process requires an iterative hands-on approach by the designer. The designer must select a trial design and then analyze the design in detail to determine if it meets the established performance criteria. The performance measures considered in this guide include joint faulting and transverse cracking for [jointed plain concrete pavement] JPCP, punchouts [and crack width and LTE] for CRCP, and International Roughness Index (IRI) for both pavement types. . . . The designs that meet the applicable performance criteria at the selected reliability level are then considered feasible from a structural and functional standpoint and can be further considered for other evaluations, such as life-cycle cost analysis and environmental impacts.

Although this guide does not explicitly calculate pay factors for use in performance specifications, it provides an analysis tool with which the sensitivity of different construction-related inputs (or ACQs) can be evaluated such that pay factors can be determined for inclusion in a performance specification. One advantage of this guide is that it considers both JPCP as well as CRCP for new construction. The guide also considers site-specific climatic conditions through the Enhanced Integrated Climatic Model (EICM) and site-specific traffic loading through axle load spectrum.

ARA, Inc. PCC Rehabilitation Design of Existing Pavements. Chapter 7 in *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Final Report, Part 3: Design Analysis, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004.
This document is part of the final report for the new AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG). Chapter 7 covers the design of rigid (PCC) pavements for rehabilitation of existing pavements. As described by this chapter,

> Several different rehabilitation strategies using PCC can be applied to existing pavements to extend their useful service life. These range from the combination of repair and preventative treatments such as full-depth repair and diamond grinding of existing jointed plain concrete pavement (JPCP) to the placement of unbonded JPCP or CRCP overlays over existing flexible, composite, or rigid pavements, to the placement of bonded PCC overlays over existing JPCP or CRCP, to the reconstruction (including adding additional lanes) of existing pavements with JPCP or CRCP.

As with the use of this guide for new pavements, the MEPDG can be used to predict pavement performance for PCC rehabilitation as well, such that proper performance parameters and pay factors can be developed for true performance specifications. Considered in a rapid renewal environment, rehabilitation—rather than reconstruction—may be the best alternative, and the use of this guide will assist in developing performance specifications for such a purpose.

California Department of Transportation. *Replace Concrete Pavement (Rapid Strength Concrete).* Standard Special Provision 40-020. Caltrans, Sacramento, 2006.
This document is a special provision used by Caltrans for concrete pavement reconstruction using rapid strength concrete. The specification details the material requirements and construction practices to use for replacement of concrete pavement, but permits the contractor to select the mixture design for the rapid strength concrete. Specific mixture durability requirements are provided for the mixture supplied by the contractor.

In addition to mixture durability requirements, pay factor adjustments (and rejection criteria) are specified on the basis of the required modulus of rupture at opening to traffic and at 7 days. In a rapid renewal environment, this specification provides guidance for the use of rapid setting concrete for rapid pavement reconstruction. One of the key features of this specification is that it permits the contractor to select the mixture design for the paving mixture.

Evans, L., M. I. Darter, and B. K. Egan. ***Development and Implementation of a Performance-Related Specification: I-65 Tennessee.*** **Research Report for Contract No. DTFH61-03-C-00109. Federal Highway Administration, U.S. Department of Transportation, March 2005.**

This report provides a summary of the development of a PCC pavement PRS and its implementation on a project constructed on Interstate 65 near Nashville, Tennessee. Appendix A of the report provides the final PRS used for the technical special provision for the project on I-65 in 2005. The report discusses the selection of the AQCs and appropriate target values for the mean and standard deviation, RQLs, and MQLs for each. For this PRS, 28-day compressive strength, slab thickness, and initial smoothness (Profilograph Index) were selected as the AQCs. The report compares the Tennessee DOT (TDOT) standard specification pay adjustments for these AQCs with the PRS pay adjustments. The report also presents the PaveSpec 3.0 inputs and analysis that were used to develop the pay factor charts for the selected AQCs.

While the intent was to use the specification as a shadow specification on the northbound lanes and formally apply it for the southbound lanes, project time constraints only permitted its use as a shadow specification for the whole project. After the project was completed, the PRS pay factors were computed on the basis of test results under the standard specifications. Overall, TDOT, the contractor, and the QC representative all gave very positive feedback on the PRS process. The final project PRS provided in the appendix of the report does not appear to refer to any TDOT standard specifications.

Evans, L., K. L. Smith, N. G. Gharaibeh, and M. I. Darter. ***Development and Implementation of a Performance-Related Specification in Florida: State Road 9A (I-295 Leg), Jacksonville.*** **Research Report FHWA-HIF-07-. Federal Highway Administration, U.S. Department of Transportation, Dec. 2006.**

This report summarizes the development of the PCC pavement performance-related specification (PRS) and its implementation on a project constructed in Florida in 2004–2005. The report discusses the selection of the acceptance quality characteristics (AQC) and appropriate target values, rejectable quality levels (RQL), and maximum quality levels (MQL) for each AQC, on the basis of previous concrete pavement projects in Florida. This work included an analysis of maintenance and rehabilitation activities and costs for PCC pavements based on historical data. The report presents the PaveSpec 3.0 inputs and analysis that were used to develop the pay factor charts for the selected AQCs.

A postmortem assessment of the project and the PRS process produced favorable responses from both the Florida DOT (FDOT) and the contractor. Contractors paid more attention to quality control and were pleased with the level of control they were given with developing the mix design and over construction operations. FDOT felt the project was successful, but because of the limited size of the project, a more thorough assessment of the PRS process was difficult. Overall, FDOT decided that moving toward PRS is beneficial and will lead to better PCC pavements in the state.

FHWA. ***Guide to Developing Performance-Related Specifications for PCC Pavements, Volume 1: Practical Guide, Final Report, and Appendix A.*** **Research Report FHWA-RD-98-155. Federal Highway Administration, U.S. Department of Transportation, Feb. 1999. http://www.tfhrc.gov/pavement/pccp/pavespec/index.htm.**

This report is a precursor to the report by Hoerner, Darter, Khazanovich, Titus-Glover, and Smith (2000); it provides a more thorough history of the development of PRS for PCC pavements. This report also documents the process for the development of the PaveSpec Version 2.0 software. The report provides additional insight into the goals of a true PRS for PCC pavement, notably, tying AQCs measured at construction with future life-cycle costs (LCC) of the pavement, such that rational pay adjustments can be employed during construction for the various AQCs.

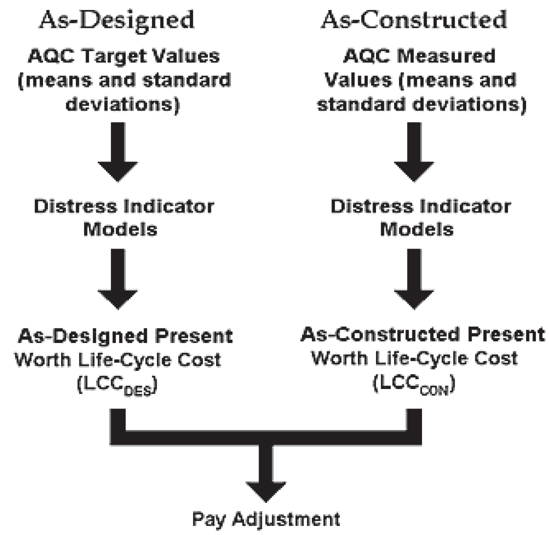

Figure D.1. PRS methodology for PCC pavements.

LCCs are computed using future maintenance and rehabilitation activities which are determined on the basis of prediction models for distresses, such as slab cracking, joint spalling, joint faulting, and roughness. The following figure taken from the report, denoted here as Figure D.1, graphically depicts the LCC-based PRS method.

As Figure D.1 describes, as-designed mean and standard deviation values are established for the various AQCs, which are then used to compute as-designed life-cycle costs using distress indicator models and anticipated maintenance and rehabilitation costs. The as-designed LCCs are compared with as-constructed LCCs, which are computed using distress indicator models based on the actual measured AQCs during or shortly after construction. This comparison of as-designed to as-constructed LCCs permits the agency to establish rational pay adjustments on the basis of the measured AQCs.

Of note in this report are the three different levels of PRS that can be anticipated given the amount of information available for each project and the AQC measurement capabilities.

- Level 1 PRS (simplified PRS) uses acceptance testing similar to the procedures currently used by state highway agencies. Computation of pay factors is based on calculating independent pay factors for each AQC, assuming all other AQCs are equal to the target values. Pay factors are a function of the measured as-constructed mean and standard deviation, target mean and standard deviation, and sample size. Final payment for each lot of pavement constructed is based on a composite pay factor equation.
- Level 2 PRS (transitional PRS) compare simulated as-designed LCC with as-constructed LCC for each lot to determine the pay adjustment. LCCs are computed on the basis of AQCs, and pay adjustments are based on the premise of liquidated damages. Acceptance testing of AQCs is conducted with the best techniques available, preferably in situ and nondestructive testing. Using computer simulations of pavement performance based on all of the AQCs obviates the need to combine individual pay factors as with Level 1 PRS.
- Level 3 PRS (ideal PRS) considers many more AQCs that are not currently measurable. All AQCs that affect pavement performance are under the control of the contractor. Level 3 PRS uses LCC procedures similar to Level 2, except that all AQCs are determined using in situ, rapid, nondestructive methods.

The appendix of this report provides a guidance performance-related specification for jointed plain concrete pavement which is based on the methodology described in the report (only for Level 1 and Level 2 PRS).

FHWA. *Guide to Developing Performance-Related Specifications for PCC Pavements, Volume 2: Appendix B—Field Demonstrations.* Research Report FHWA-RD-98-156. Federal Highway Administration, U.S. Department of Transportation, February 1999. http://www.tfhrc.gov/pavement/pccp/pavespec/index.htm.
This publication is Appendix B of the report discussed above. It discusses a prototype PRS that was developed under this effort and the specific PRS that were developed for shadow field trials on projects in Iowa, New Mexico, Missouri, and Kansas.

FHWA. *Guide to Developing Performance-Related Specifications for PCC Pavements, Volume 3: Appendices C–F.* Research Report FHWA-RD-98-171. Federal Highway Administration, U.S. Department of Transportation, Feb. 1999. http://www.tfhrc.gov/pavement/pccp/pavespec/index.htm.
This publication contains additional appendices for the original report which include

- Appendix C, Literature Search Summary;
- Appendix D, Typical Acceptance Quality Characteristic Variability;
- Appendix E, Distress Indicator Prediction Models; and
- Appendix F, Annotated Bibliography.

Florida Department of Transportation. *Technical Special Provisions for Performance-Related Specification for Rigid Pavement.* Project ID 209600-1-52-01, State Route 9A (I-295 Leg), Duval County. Florida DOT, Tallahassee, 2001.
This PRS was developed for a PCC pavement project in Duval County, Florida, and is based on the PRS methodology developed under FHWA efforts using the PaveSpec 3.0 software. The AQCs used in this specification are 28-day compressive strength, slab thickness, and initial smoothness (Profile Index). RQLs and MQLs are provided for each AQC. A composite lot pay factor equation is provided which includes the pay factors for the three AQCs (strength, thickness, and smoothness), based on the mean and standard deviation for each AQC.

This PRS is a trial specification used for a specific project, not a standard special provision. This PRS does refer to FDOT standard specifications for PCC pavement, with modifications noted in the specification.

Hoerner, T. E., M. I. Darter, L. Khazanovich, L. Titus-Glover, and K. L. Smith. *Improved Prediction Models for PCC Pavement Performance-Related Specifications, Volume 1: Final Report.* Research Report FHWA-RD-00-130. Federal Highway Administration, U.S. Department of Transportation, Sept. 2000.
This report documents the development of PRS for PCC pavement over the past 20 years. The work conducted under the effort described in this report was used to upgrade the FHWA PaveSpec PRS software to version 3.0. This upgrade to the PaveSpec 2.0 software provided (1) improved or validated distress indicator models, (2) the ability to calibrate or modify the default distress indicator models, (3) sensitivity analysis capabilities, and (4) the ability to assess risks to both the contractor and agency through the development of project-specific expected pay charts. As stated in this report,

> A PRS is a construction specification that describes the desired level of key materials and construction acceptance quality characteristics (AQCs) that have been found to correlate with fundamental engineering properties that predict performance. These AQCs (e.g., smoothness, thickness, strength, air content, and percent consolidation around dowels) are amenable to acceptance testing at the time of construction.

The basis for PRS for PCC pavement, described in detail in this report, is the use of distress indicator models to predict the performance of PCC pavement over time on the basis of specific AQCs that can be measured during or shortly after construction. The AQCs which were considered include

- Slab thickness;
- Concrete strength (flexural or compressive);
- Air content;
- Initial smoothness; and
- Percent consolidation around dowels.

Although included in the software, the final AQC listed (percent consolidation around dowels) is generally not included in most PCC PRS because that AQC is difficult to measure accurately in the field at present. The report recommends consideration and inclusion of additional AQCs once distress indicator models can be developed for them. The additional AQCs include joint sawing depth, surface texture, concrete mixture components, base course quality, subgrade quality, air content characteristics, calorimetry, and coefficient of thermal expansion (CTE) of the paving concrete.

On the basis of the AQCs presented above, distress indicator models are used to predict some of the most commonly observed PCC pavement distresses, which encompass both structural performance as well as functional performance. Improved distress indicator models were provided for

- Transverse joint faulting;
- Transverse fatigue cracking;
- Transverse joint spalling; and
- International Roughness Index (IRI) (roughness/roughness progression).

A detailed investigation of available pavement performance data and distress indicator models was conducted to identify the most suitable models and performance data for inclusion. This investigation considered pavement performance data collection efforts and databases from a number of sources including FHWA Rigid Pavement Performance and Rehabilitation (RPPR) study, Long-Term Pavement Performance (LTPP), NCHRP concrete pavement evaluation system (COPES), AASHO Road Test, and Mn/ROAD. This report provides a comprehensive summary of the distress indicator models that were used and the process of selecting the models.

Note that this report and the PaveSpec 3.0 software consider only new jointed plain concrete pavement and not continuously reinforced concrete pavement (CRCP), jointed reinforced concrete pavement (JRCP), or bonded/unbonded concrete overlays. Also note that the smoothness prediction models are based on IRI, even though most state highway agencies currently use profilograph testing to determine initial smoothness. A significant effort was devoted to establishing a correlation between IRI and the Profilograph Index (PI) that could be used by the software.

Indiana Department of Transportation. *Special Provision, Section 509: Performance-Related Specification for Portland Cement Concrete Pavement.* Indiana DOT, Indianapolis, 2003.
This PRS for PCC pavement evolved from the work described in the FHWA and Hoerner et al. reports in this section. The Indiana PRS is perhaps one of the most mature as it was developed and refined on the basis of trial projects in Indianapolis (I-465 and I-70) and Clarksville (I-65), using PaveSpec 3.0 software and life-cycle cost PRS procedures. The specification states, "Pay adjustment is based on the AQC quality-related

increase or decrease in future LCCs expected to be incurred by the Department over the analysis life of the project."

The AQCs selected by the Indiana DOT (INDOT) for this PRS are flexural strength (a 28-day equivalent of the measured 7-day strength), slab thickness, air content, and initial smoothness (PI). Acceptance testing of the AQCs is based on lots for strength, thickness and air, and sections for smoothness. RQLs and MQLs are provided for each AQC to ensure that no unacceptable levels of AQCs are provided and that the maximum pay adjustment is within reason. Additional acceptance criteria based on unit weight and water/cement ratio are also provided but are not included in the pay adjustment. A composite pay factor is provided for strength, thickness, and air AQCs based on the mean and standard deviation for each lot, and a separate pay factor is provided for smoothness based on the mean and standard deviation for each section. These are combined for an overall performance-related adjustment. The contractor is required to submit a quality control plan for the paving operation at least 15 days before commencement of paving.

While this is considered a performance-related specification, the specification still prescribes material requirements and certain mix design limits, and it refers extensively to INDOT standard specifications for both material and construction requirements. INDOT has extensive experience with QC and QA specifications and some experience with warranties for PCC pavement. The intent of moving to a PRS was to reduce the variability of the PCC paving operation that was experienced under QC/QA contracting.

Minnesota Department of Transportation. *Standard Specification Section 2301: Concrete Pavement.* Minnesota DOT, St. Paul, 2005.
Section 2301.2A5d provides an optional incentive for well-graded aggregate of up to $2.00 per cubic yard. The two provisions for gradation to achieve this incentive are based on the ACI 8%–18% retained chart (7%–18% for a lower incentive). Although this is not a true performance specification, MnDOT believes it will achieve better long-term performance from the pavement if a well-graded aggregate is used. This gradation incentive provides the contractor with some flexibility in achieving it.

Section 2301.2A7b(5) provides an incentive/disincentive clause for water-cement ratio of the concrete mixture used for paving. Although this is not a true performance specification, it will help ensure that either a more durable, long-lasting concrete mixture is used or that the contractor does not receive full payment. This specification is based on well-understood principals that concrete mixtures with lower water-cement ratios generally result in more durable pavement. This type of specification will reward contractors who make an effort to carefully develop their mix design and monitor it carefully during the mixture production process.

Section 2301.2A5c provides an incentive/disincentive clause for coarse aggregate quality based on absorption and percent carbonate for different classes of aggregate. Although this is not a true performance specification, it is based on payment for material quality, which directly affects pavement performance. If a better quality aggregate is used, better performance is expected from the pavement, and therefore the contractor receives an incentive.

Section 2301 also contains a deduction/disincentive clause for slab thickness deficiency and an incentive/disincentive clause for surface smoothness, which are fairly standard clauses for PCC pavement specifications.

Minnesota Department of Transportation. *Special Provision S-111, Section 2301: Concrete Pavement.* Minnesota DOT, St. Paul, 2006.
This special provision provides a requirement for PCC pavement texture in term of average texture depth, as measured according to ASTM E965 (sand patch test). Although this is not a true performance specification, it dictates what is required from the contractor in terms of texture without prescribing the technique for achieving it.

Missouri Department of Transportation. *Standard Specifications Section 502: Portland Cement Concrete Base and Pavement.* Missouri DOT, Jefferson City, 2004.
Section 502.4.8.3 provides requirements for surface texture. Acceptance is based on the minimum texture depth provided as measured using ASTM E965 (sand patch test). The contractor can opt to diamond grind or tine the surface (in accordance with a prescribed technique) in lieu of this requirement.

This specification represents a potential component of a performance specification. The contractor is required to achieve a minimum texture depth, but the specification prescribes the technique for achieving it. Although texture is not itself a functional performance measure, it has a direct impact on friction and tire-pavement noise.

Morgan, P. (ed.). *Guidance Manual for the Implementation of Low-Noise Road Surfaces.* FEHRL Report 2006/02. Forum of European National Highway Research Laboratories, Brussels, Belgium, 2006.
This report is one of the products from the Sustainable Road Surfaces for Traffic Noise Control (SILVIA) framework project in Europe. The SILVIA project was initiated to help develop solutions for addressing roadway noise issues (specifically, tire-pavement noise) at the pavement level by providing guidance for low-noise pavement surfaces. This report provides background information on tire-pavement noise issues and an overview of low-noise solutions for pavement surfaces. The manual also summarizes the different measurement methods that are available for the evaluation of the acoustic performance of a road surface, presents a noise classification procedure that provides accurate and reproducible characterization of the acoustic performance of a specific pavement, and presents a conformity-of-production (COP) method for assessment. The manual also addresses some of the economic considerations of specifying low-noise surfaces.

North Dakota Department of Transportation. *Dowel Bar Warranty, Special Provision IM-2-094(064)275.* North Dakota DOT, Bismarck, 2005.
This special provision is a warranty specification for dowel bars. The specification is not explicitly for dowel-bar retrofits or new construction and could likely be used for either. The specification is based on measurement of load transfer across the joint as quantified by deflection testing, as well as visual inspection of the area around the dowel bars for visual distresses. Thresholds are provided for full payment, reduced payment, and rejection of joints. No warranty period is specified, but two rounds of testing are conducted. The first test is conducted shortly after construction, the second test after approximately 1 year in service. Testing is conducted between September 1 and November 1, presumably when joints are neither locked up nor opened widest.

Österreichische Forschungsgesellschaft (FSV). Austrian PCC Pavement Specification: Concrete Pavements—Pavement Construction, RVS 08.17.02. 2007.
This specification is essentially a warranty specification for PCC pavements. However, it includes some unique components that could be considered for PCC pavement performance specifications. Notably, deductions are assessed for excessive rolling noise (functional performance) and also for poor performance in a freeze-thaw condition resulting from poor air void parameters. The specification requires a guarantee (warranty) of 5 years by the contractor after the completion of construction, but requires a 2-year extension of that guarantee if certain performance parameters are not achieved.

Section 9, Acceptance Factors, and Section 10, Deductions for Substandard Quality, describe the pavement characteristics which are measured during and shortly after construction, and the potential deductions associated with each. While the deductions (penalties) for substandard quality are more extensive than most used in the United States, the pay deductions are not clearly tied to life-cycle costs for the pavement. The acceptance parameters include the following:

- *Thickness.* No deductions are specified for deficiencies in smoothness, but if the thickness measured from any given test core is more than 2 cm less than the required thickness, the guarantee period is extended for 2 years for the test lot.
- *Strength (splitting tensile).* Deductions are specified for substandard strength. If the concrete strength is more than 15% lower than the prescribed strength at any test location, the contractor has the option to remove and replace the pavement, or accept an additional pay deduction, presumably reflecting the expected loss of pavement life.
- *Evenness (profilograph testing).* Deductions are specified for substandard evenness. If the contractor elects not to take corrective action for substandard evenness, an additional deduction is applied.
- *Cracks.* Deductions are specified on the basis of the area of cracked slabs.
- *Air content.* Air content is measured at the point where the concrete is placed. If an impermissible air void parameter is established during the conformity tests on fresh concrete, cores are taken to determine the air void parameters. If the air void parameters are still substandard, the guarantee period is extended by 2 years. If damage occurs to the pavement in the presence of deicing chemicals during the guarantee period because of a lack of scaling resistance from substandard air voids, deductions are assessed.
- *Excessive rolling noise.* For exposed aggregate surfaces, deductions are assessed for excessive rolling (tire-pavement) noise.
- *Substandard skid resistance.* Deductions are specified for substandard skid resistance, which is evaluated at "handover" (up to 12 weeks after pavement has been open to traffic), during the guarantee period, and at 4 weeks to 16 weeks before the end of the guarantee period. The guarantee period is extended by 2 years if skid resistance is substandard at the end of the guarantee period. Additional deductions are assessed as a penalty for traffic restrictions when correcting skid resistance or for traffic restrictions because of low skid numbers.

Sandberg, U. Low-Noise Road Surface Classification and Procurement System in Japan. Commentary. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden, 2005.
A performance-based system for procurement of low-noise road surfaces has been used for several years in Japan. Performance is based on prescribed tire-pavement noise levels. Tire-pavement noise levels are measured by the transportation authority using special vans (Road Acoustic Checkers) equipped with a special tire as a fifth wheel, and using a method resembling the close proximity (CPX) method. Currently, five such vans operate in Japan; they are calibrated once per year at a test track facility at the Public Works Research Institute in Tsukuba City.

For construction acceptance, tire-pavement noise levels are measured twice: soon after completion of construction and after 1 year of traffic exposure. The noise level should not exceed 89 dB soon after the completion of the road surface and should not exceed 90 dB 1 year later. An extra dB is allowed for projects in which an aggregate of poorer quality has been accepted. A special version of the procurement system allows for surfaces which are quieter than the normal requirement; the intent is to encourage development of quieter surfaces than those that merely meet the required limits. In this case, the bidder (the road contractor) specifies a lower noise level for his surface than the required limit; after construction, the measured noise level must not exceed that specified level. One year after completion, an increase of one dB is allowed. Beginning with only three procurement contracts under this system in 1999, the number of contracts increased to about 130 in 2003; and that number is still steadily increasing.

Wisconsin Department of Transportation. *Technical Special Provisions for Performance-Related Specification for Rigid Pavement.* Item SPV.0055.01, Project ID 1011-01-88, IH-39/90/94. Lake Delton–Madison Rd., District 1, Dane County. Wisconsin DOT, Madison, 2005.
This PRS was developed for a PCC pavement project in Dane County, Wisconsin, and is based on the PRS methodology developed under FHWA efforts using the PaveSpec 3.0 software. The AQCs in this specification are 28-day compressive strength, thickness, air content, and initial smoothness (Profile Index). RQLs and MQLs are provided for each AQC. A composite lot pay factor equation is provided which encompasses pay factors for all four AQCs (smoothness, air, strength, and thickness), based on the mean and standard deviation for each AQC.

Although this is considered a performance-related specification, it does refer to PCC pavement standard specifications for materials, mixtures, and so on—much of which contain prescriptive requirements.

Wisconsin Department of Transportation. *Pavement Dowel Bars Retrofit Warranted.* Item 416.0623.S. Wisconsin DOT, Madison.
This document is a warranty specification for dowel bar retrofit (DBR) projects. Performance evaluation of the DBR is based on a visual distress survey of retrofit. The warranty covers material and workmanship for a 3-year period. The specification provides materials and construction procedures for DBR, including tolerances for dowel bar alignment. Thresholds and remedial actions are provided for the following:

- Distressed joints within the DBR slot;
- Cracking in the existing pavement between the slots or across slab to pavement edge;
- Loss of surface and concrete patch material within the DBR slot;
- Debonding of the patch concrete with existing concrete; and
- Breakup or dislodgement of concrete patch material within the slot.

Hot-Mix Asphalt (HMA) Pavement

ARA, Inc. Design of New and Reconstructed Flexible Pavements. Chapter 3 in *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Final Report, Part 3: Design Analysis, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004.
This document is part of the final report for the new AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG). Chapter 3 covers the design of flexible pavements and is most applicable for pavements with conventional dense-graded HMA mixtures; but it can also be used to a limited extent for stone matrix asphalt (SMA), polymer-modified asphalt (PMA), and recycled asphalt pavement (RAP) mixtures. While the MEPDG is a guide for design of new and reconstructed pavement, the models contained within the guide predict the performance of flexible pavements on the basis of project-specific inputs for design. The models used in the software are not purely empirical, as with the original AASHO pavement design guide, but also use mechanistic modeling to compute stresses and strains to predict performance based on site-specific inputs. As with the rigid pavement section of the MEPDG, the flexible pavement design requires

> . . . an iterative hands-on approach by the designer. The designer must select a trial design and then analyze the design in detail to determine if it meets the established performance criteria. The flexible performance measures considered in this guide include pavement deformation (rutting),

> fatigue cracking (both bottom-up and top-down), thermal cracking, and smoothness (International Roughness Index). . . . The designs that meet the applicable performance criteria at the selected reliability level are then considered feasible from a structural and functional standpoint and can be further considered for other evaluations such as life-cycle cost analysis.

Although this guide does not explicitly calculate pay factors for use in performance specifications, it provides an analysis tool with which the sensitivity of different construction-related inputs (or acceptance quality characteristics) can be evaluated such that pay factors can be determined for inclusion in a performance specification. One advantage of this guide is that it conducts a comprehensive analysis that considers site-specific climatic conditions through the EICM and site-specific traffic loading through axle load spectrum, among other variables.

ARA, Inc. HMA Rehabilitation of Existing Pavements. Chapter 6 in *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Final Report, Part 3: Design Analysis, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, D.C., 2004.

This document is part of the final report for the new AASHTO *Mechanistic-Empirical Pavement Design Guide* (MEPDG). Chapter 6 covers the use of HMA for rehabilitation of existing pavements. Rehabilitation strategies considered by this guide include the following:

- HMA overlay of existing HMA surfaced pavements, both flexible and semirigid;
- HMA overlay of existing PCC pavement that has received fractured slab treatments, crack and seat, break and seat, and rubbilization; and
- HMA overlay of existing intact PCC pavement (JPCP and CRCP), including composite pavements or second overlays of original PCC pavements (not including JRCP).

As with the use of this guide for new pavements, the MEPDG can be used to predict pavement performance for HMA overlays, such that proper performance parameters and pay factors can be developed for true performance specifications. In a rapid renewal environment, rehabilitation—rather than reconstruction—may be the best alternative, and the use of this guide will assist in developing performance specifications for such a purpose.

Epps, J. A., et al. *NCHRP Report 455: Recommended Performance-Related Specification for Hot-Mix Asphalt Construction: Results of the WesTrack Project.* TRB, National Research Council, Washington, D.C., 2002.

This is the final report from NCHRP Project 9-20, which sought to develop performance-related specifications for hot-mix asphalt pavement construction by examining how deviations in materials and construction properties, such as asphalt content and degree of compaction, affect long-term pavement performance. The experiment was also intended to provide early field verification of the SHRP Superpave volumetric mixture design procedure. The testing program consisted of heavy truck loading on 34 different Superpave HMA pavement sections (26 original test sections with eight reconstructed during the testing) constructed on a 1.75-mi closed loop test track (WesTrack pavement test facility) over a 2½-year period. On the basis of the work from this study, a prototype version of the HMA Spec software was developed. The software helps state highway agencies determine pay adjustments for the various HMA pavement quality characteristics such that they relate to the predicted life-cycle costs of the pavement.

Part I of the report provides information on the overall WesTrack project, including construction of the test sections, trafficking operations, and materials characterization and performance models. Part II presents the development of the performance-related specification for HMA pavement and the development of the HMA Spec software. The intent of the PRS and HMA Spec software is to provide rational pay adjustment levels for as-constructed HMA pavement quality that are based on the difference between as-designed life-cycle costs and as-constructed predicted life-cycle costs. The report describes the two levels of performance models that were considered in the PRS. Level 1 models are based on direct regressions among specific performance measures (rut depth or fatigue cracking) and traffic (equivalent single axle loads, or ESALs) and mix characteristics. Level 2 models are based on mechanistic-empirical analyses which assume the pavement behaves as a multilayer elastic system.

The performance criteria primarily considered in the PRS development process were permanent deformation (rutting) and fatigue cracking, though other ways to characterize performance exist (e.g., low temperature cracking, roughness, and friction loss). The AQCs considered in the WesTrack experiment were HMA surface layer thickness, initial smoothness, asphalt content, air void content, and an aggregate gradation parameter (percent passing the no. 200 sieve). The initial smoothness performance criterion is not included in the HMA Spec software.

Chapter 10 of the report provides a summary of the Guide Performance Specification for WesTrack that is contained within the HMA Spec software. The actual Guide Specification is provided in Appendix C of the report as AASHTO Provisional Specification PP 400.

Huber, G. A., and J. S. Scherocman. Superpave and WesTrack: Did They Perform as Expected? *Proc., 1999 Canadian Technical Asphalt Association Conference,* Quebec, Canada, Canadian Technical Asphalt Association, Victoria, British Columbia, 1999.

This paper presents a summary of the WesTrack study and a summary of a forensic investigation as to why some of the test sections did not perform as expected. The WesTrack study was intended to provide early field verification of Superpave HMA mixtures; so the poor performance of certain sections was of great concern to the HMA paving community as they were beginning to adopt the Superpave process and construct Superpave HMA pavements. Of particular note was the poor performance of coarse-graded test sections which were expected to perform better than fine-graded sections and did not.

One of the key observations from this investigation was that the use of relatively thin HMA pavement layers—which were intentionally underdesigned (thinner than the 20-year design thickness) to ensure that fatigue cracking would occur within the life of the project—may have had unintentional effects on the performance of the test sections. The thinner pavement sections resulted in significantly higher deflections under load than normally measured on interstate pavements. As a result, deflections were influenced more than usual by the underlying base and subgrade and influenced less than usual by differences in the asphalt mixture properties between test sections. This hypothesis and supporting evidence are discussed in greater detail in Appendix A of the FHWA report *Performance of Coarse-Graded Mixes at WesTrack: Premature Rutting* found at http://www.tfhrc.gov/pavement/pubs/westrack/westrack.htm#6.

The underlying significance of this investigation is that because of the experimental design (specifically the structural design which would not likely be used for a typical interstate pavement), the pavement sections did not perform as expected. Therefore, the development of performance-related specifications based solely on the WesTrack experiment may not be appropriate.

Monismith, C. L., J. A. Deacon, and J. T. Harvey. *WesTrack: Performance Models for Permanent Deformation and Fatigue.* Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, June 2000.

This report presents performance models based on the results of the WesTrack experiment that can be used for PRS for HMA pavement. The models developed are for permanent deformation (rutting) and fatigue cracking. The models presented are for both Level 1, based on direct regressions from measured performance, traffic loading, and mix characteristics; and Level 2, based on mechanistic-empirical analyses.

Chapter 5 of the report discusses how the performance models can be used to develop pay factors that can be used for PRS for HMA pavements. The cost model presented considers the present worth of rehabilitation costs resulting from the as-constructed versus as-designed quality of the pavement. The pay factors consider the quality characteristics of air-void content, asphalt content, HMA thickness, and aggregate gradation.

NCHRP. *Quality Characteristics for Use with Performance-Related Specifications for Hot Mix Asphalt.* NCHRP Research Results Digest 291. Transportation Research Board of the National Academies, Washington, D.C., Aug. 2004.
This digest summarizes the key findings of NCHRP Project 9-15, Quality Characteristics and Test Methods for Use in Performance-Related Specifications for Hot Mix Asphalt Pavements, which investigated simple and rapid nondestructive testing procedures for evaluating properties of as-constructed HMA pavements. The tests measure the quality characteristics included in HMA performance-related specifications.

This project evaluated the following quality characteristics of as-constructed HMA pavement using the testing devices indicated:

- Segregation, measured/evaluated using the Road Surface Analyzer (ROSAN), which detects and measures segregation, calculating estimated texture depth, as described in NCHRP Research Report 441;
- Initial smoothness, evaluated using the Lightweight Inertial Profiler to determine the IRI;
- In-place mat density, measured using the Pavement Quality Indicator (PQI) or nuclear density gauge (both appropriate only for dense-graded mixtures);
- Longitudinal joint density, measured with the PQI (dense-graded mixtures only); and
- In-place permeability, measured using the National Center for Asphalt Technology (NCAT) Field Permeameter, which provides a *K*-value for the surface.

Initial specification criteria and threshold values for these five parameters for a PRS are presented in the appendix of the final report from Project 9-15. Note, however, that with the exception of measuring smoothness and permeability, the digest recommends further evaluation and validation of these test methods and recommended values before full adoption in a PRS.

New Jersey Department of Transportation. *Ride Quality Specification for HMA Pavements.* Section 406.13: Acceptance of Surface Course Rideability. New Jersey DOT, Trenton.
This ride quality specification for HMA pavements in New Jersey is currently being implemented on pilot projects. The specification is based on the IRI, which best correlates to user perception of ride quality, as opposed to the Profilograph Index or Rolling Straightedge.

The key feature of this specification is that the incentive and disincentive pay adjustments for the various levels of ride quality were set on the basis of expected pavement life (and associated cost of reconstruction) for those various levels of initial ride quality. For more detail, see the TRB paper, *Conceptual Framework for Pavement Smoothness Specification* (Weed and Tabrizi 2005; citation follows in this section of Appendix D). This specification is a true performance specification, as it pertains to ride quality, in that the pay adjustments for initial measure ride quality are based on expected performance of the pavement.

Transit New Zealand. *New Zealand Performance-Based Specification for Structural Design and Construction of Flexible Unbound Pavements.* TNZ B/3 (provisional). 2000.
This is a provisional specification (current status unknown) for the design, maintenance, and performance requirements for flexible unbound pavement layers for the construction of new pavements and reconstruction of existing pavements. The contractor is responsible for the pavement design, including selection of materials, layer thicknesses, drainage, and the binder type. The contractor is also responsible for maintaining the pavement and seal, including the shape and structural integrity of the pavement, for 12 months after construction. The notes to this specification state,

> This performance based specification has primarily been developed to allow the use of any material (lightly stabilized or otherwise) in the pavement. . . . There is some risk in allowing the use of alternative materials as other factors can not be assessed in the laboratory such as: constructability; seal adherence; and environmental performance. Therefore, it was considered appropriate that the Contractor is responsible for the pavements performance for the maintenance period of at least 12 months as per this specification.

Compliance assessment requirements are provided for

- Pavement design;
- Pavement materials (quality plan required from contractors);
- Pavement layer compaction;
- Pavement stiffness (moduli) or strength;
- Surface shape;
- Rut depth;
- Roughness;
- Surface texture (minimum texture depth from sand patch test);
- Chip retention;
- Surface waterproofness;
- Saturation before sealing (moisture content of pavement surface before sealing); and
- Repairs.

While this specification does provide certain performance parameters for the pavement, it stipulates a 12-month maintenance period, which is essentially a warranty. These performance parameters, however, should be analyzed and considered for potential performance specifications for HMA pavement.

Transit New Zealand. *New Zealand Performance Based Specification for Hotmix Asphalt Wearing Course Surfacing.* TNZ P/23. 2005.
This specification provides performance requirements for open graded porous asphalt (OGPA), textured high stress resistant type asphalts (e.g., SMA), and dense graded asphaltic concrete (DGAC). Material performance requirements are provided for the binder properties and aggregate properties tested using standard test procedures. Mixture and finished pavement performance criteria are provided as follows:

- Open graded porous HMA: surface ride, permeability, and mix design properties;
- Textured high stress resistant HMAs: surface ride, permeability, safety (texture depth), and mix design properties;
- Dense graded asphaltic concrete: surface ride, permeability, mix design properties; and
- Minimum voids in mineral aggregate (VMA) requirements for DGAC and SMA based on traffic conditions and mix nominal size.

This specification is termed a performance-based specification, and it provides criteria for different types of mixtures in terms of material, mixture, and finished surface properties. The key aspect of this specification is that it does not prescribe the mixture and construction requirements; rather, it requires the contractor to develop the mixture (meeting certain performance requirements) and control construction operations such that the finished surface will meet certain functional performance requirements.

Transit New Zealand. *New Zealand Performance-Based Specification for Reseals.* TNZ P/17. 2002.
This specification provides performance requirements for reseal (chip seal) operations to restore HMA surface texture. The contractor is given control of design and construction of the reseal method. For compliance assessment, the surface texture and chip retention is tested between 10 months and 12 months after construction. The performance criteria, method of assessment, test methods, and threshold values specified for the reseal include the following:

- Safety: skid resistance, light reflectance, chip retention, site safety, color uniformity, and roadmarking (striping) contrast;
- Environmental: noise (measured using texture depth);
- Waterproofness: impermeability (measured through chip size);
- Economics: tyre [tire] wear [indicated by aggregate present system value (PSV) and texture depth] and rolling resistance (indicated by texture depth); and
- Durability: aggregate (crushing value and weathering resistance), bitumen (durability and flux content), bitumen application rate (texture depth).

An additional performance requirement is specified: any areas repaired more than 9 months after construction will be subjected to an additional 12-month maintenance period; and if the area of repairs at the end of 12 months are greater than 10% of the section, the section will be subject to an additional 12-month maintenance period.

This performance-based specification uses measurement of properties of the aggregates and finished surface. It describes the performance of the finished product but does not indicate that the performance parameters have an influence on the long-term performance of the reseal. Pay adjustments are provided for single-coat seals, however, based on the expected life of the reseal from the size of the chips used and the texture depth of the finished surface.

Weed, R. M. Multicharacteristic Performance-Related Specification for Hot-Mix Asphalt Pavement: Complete Development Process. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1861,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 53–59.
This paper proposes a simplified procedure for developing performance-related specifications for HMA pavements, which directly considers the effects of as-constructed quality characteristics on expected pavement life-cycle costs in the selection of pay adjustment factors for these quality characteristics. The procedure considers in-place air voids, thickness, and initial smoothness of HMA pavement as the primary as-constructed quality characteristics that affect pavement performance and expected pavement life. The paper presents a generic exponential model for computing expected pavement life on the basis of acceptable and rejectable levels of each quality characteristic. A separate model can then be used to convert expected pavement life to a pay adjustment and pay schedule or incentive/disincentive for the different quality characteristics.

This procedure provides a rational approach to relating as-constructed quality to the life-cycle cost of an HMA pavement and, therefore, the justification for various levels of construction pay adjustments. However, when using this procedure to develop the pay adjustment schedule, the owner agency must have a good understanding of the effects that deficiencies in each of the as-constructed quality characteristics have on pavement life, and the costs associated with rehabilitation resulting from those deficiencies.

Weed, R. M., and K. Tabrizi. Conceptual Framework for Pavement Smoothness Specification. TRB Paper 05-0922. Presented at the 84th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2005.
This paper presents the framework for the New Jersey IRI Ride Quality Specification for HMA pavements (New Jersey DOT). The paper highlights the idea that pavements built smoother initially will last longer than those built rougher. The paper discusses the concept of relating expected pavement life to the initial percent defective pavement in terms of initial ride quality. Once the expected pavement life (based on ride quality) is known, specific dollar values can be assigned to the as-constructed ride quality based on the anticipated cost of future rehabilitation and reconstruction. The paper draws values of improvement in expected pavement life from FHWA studies which correlated pavement life to initial smoothness. As described in the paper (and required by the New Jersey DOT specification), the contractor pays very high penalties for constructing very rough pavement (PD > 90). This reflects the anticipated future cost to rehabilitate or reconstruct a pavement that is not anticipated to last as long as a pavement initially constructed with greater smoothness.

Weed, R. M. Mathematical Modeling Procedures for Performance-Related Specifications. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1946,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 63–70.
This report is a continuation of the PRS modeling procedure described in the previous paper. It presents a more general model which allows greater flexibility in developing multicharacteristic relationships. The refined model also allows "high" and "low" failures for two-sided requirements such as high and low limits for air voids in HMA pavements since conditions either too high or too low can negatively affect pavement performance. The model provides a rational approach for tying expected pavement life to pay adjustments for as-constructed quality.

Design-Build Documents with Pavement Requirements

Maine Department of Transportation. *I-295 Commercial Street Connector Design-Build Project.* RFP, MDOT Project No. 7589.30. Maine DOT, Augusta, 2003.
This document is the request for proposal (RFP) for a design-build project for the I-295 Commercial Street Connector in Portland, Maine. Section 6.7.1.3 specifies that pavement design shall be in accordance with the 1993 AASHTO design guide and with 20-year design life. It identifies the criteria (initial serviceability, terminal serviceability, reliability, and standard deviation) for use with the design guide.

Section 11 describes the warranty for the asphaltic pavement structure. The design-builder is to establish the job mix formula and select materials to be used, and is to provide a quality control plan. The warranty stipulated for the project is either (a) 5 years from final acceptance with the design-builder given the option to propose additional 1-year increments for a period of up to 5 years following the expiration of the initial 5-year term; or (b) "to the end of the calendar year in which the cumulative ESALs for a particular segment or project reach or exceed the amount determined in Attachment 2 of the Special Provision."

Attachment 1 provides the pavement performance criteria for the project. Thresholds and remedial action requirements are provided for the initial 5-year warranty period and any additional warranty period for the following distresses: smoothness (IRI), rutting, cracking, raveling and popout areas, potholes, depressions and shoving, and roadway settlement (near to and away from abutments).

Maryland State Highway Administration. *Maryland Intercounty Connector (ICC) Project.* Contract A, Contract No. AT3765960, Part 3.0 Design Requirements, Appendix A: PS 307, Pavement Performance Specification. Maryland SHA, Baltimore, 2006.

This document is part of an RFP for Contract A of a major design-build project for the Intercounty Connector (ICC) project. Contract A covers the westernmost portion of the ICC which is approximately 7-miles long. This portion of the RFP covers the pavement performance specification for the project. The intent of the pavement performance specification is to leave much of the pavement design and construction to the design-builder, providing only the essential performance parameters desired from the Maryland State Highway Administration (SHA) for the finished pavement.

The performance specification provides standards and references from Maryland SHA, AASHTO, ASTM, and Montgomery County but permits the design-builder to select which standards to use. The contract does list the appropriate standards in order of priority such that the higher priority standard should be used if different standards conflict.

The design-builder is responsible for all pavement engineering including, but not limited to, pavement investigation, pavement type selection, new pavement design, pavement rehabilitation design, and material selection. The requirement for a thorough pavement investigation by the design-builder is critical and helps ensure that contingencies are covered and no unexpected issues are encountered during the design and construction process.

Pavement type selection is left to the design-builder. The primary stipulations for pavement design are as follows:

- An initial structural design service life of not less than 25 years must be provided;
- A consistent pavement type must be used throughout each roadway element;
- The 1993 AASHTO and Maryland SHA pavement design guides are required for pavement design;
- Flexible/rigid pavement combinations and CRCP are not permitted; and
- Flexible pavements must use Superpave mix design criteria.

Design criteria (for use with pavement design guides), including traffic and other inputs, are provided along with additional criteria, such as minimum thickness and the use of dowels for PCC pavement, for both flexible and rigid pavements. Design criteria are also provided for the sections of the project subject to rehabilitation. The finished pavement performance parameters stipulated for final acceptance of the pavement include the following:

- Structural capacity, evaluated by monitoring thickness, strength, and quality of materials throughout design and construction.
- Ride quality, evaluated using inertial profiler throughout and at the completion of construction.
- Skid resistance, evaluated using ASTM E274 and E501. Average friction number of 45 must be provided along with justification that it will remain at least 45 for 5 years after construction.
- Visual appearance, evaluated according to overall appearance and by visual distress surveys.

While this document leaves many of the pavement design and construction decisions to the contractor, the specification includes a number of prescriptive elements. There are no indications that pay adjustments are made for the various performance criteria. This document is a good example of a move toward true performance specifications.

Minnesota Department of Transportation. *Trunk Highway 100–Duluth St. Design Build Project.* RFP, Project S.P. 2735-172, Part I: Scope of Work. Minnesota DOT, St. Paul, 2001.

This document is part of an RFP for a design-build project for improvements to Trunk Highway 100 at Duluth Street in Golden Valley, Minnesota, reconstructing Trunk Highway 100 from a four-lane divided highway to a six-lane divided highway. Section 1.1.3.1 of the RFP stipulates, "All design and construction must be performed in accordance with the Minnesota Department of Transportation Standard Specifications for Construction, 2000 Edition."

Section 15.4 provides the material and workmanship warranty specifications. A 5-year warranty (after final construction acceptance or FCA) is stipulated for both flexible pavements. Definitions, threshold limits, and remedial actions are provided for the following pavement distresses:

- HMA pavement: transverse, longitudinal, block, and fatigue cracking; debonding; raveling; flushing; and rutting.
- PCC pavement: transverse, longitudinal, corner, map, and shrinkage cracking; joint spalling and sealant failure; and surface defects (shattered slab, nonfunctioning joints, popouts, scaling).

Utah Department of Transportation. *Utah DOT I-15 NOW Project.* RFP, Part 4: Pavement Performance Specification. Utah DOT, Salt Lake City, 2005.

This document is part of the RFP for the Utah I-15 corridor reconstruction design-build project (I-15 NOW). The document provides the requirements for pavement performance, both flexible and rigid. The contractor is given responsibility for pavement design and control of construction operations. Guidance documents are referenced in the RFP and given priority ratings in case of conflict in requirements between documents.

The design requirements specified are a minimum 20-year design life for HMA pavement and 40-year design life for rigid pavement. Design ESALs for both flexible and rigid pavement design are provided in the RFP for various sections of the project.

Performance requirements for the finished pavement include functional requirement for ride quality (profilograph measurement) and skid resistance (evaluated by the Utah DOT) thresholds both during construction and at the end of the project (final owner acceptance, or FOA). Various other requirements are also provided for drainage, minimum thickness, and selected material requirements for bases, paving materials, and asphalt grade.

Utah Department of Transportation. *Utah DOT I-15 NOW Project.* RFP, Part 9: Warranty Provisions. Utah DOT, Salt Lake City, 2005.

This document is part of the RFP for the Utah I-15 corridor reconstruction design-build project (I-15 NOW). The document provides the warranty provisions for the project, including pavement warranties. For most elements, a 2-year warranty (after FOA) is specified. A 5-year warranty is specified for pavement settlement as well as rigid pavement cracking and joint deficiencies.

Thresholds are provided for maximum permissible settlements for pavements, both flexible and rigid. For PCC pavements, threshold distress levels, extent, and corrective actions (during the warranty period) are provided for the following distresses: cracking, joint deficiencies, surface defects, and miscellaneous distresses. For flexible pavements, threshold distress levels, extent, and corrective actions (during the warranty period) are provided for the following distress types: cracking, patching and potholes, surface deformation, surface defects, and miscellaneous distresses.

Washington State Department of Transportation, *Guidebook for Design-Build Highway Project Development.* Washington State DOT, Olympia, 2001.

This document provides a framework for developing contract documents for design-build projects in Washington State. The last half of the document provides a template for scope of work for design-build projects. Some of the sections related to pavements in the scope of work include the following:

- Section 416, Pavement Design, provides design criteria (e.g., design life) for pavement design, with specific criteria for asphalt concrete pavement (ACP) and Portland cement concrete pavement (PCCP) and for PCC pavement rehabilitation.
- Section 1300, Product Warranty Provisions, specifies the performance parameters to be evaluated for all constructed pavements during the warranty period: ride quality, pavement friction, pavement surface condition, structural capacity, and material quality.
- Section 1330, Asphalt Concrete Pavement, provides the requirements for the elements of ride quality, pavement friction, pavement surface condition, structural capacity, and material quality for warranted ACP.
- Section 1340, Portland Cement Concrete, provides the requirements for the elements of ride quality, pavement friction, pavement surface condition, structural capacity, and material quality for warranted PCCP.
- Section 1350, Required Corrective Actions, provides tables which describe distress types, allowable levels of severity, allowable extent of severity, and corrective action for asphalt pavements, new concrete pavements, and dowel bar retrofits. Criteria specified for each pavement type include the following:
    - ACP: rutting and wear, alligator cracking, longitudinal cracking, transverse cracking;
    - PCCP: cracking, joint cracking/spalling, pumping and blowing, faulting, patching, scaling, wear, and joint seal damage; and
    - DBR: cracking within slot, wear within slot, bond failure within slot, faulting, spalling within slot.

Performance-Based Maintenance Contracts with Pavement Requirements

Engelke, T. Long Term Performance Based Road Maintenance Contracts in Western Australia. *Proc., Bay Roads Exposed Conference,* Rotorua, New Zealand, April 2003.

This paper discusses Main Road's Western Australia experience with performance-based road maintenance through six different contracts. This form of maintenance contracting provides performance levels for pavements, including intervention parameters and key performance indicators (KPI). Intervention parameters are quantified according to maximum intervention level or the severity of a defect, maximum response time, and maximum defective condition. Threshold levels are provided for each for different forms of maintenance. Intervention parameters for pavement surfaces include roughness, skid resistance, isolated pavement failure, and edge breaks.

KPIs measure the contractor's performance, and payment to the contractor is adjusted on the basis of KPIs. KPIs for maintenance performance for pavements maintenance (which falls under the category of asset management) include pavement strength (measured using FWD), roughness, rutting, texture, skid resistance, and maximum defective condition.

Robinson, M., E. Raynault, W. Frazer, M. Lakew, S. Rennie, and E. Sheldahl. DC Streets Performance-Based Asset Preservation Experiment: Current Quantitative Results and Suggestions for Future Contracts. Paper No. 06-2075. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C., 2006.

This paper describes an experimental performance-based asset preservation project implemented in Washington, D.C., from 2000 to 2005. The goal was to reduce overall maintenance and rehabilitation costs for 75 miles of the National Highway System in the District of Columbia by encouraging innovative, cost-effective, and flexible preservation strategies. This type of contract is different from traditional maintenance contracts in that the owner specifies performance standards for the roadway, permitting the contractor to choose what materials and methods to use.

In this case, 170 performance measures were included, covering all aspects of the roadways, including pavements. Each performance measure had five levels of service; the minimum acceptable performance was "Good" or "Level 4." For pavement surfaces, ride quality (IRI), pavement condition index (PCI), and friction number were the primary performance measures specified.

Work Zone Management

Curtis, D., and K. A. Funderburg. States Estimate Work Zone Traffic Delay Using QuickZone. *ITE Journal,* Vol. 73, June 2003, pp. 40–43.

This article describes QuickZone, a software tool for estimating work zone delays and maximum queue lengths. The article touts the customizable nature of the product, citing specific states that have modified QuickZone to their needs. The implication is that transportation agencies could use QuickZone (or a similar product) to produce reasonable targets and tolerances for use in performance specifications on specific projects.

Maryland Department of Transportation. *Haul Routes and Access During Construction.* Performance Specification 306: Maintenance of Traffic. Maryland DOT, Hanover, July 2006.

This bid document outlines temporary traffic control restrictions for a highway project. It is largely prescriptive but includes a temporary lane and shoulder closure schedule and contractor disincentives related to that schedule. The document is useful in that it makes reference to the QuickZone program, requiring the contractor to use computer models to determine queuing impacts before construction. Also, the document includes a thorough temporary lane and shoulder closure schedule, clearly communicating acceptable days and times for closures. This gives the contractor significant flexibility with its maintenance-of-traffic plan, and penalties for deviating from the schedule are clearly defined.

Michigan Department of Transportation. *Contractor Proposal Using Best Value Practices.* Special Provision for Highways for Life. Michigan DOT, Lansing, Aug. 2007.

This bid document uses a true performance contracting approach with clear methods of measurement and contractor incentives/disincentives. Traffic measurements include an open-to-traffic date, number of work zone crashes, and motorist delay. While not truly a specification document, this is an excellent example of a structured performance approach to work zone traffic control. Clear parameters are defined for traffic-based criteria. For example, motorist delay includes explicit information dictating how the contractor will be paid based on the amount of delay measured during four random weekly on-site measurements.

Oregon Department of Transportation. *I-5 Weaver Bundle 306.* Temporary Traffic Control Performance Specification. Oregon DOT, Salem, Nov. 2006.
As of September 2007, this document is the most up-to-date temporary traffic control performance specification for the Oregon DOT. It uses a specified measured-volume to projected-volume ratio target to assess contractor performance. Although it includes some prescriptive elements, the overriding direction of this specification is performance-based. The document is specific regarding the design parameters to which the contractor is restricted but is not specific regarding contractor penalties for deviating from those parameters.

Pennsylvania Department of Transportation. *Publication 352.* Contract Management Division, Bureau of Design, Pennsylvania DOT, Harrisburg, June 2001, pp. 3.28–3.31.
This is the Pennsylvania DOT's sample specification (adapted from FHWA) for lane rental on both a daily and an hourly basis. Both versions include the clause, Failure to Complete Work on Time, which assesses liquidated damages. Since the specification is intended as an example, the values and prices included are for sample purposes only. The document concisely illustrates a straightforward lane rental agreement which is one type of work zone, traffic control performance specification.

Pennsylvania Department of Transportation. Section XXX—Maintenance and Protection of Traffic During Construction. Pennsylvania DOT, Harrisburg, Sept. 2006.
This draft document is a straightforward, sample, lump sum, work zone traffic control specification. Some prescriptive elements are included, but the specification leaves much to the "sound engineering judgment" of the contractor. Duration of traffic stoppages and 85th percentile speed measurements serve as performance measures. This document is useful as an example of the means and metrics necessary to implement lump sum traffic control as a performance specification.

Trauner Consulting Services. Work Product Stemming from FHWA Workshop Held in Seattle, Washington, (March 6–7, 2003).
This document is a general work zone traffic control performance specification, designed to be customized by the specifying agency. A large variety of possible performance measures are presented, although quantitative thresholds are not included because of the intentional ambiguity of the specification. This document provides a valuable performance-based framework for a traffic control specification, despite the lack of sample values for restrictions and incentives.

Utah Department of Transportation. *I-15 NOW Project.* RFP Part 4: Maintenance of Traffic Performance Specification. Utah DOT, Salt Lake City, Dec. 2005.
This document is the maintenance of traffic performance specification for a major highway design-build project. Although the document is titled a performance specification and although it contains several performance elements, the document is wholly prescriptive in nature. This serves as an example of what several DOT's are loosely terming *performance specifications* for work zone traffic control.

Vassallo, J. M. Implementation of Quality Criteria in Tendering and Regulating Infrastructure Management Contracts. *Journal of Construction Engineering and Management,* Vol. 133, No. 8, Aug. 2007, pp. 553–561.
This article describes contemporary contracting procedures designed to combine price and quality standards, specifically in the field of infrastructure management contracts. The author describes the increasingly common concept of lane rental, including a list of states in which the concept is fully operational.

Washington State Department of Transportation. *Lane Rental.* Washington State DOT, Salem, Wash. http://www.wsdot.wa.gov/Projects/delivery/alternative/LaneRental.htm. Accessed Nov. 9, 2007.
This document, posted on the Washington State DOT website, includes an overview of lane rental, decision criteria for incorporating lane rental into a particular bid document, and associated sample special provisions. This brief document is most useful for the decision criteria suggested for determining appropriate uses for lane rental.

Washington State Department of Transportation. *Lump Sum Traffic Control.* Washington State DOT, Salem. http://www.wsdot.wa.gov/Projects/delivery/alternative/LumpSum.htm. Accessed Nov. 2007.
This document, posted on the Washington State DOT website, includes an overview of lump sum traffic control, decision criteria for incorporating lump sum traffic control into a particular bid document, suggested prebid procedures for use with lump sum traffic control, and associated sample special provisions. This brief document is most useful for the decision criteria suggested for determining appropriate uses for lump sum traffic control.

Public Involvement

Oregon Department of Transportation. *I-5 Weaver Bundle 306.* Public Information and Involvement Performance Specification. Oregon DOT, Salem, Nov. 2006.
As of September 2007, this document is the most up-to-date public involvement performance specification for the Oregon DOT. While the document is titled a performance specification, it is wholly prescriptive in nature. The contractor is given latitude in the means of achieving the stated goal of "fully informed and meaningful participation by Stakeholders and the public for the duration of the Project," but no performance targets or parameters are established. This document is useful in that it concisely articulates the goal of most public involvement processes. Also, the document is a good source of potential steps to be taken in a public involvement process even though the steps take the form of a prescriptive specification.

Utah Department of Transportation. *I-15 NOW Project.* RFP, Part 4: Public Information and Performance Specification. Utah DOT, Salt Lake City, Dec. 2005.
This document is the public involvement performance specification for a major highway design-build project. The document contains few performance elements despite its title. The document is indicative of the misconceptions that exist in several agencies regarding the use of the term *performance specification,* especially as it applies to public involvement. While the document does not prescribe extremely detailed steps for performing work, it is far too specific in its language to be termed a performance specification.

Total Quality Index

Griffith, A. F., E. G. Gibson, Jr., M. R. Hamilton, A. L. Tortora, and C. T. Wilson. Project Success Index for Capital Facility Construction Projects. *Journal of Performance of Constructed Facilities,* Vol. 13, No. 1, Feb. 1999, pp. 39–45.
This article documents research done in an effort to create a success index for facility projects. The study uses mail surveys and phone interviews to collect historical data on facilities projects and bases the derived success index on four variables: budget achievement, schedule achievement, design capacity, and plant utilization. The resulting index gives a snapshot of the cumulative success of the project, but the subjectivity of the inputs makes this a poor tool for use in evaluating contractors.

Lee, D.-E., and D. Arditi. Total Quality Performance of Design/Build Firms Using Quality Function Deployment. *Journal of Construction Engineering and Management,* Vol. 132, No. 1, Jan. 2006, pp. 49–57.
This article describes an index that owners may use to rank design-build firms relative to their total quality performance; it also describes the development of that index. The article is useful in that it presents a logical matrix approach to correlating the owner/agency requirements with the technical characteristics of the contractor: quality function deployment. The model developed in the article has value as a product quality performance measurement tool, both for predicting future quality and assessing past value received.

Michigan Department of Transportation. *Contractor Proposal Using Best Value Practices.* Special Provision for Highways for Life. Michigan DOT, Lansing, Aug. 2007.
This bid document uses a true performance contracting approach with clear methods of measurement and contractor incentives/disincentives. A best value practice is used for contractor selection. Even though the indexing takes place before the contractor's work, the best value practice illustrated in this document is useful in researching the concept of a total quality index. The contractor is scored on several aspects of its proposal. A higher score produces a multiplier that factors the contractor's bid price downward (valuing dollars spent on a high-quality contractor higher than dollars spent on a low-quality contractor). The open-to-traffic date proposed by the contractor is one of the inputs that determine the multiplier. Of note is that the contractor may be assessed liquidated damages based on the open-to-traffic date that it provides.

North Carolina Department of Transportation. *Design Build Package.* Project No. 8.1674402. North Carolina DOT, Raleigh, Oct. 2001.
This bid document describes the scoring system for evaluating technical proposals submitted by contractors for a design-build highway project. The document is useful as it provides an example of an adjusted bid price selection process in use at a state DOT. The process allows for a price adjustment of up to 15% based on the contractor's quality score.

Pongpeng, J., and J. Liston. Contractor Ability Criteria: A View from the Thai Construction Industry. *Construction Management and Economics,* Vol. 21, No. 3, Jan. 2003, pp. 267–282.
The study described in this article aimed to develop a common set of contractor ability criteria for both government and the private sector. The study concludes that the ability criteria may be classified similarly to the hierarchal organization of a construction firm. Percentages of influence to be used to evaluate a contractor based on the project requirements—including time, cost, quality, and safety—are assigned to the various organizational units of a typical construction firm. The article is useful in that it analytically determines an indexing formula for the evaluation of potential contractors. Each organizational unit (engineering/construction, project managers, human resources, public relations, etc.) of a typical contracting firm has been assigned a weight of relative importance in determining a final total score. While not a true total quality index (especially in a project sense), the methods and findings of this study may be projected for use in determining a total quality index performance specification.

Vassallo, J. M. Implementation of Quality Criteria in Tendering and Regulating Infrastructure Management Contracts. *Journal of Construction Engineering and Management,* Vol. 133, No. 8, Aug. 2007, pp. 553–561.
This document describes contemporary contracting procedures designed to combine price and quality standards, specifically in the field of infrastructure management contracts. The article applies fundamental economic thinking to the problem of developing quality criteria and provides a sound framework for conceptualizing the quantification of quality. But the author does not develop numerical values for finalized equations.

Risk

Armistead, A. Performance Specifications and Contracts: The State of the Art. *Proc., 21st Australian Road Research Board Conference,* Cairns, Australia, 2003.
Based on the work done by Opus International Consultants Limited for Austroads (association of Australian and New Zealand state highway authorities), this report narrows the focus of performance specifications and contracts to three contractual arrangements: design-construct-maintain contracts that typically extend to 5 years or 10 years; build-own-operate-transfer contracts that typically extend to periods over 20 years; and maintenance contracts. This report excluded performance-based specifications, performance-related specifications, and end product specifications because they rely on predictive methods to evaluate performance. The main conclusion is this: "The consultant has reviewed, to the extent possible, experience with performance contracts and specifications. . . . Due to the time frame of these contracts, and the fact that most of them are in relatively early stages, it is not possible to absolutely quantify the achievement of outcomes. There are still many issues surrounding these contract types that remain unanswered, and as many of these contracts move towards their conclusion, there will be an opportunity for further analysis and development of improved practices." The benefits, risks, and constraints identified in this report are as follows:

- Potential benefits:
  - Better customer focus;
  - Improved risk recognition, allocation, and management;
  - Reduced administration;
  - Budgetary certainty;
  - Greater ability to innovate; and
  - Improved use of industry skills.
- Risks:
  - Performance measures that do not fully reflect the performance required;
  - Scale and tendering costs that will reduce competition;
  - Potentially greater effects of contract failure when compared with traditional contracts;
  - Reduced ability to deal with physical, political, or environmental issues;
  - Reduced road authority technical expertise leading to loss of "informed purchase" status;
  - Loss of road authority's control, leading to reduction in standard of service; and
  - Restricted availability of innovation to the wider market.
- Constraints:
  - Difficulty in defining the performance required;
  - Limitations with repeatability and reproducibility of condition data;
  - Inability to measure remaining life of pavements;
  - Prohibitive cost of tendering for contractors and the road authorities;
  - Absence of accepted methods of assessing ongoing benefits;
  - Time and resource capability limitations within the industry;
  - Absence of complete, accurate, and up-to-date asset data in some road authorities;

- ○ Politically unacceptable social consequences of large region-wide contracts;
- ○ Perceived threat of job losses in the road authority; and
- ○ Greater potential financial implications of contract failure.

Shuler, S., T. Aschenbrener, and R. DeDios. Effect of Performance Warranties on Cost and Quality of Asphalt Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2040,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 100–106.

This paper presents the lessons from using warranties over a 3-year period in which the contractor was responsible for several forms of pavement distress. The contractor was allowed to choose materials and methods for constructing the pavements. Based on the cost-benefit relationship for the projects during the warranty period and beyond and comparison with the comparable nonwarranty pavements, the authors found no significant difference in competition or performance of the warranty projects compared with the control projects; the difference in cost of the warranty projects compared with the nonwarranty projects was negligible. Cost comparisons included the initial hot-mix asphalt, maintenance, pavement evaluation team, weigh-in-motion station, and construction engineering.

The warranty analyzed in this study was developed so the contractor had control of materials selection and construction methods. This meant that mixture design was under control of the contractor and not required to be approved by the Colorado Department of Transportation (CDOT). The contractor was responsible for correcting defects in work elements within the contractor's control, including distresses resulting from defective materials and workmanship, during the warranty period. CDOT remained responsible for the pavement design and those distresses that resulted from the design.

Six warranted projects were evaluated in this analysis as follows:

- I-25, Fountain (constructed, 1998);
- C-470, Santa Fe to Wadsworth Boulevard (constructed, 1998);
- US-36, Superior Interchange (constructed, 1998);
- I-25, Pueblo (constructed, 2000);
- I-70, Eagle to Avon (constructed, 2000); and
- US-50, Kannah Creek (constructed, 2001).

Control, or nonwarranty, projects were compared with the warranty projects to develop economic and performance comparisons. The control projects were constructed using traditional CDOT specifications (nonwarranty) and were comparable to the warranty projects in terms of year of construction, rehabilitation strategy, traffic, environment, and original pavement condition. The performance of the experimental and control projects was measured by two methods to minimize errors: a pavement evaluation team made up of private and CDOT personnel, and the pavement management automated data collection van.

The key recommendations follow:

- Monitor competition on future warranty projects to determine if a reduction in the level of competition occurs as a consequence of using warranties;
- Consider the role of agency specifications for QC/QA because contractors involved in this study had worked with QC/QA specifications implemented by CDOT 10 years earlier;
- Ensure that the distress thresholds for identifying warrantable and nonwarrantable distresses are carefully evaluated; and
- Evaluate the requirement of a weigh-in-motion scale in conjunction with projected traffic flow increases over the warranty period.

Cost-benefit evaluations should be based on the design life of the pavement and not just the warranty period.

Blankenship, P., and D. R. Leach. Performance-Related Specifications for Pavement Preservation Techniques. *National Pavement Preservation Forum II: Investing in the Future* (CD-ROM), Publication No. FHWA-IF-03-019, Federal Highway Administration, Washington, D.C., November 2001.

The authors gave this presentation at a conference in 2001. The authors' premise is that prescriptive specifications do not always give the expected performance. The authors show a spectrum of different specifications that include material property/prescriptive specifications, performance-related specifications, performance-based specifications, performance-modeled specifications, and performance specifications. Without illustrating who is at risk, the authors claim that prescriptive specifications are high risk, whereas performance specifications, at the other end of the spectrum, are low risk.

The presentation includes some slides about microsurfacing, macrosurfacing, and several types of pavement quality tests. The slides in themselves are inadequate to discern what the authors might have explained in their talk, but one of the conclusions—that "performance related specifications and innovative products lower overall costs"—is not supported anywhere in the presentation.

Buttlar, W. G., L. Shanley, and S. Aref. End-Result Specification Development: The Illinois Demonstration Projects. Illinois Cooperative Highway Research Program, Project ICHRP, IHR-R23 (1999).

In May of 1999 a committee consisting of industry, the Illinois Department of Transportation, and the University of Illinois at Urbana-Champaign was formed. The main charge of the committee was to develop a prototype end-result specification for asphalt pavement construction and to develop a series of demonstration projects to collect data for evaluation of the new specification in the year 2000. The key items addressed by the task force included the following:

- Selecting the number and type of quality characteristics to be used as pay items;
- Determining the required sample size to minimize pay factor uncertainty (risk);
- Setting specification limits and pay factor equations; and
- Evaluating the feasibility of using contractor test results in computation of pay factors, to minimize agency test burden to the extent possible.

From the work of the task force, this paper specifically discusses the following:

- Evaluation of a stratified-random technique for field density measurement in the new end-result specification;
- Development and evaluation of a single lot system for establishing pay factors; and
- Development of QA comparison limits in the new end-result specification.

The key findings presented in the paper are as follows:

- Random field sampling techniques, involving "dual-stratified" random sampling in both the longitudinal and transverse directions, appeared to lead to increased contractor awareness and response to densification levels throughout the pavement.
- The use of contractor data for development of project pay factors appeared to be appropriate.

- Statistical analysis showed very little evidence of contractor bias in test results. (Only in the case of plant voids was a statistically different result obtained.) Evaluation of demonstration project pay factors showed a 0.7% increase in pay factor when comparing contractor and agency results.
- It is feasible and in fact desirable to analyze each job as a single lot of material, which has the effect of a very large sample size and reduced payment risks. Simulation analyses were conducted to verify that this method would give appropriate pay factors even for bimodal data distributions.
- A statistically based, tiered approach for developing quality assurance comparison limits was presented. The method minimizes agency test burden, while providing additional measurements when marginal comparisons are detected.

A key benefit of this paper is the reduction in agency test burden. Although the analysis and the findings are credible, the repeatability on other projects is suspect.

Gallagher, P. J., and D. Mangan. Risk Issues in Performance-Specified Flexible Paving Contracts. *Proc., 19th ARRB Transport Research Conference,* Sydney, Australia, Dec. 1998.

The synopsis of this paper starts with this paragraph: "It is widely accepted that true performance specifications are a 'pipe dream' while there are no adequate performance models of pavement behavior. In the United States, the SHRP Superpave performance prediction model was found to have 'significant technical problems' which have prompted a review that will not be completed until the year 2005."

The background section concludes with the following: "There is little doubt that the new contractual forms (Design-Construct-Maintain, Build-Own-Operate-Transfer) have been driven by management and economic reform, rather than by technology. However, tenderers for contracts such as Design-Construct-Maintain need to be aware of the existing boundaries of knowledge and technology if they are to exercise due diligence in relation to the risks which they are assuming."

More innovation, which is a premise behind the use of performance specifications, is weakened somewhat by an observation in this paper: "The final outcomes of the tenderer assessment process are regarded as commercially confidential, and unsuccessful proponents remain uncertain of the standards that they ought to pursue in further proposals."

An appendix to the paper lists the risks to be addressed in contractor's detailed proposal (other than normal contractual risk of construction quality, climate, productivity etc.):

- Adequacy of data acquisition on subgrade and traffic and of available climatic records;
- Pavement design to be "fit for purpose" (i.e., to meet proposed level of service at all times);
- Whole-of-life analysis for full design period (20, 30, or 40 years?);
- Residual life analysis at end of warranty period;
- Quality system for assurance of product quality and conformity with design intent, including independent verification as stipulated by the client;
- Refinement of the client's proposed criteria for pavement performance, if necessary;
- Methods and frequency of measurement for each criterion;
- Process/program for checking compliance for each criterion at practical completion and during the warranty period;
- Maintenance plan, if required, to detail
  - The intervention level in relation to the level of service for each performance parameter;
  - Inspection frequencies and procedures;
  - Maintenance procedures and work plans; and
  - Response plans to manage deterioration and emergency incidents.
- Any particular local factors relating to raw material supply/quality, environmental, or other issues.

A second appendix lists the specific risks affecting pavement performance but outside control of paving contractor:

- Traffic:
  - Future volume and classification (Warranty term may be based on monitored ESALs or specified term as agreed.);
  - Allowable load limits (e.g., national proposal for increase); and
  - Individual overloads or damaging loads (e.g., army tanks).
- Subgrade or subbase by others:
  - Uniformity in level and quality/uniformity of subgrade support;
  - Latent conditions for reasonable departures from client's information;
  - Susceptibility to saturation/moisture damage; and
  - Pavement/subsoil drainage maintenance.
- Network operations:
  - Nonfeasance versus malfeasance
    - Does private sector inherit indemnity for nonfeasance available to the agency?
    - What is the impact of the contract's incident response plan on liability?
  - Accident damage (physical damage, spillages, fires);
  - Natural disasters (floods, bushfire, earthquake), severity; and
  - Utility services in the pavement
    - Leaks/defects; and
    - Quality of repairs/restoration.

General issues for negotiation and inclusion in contract include

- Independent audit of quality compliance during construction and of performance compliance during warranty period;
- Agreed process for determining causes of failure and identifying contributing factors;
- An alternative dispute resolution process in the event of differences arising on the nature and cause of failure; and
- Construction program constraints on site access and on required completion date which may necessitate construction in adverse climate.

The paper concludes with the following: "The future of [design-construct-maintain] and similar performance specified contracts seems assured by the current perception that they offer real economic benefits to tax payers and road users. If this perception is to survive and if this contract strategy is to be applied to a wider range of, and to smaller, projects, clients and industry must cooperate to collect more credible pavement performance data and to develop realistic performance criteria. Then, all parties can be confident that performance specified contracts will give us the better pavements that we are all looking for."

Gruneberg, S., W. Hughes, and D. Ancell. Risk Under Performance-Based Contracting in the UK Construction Sector. *Construction Management and Economics,* Vol. 25, No. 7, 2007, pp. 691–699.

According to the authors, "the essence of a performance-based approach is that the focus is on what a building does, rather than its inputs." The authors also state that "little empirical research work has been carried out on the management of risk under [performance-based contracting]

PBC" and "only those producers who are confident in calculating the subjective risks and reward structures would be willing to accept a PBC project." Interestingly, J. T. van der Zwan (2003) argues that, because the results of empirical models apply only within the limits of the empiricism, producers cannot do much other than "control the recipe."

On the basis of a telephone survey of 22 construction companies in the UK, the authors of this paper identified 27 risks associated with PBC. The top 10 are

Risk	Frequency
Fitness for purpose (FFP)	7
Lack of insurance for FFP	6
Lifetime costs (including responsibility for lifetime maintenance)	4
Price (capital cost)	3
Inadequate client specification	3
Difficulty of changing mindset of clients, consultants, designers, and contractors	2
Process of setting key indicators	2
Measurements of key indicators over time	2
"Wouldn't touch it!"	2
The FFP changing after completion	2

The authors conclude that although PBC gives contractors the freedom, responsibility, and authority to perform their work as they see fit, they also face many risks. Longer-term risk obligations will require contractors to have new organizational structures. The difficulties of insuring and dealing with FFP are major obstacles to the adoption of PBC by contractors. Contractors prefer suppliers to assume responsibility for their products under PBC. In the end the question becomes one of balancing the increased risks against the possibility of increased rewards. Given the nature of the construction market, it may not always be possible for contractors to pass on expected increased costs to their clients.

Kuzyk, P., R. C. G. Haas, and R. W. Cockfield. Performance-Based Specifications for Pavements, *Canadian Journal of Civil Engineering,* Vol. 18, No. 6, 1991, pp. 1054–1061.

This article provides an interesting snapshot of the status of performance specifications as of 1991. The authors view a pavement management system (PMS) as being central to any efforts to improve pavement performance. Specifications and contract documents are one part of a comprehensive PMS. The authors illustrate the idea and the associated risk factors through an excellent graphic (Figure 1 in the article) and discuss the problems associated with the idea of transferring risks from the agency to the contractor.

The authors' study used an Ontario Pavement Analysis of Costs (OPAC) model that had the ability to separate pavement deterioration due to environmental exposure from that due to traffic loads. This distinction is critical when using performance specifications because both the specifications and the contractor's design have to be based on assumed levels of traffic supplied by the agency. Over the course of the contract period the actual traffic levels may have to be taken into consideration.

To facilitate the implementation of performance specifications, the authors acknowledge the need to modify the system of contracting as follows:

- Use sliding scale bonds. The sliding scale bond should include a portion based on the payments to date, putting the contractor's prior profits at risk in case of default.
- Develop a measure for traffic interruptions resulting from maintenance during peak and nonpeak hours over the performance period, with a predefined level beyond which penalties can be levied against the contractor. The contractor will have to submit a schedule ahead of time for performing maintenance.

In conclusion the authors cite the reliability of models for estimating pavement performance as a major risk factor.

Manik, A., and W. G. Buttlar. Monte Carlo Based Simulation for Managing Risk in End-Result Construction Specifications. (Paper supplied by Prof. Buttlar; publication details not known.)

This paper begins with a sweeping claim: "Over the years many highway agencies in North America have made a valued commitment to End Result Specifications (ERS). As a direct result, it is believed that the quality of our roadways has improved" (Smith, 1998; Benson, 1999). The authors also point out that the highway community continues to struggle with the problems of comparing the owner's QC tests to the contractor's. The quality characteristics (defined as that characteristic of a unit or product that is actually measured to determine conformance with a given requirement) that are being used to determine the quality of the pavement are generally in situ density of the constructed pavement, voids and asphalt content of the plant mix, aggregate gradation, and so on. These quality characteristics are believed to be related to performance, but the exact relationships are not yet firmly established.

The risk addressed in this study is the payment risk, expressed as payment made to the contractor (e.g., baseline, or "correct," pay). Overpayment is referred to as *agency risk,* while underpayment is often termed *contractor risk.*

A key contribution of this study is a strategy for using fewer samples/cores than the current Illinois DOT end-result specifications, from a constructed pavement. The data from the samples feed into a simulation model that estimates the quality of the population from which the samples are taken.

A simulated risk analysis (SRA) model developed by the authors is presented. The SRA computes the agency risk and the contractor risk as a function of many factors, including sample size, production and measurement variability, bias, pay formula and pay caps, and specification limits; and it considers the quality assurance and third-party testing schemes used. The SRA replaces all earlier models such as ILLISIM. The key contributors to payment risk in SRA are as follows:

- Contractor data versus agency data;
- Frequency of testing and/or number of samples;
- Variability and/or bias of test device and/or test procedure;
- Specification parameters, including
  - Specification limits (percent within limits);
  - Pay factor equation;
  - Pay caps;
  - Acceptance test frequency and acceptance tolerance; and
  - Third-party testing provisions.

The authors conclude with the claim that SRA can be used to develop a better understanding of how changes in individual ERS specification parameters can affect the payment risk for the contractor and agency. This knowledge can be used to explore the possibility of developing desirable changes in an existing ERS—such as reducing sample size, reducing risk, optimizing tolerance limits, changing pay factor equations—and the pros and cons of pay factor equations with payment caps.

(Smith, G. 1998. *NCHRP Synthesis of Highway Practice 263,* TRB, National Research Council, Washington, D.C.; Benson, P. 1999. Performance Review of a Quality Control/Quality Assurance Specification for Asphalt Concrete. *Transportation Research Record: Journal of the Transportation Research Board, No. 1654,* Transportation Research Board of the National Academies, Washington, D.C.)

Piewerbesky, B., D. Alabaster, and J. Fulton. New Zealand's Performance-Based Pavement Design and Construction Specifications: Case Studies. *Proc., 21st Australian Road Research Board Conference,* Cairns, Australia, 2003.

This paper agrees with J. T. van der Zwan's argument (2003) that new materials are one key driver behind the move toward performance specifications. That was Transit New Zealand's rationale when the agency did not have the resources to develop new pavement and material specifications for every possible alternative material.

New Zealand's B/3 performance-based specification for structural design and construction of flexible unbound pavements, including chip seal surfacing, was introduced in 2000 to foster the use of marginal and nonconforming materials that give similar performance to standard basecourse and subbase materials. This paper provides an overview of B/3 and its accompanying document for materials (M/22: Notes for the Evaluation of Base and Subbase Aggregates) as they are and proposed improvements. Three pilot projects using B/3 were completed. Details of two of the projects are presented as case studies, and the relevant outcomes of each are discussed. Both projects involved the same contractor. Under the B/3 contract, the contractor was responsible for the design, construction, and maintenance of the pavement and seal. The contractor had to demonstrate that design, materials, and construction techniques were appropriate (through its quality assurance systems) and that the pavement performance at the end of the defects liability period (1 year to 3 years) was acceptable. The following measures were checked to ensure that the performance criteria were met:

- Surface shape and rut depth;
- Roughness;
- Texture depth;
- Skid resistance;
- Surfacing aggregate retention; and
- Surface waterproofness.

The paper presents the following conclusions:

- Contractors undertaking work involving performance-based specifications require highly skilled and experienced pavement designers (either in-house or out-sourced); the road authority must also possess or have access to experienced, knowledgeable pavement engineers to adequately assess submitted proposals.
- Statistical analysis techniques are a valuable tool for both the contractor and road authority in quantifying the condition of the pavement and verifying compliance with acceptance criteria, and should be an integral facet of performance-based contracts. The contractor in these case studies completed an extensive suite of tests on the subgrade and pavement layers during and after construction, and analyzed the data to determine statistically valid testing regimens for future projects.
- Road authorities and industry must collaborate, including sharing knowledge and expertise, for performance-based specifications to be successfully introduced and implemented. These parties must also work together to ensure that pavement research is relevant to their needs; better, more accurate, and robust (but not complex) techniques must be developed for predicting pavement performance, so that the risks for the contractor and the road authority can be more readily quantified.

The last conclusion begs the question: should performance specifications be used in conjunction with reimbursable (not unit price) contracts for construction, similar to many private-sector owners, separating the maintenance work during the warranty period?

Queener, J., T. Hill, and M. Horn. A Contractor's Experience with the Caltrans Maintenance Warranty Pilot Program. *National Pavement Preservation Forum II: Investing in the Future* (CD-ROM), Publication No. FHWA-IF-03-019, Federal Highway Administration, Washington, D.C., November 2001.

This paper includes a glossary of terms related to pavement failure and maintenance procedures. The paper itself describes a case study for an I-5 asphalt pavement overlay project near Fresno using Type O-HB asphalt on approximately 240 lane kilometers. The specification allowed the contractor to identify areas of the project that had specific defects before the placement, and those areas would be exempt from the warranty requirements. Granite Construction Company was awarded the contract, with a 1-year warranty.

According to the contractor, what was unique about this project was the lack of history for this material in thin-lift overlays in California. The specification required that the contractor provide warranty for rutting, raveling, flushing, and cracking within the limits specified. The specification excluded certain areas that were determined to have existing defects that could affect the performance of the asphalt-rubber overlay.

The paper concludes that this was a positive experience overall for Caltrans. But the short duration of the warranty and the prescriptive exclusions make it a case study with limited relevance to other scenarios.

Russell, J. et al. *Asphalt Pavement Warranties—Technology and Practice in Europe.* FHWA-PL-04-002. American Trade Initiatives, Alexandria, Va.; Office of International Programs, Federal Highway Administration, Washington, D.C. 2003.

Warranty contract is defined as a type of performance-based contract that guarantees the integrity of a product and assigns responsibility for the repair or replacement of defects to the contractor.

This report provides an excellent overview of warranty or similar contracting in Europe (Denmark, Germany, Sweden, Spain, and the United Kingdom) and gets into some detail of the pavement performance criteria used in Europe. Interestingly, the report notes that the use of pavement performance contracts in these countries at the time was quite limited, typically only a handful of contracts with the most in Sweden (about 10%). However, one of the conclusions is that "PPCs [pavement performance contracts] in particular may hold great benefit for counties and municipalities throughout the United States, and could gain acceptance relatively quickly." The chapter on warranty evaluation concludes, "Transparent warranty evaluation processes are a key to any warranty program's success." But the ARRB paper (Gallagher and Mangan 1998) rightly points out that pavement evaluation processes offered by successful proposers are likely to be treated as commercially confidential.

Page 53 of this report states that in Europe contractor responsibility for pavement maintenance is a part of all warranty contracts if pavement performance criteria are not achieved or maintained. It also says, "The relationships and cooperation between owner agencies and warranty contractors is significantly different than in the United States." However, the report does not make clear what those differences are and how they manifest themselves in written contracts.

Subramanian, R., and F. T. Najafi. Current Status of the Development and Use of Portland Cement Concrete Performance Related Specifications. Presented at the Annual Conference of the Canadian Society of Civil Engineering, Montreal, June 2002.
This paper provides a statistical approach for contractors to maximize profit while improving quality in contracts involving performance specifications for PCC pavements. The project involved in this study was the Florida Department of Transportation (FDOT) I-295 project in which FDOT decided to base the specifications on concrete strength, slab thickness, and initial smoothness. The test proposed, and the target mean and standard deviation for each of the three AQCs were established in the specifications. Other AQCs (air content and percent consolidation around dowels) were not included in the performance specifications.

The paper also discusses the role of the seller's risk and the buyer's risk. The seller's risk is the probability of rejecting or assigning a payment reduction (disincentive) to a pavement lot that has a true mean and standard deviation that meets the targets. The buyer's risk is the probability of accepting or assigning a payment increase (incentive) to a pavement lot that has a true mean and standard deviation that do not meet the targets.

On the basis of tests involving five different concrete mixes ranging from 3500 psi to 5500 psi and five different slab thicknesses, the authors demonstrate how a contractor's choice of the mix or slab thickness could depend on whether it is a risk-taking or a risk-averse contractor.

The paper includes a graphic that ties life-cycle costs for projects using performance specifications to contractor pay adjustments. In conclusion, the authors note that recent FHWA studies validated the distress indicator prediction models for transverse joint faulting, transverse joint spalling, transverse slab cracking, and smoothness, and updated PaveSpec from version 2.0 to version 3.0. However, they suggest that additional AQCs be included in the modes, such asphalt air content and consolidation around dowel bars.

van der Zwan, J. T. Functional Specifications for Road Pavements: A Question of Risk Assignment. *Proc., 22nd PIARC World Road Congress,* Durban, South Africa, 2004.
This paper stands out because of its effort to understand and explain the theory behind performance specifications. It presents a "pyramid of demands," with road user demands on top and demands on raw materials at the bottom; this is followed by a discussion of how specifications relate to the different levels on the pyramid. The pyramid serves as a theoretical basis for discussing the risks associated with performance specifications. The demands can be from national priorities, financing mechanisms, maintenance criteria, economic considerations, climatic circumstances, quality of natural raw materials, and safety considerations. The author identifies two main drivers of the move toward performance specifications: changing materials and new materials with which owners have little experience; and the continuing momentum (right or wrong) to transfer tasks traditionally done by owners, to contractors.

Perhaps most important, the author questions the use of empirical models to justify the use of performance specifications because the results of empirical models apply only within the limits of the empiricism. As for the potential for innovation, this author believes that innovative products and techniques are out of the bounds of empirical knowledge; therefore, innovation as a premise for using performance specifications is risky, and the allocation of that risk is easier said than done.

With a specific example, the author discusses how a contractor cannot make adjustments to production on the basis of functional properties because that requires knowledge of how different parameters affect functional properties, for which adequate models do not exist. Also, for reasons already mentioned, empirical modeling does not help. Therefore, the producer cannot do anything other than "control the recipe."

The notion of the pyramid in this paper is important because it puts the issues in perspective. As the author notes, the changing methods of construction are not prompting the move to use performance specifications; rather, the desire to transfer responsibilities from owner to contractor and change the contractual relationships provides the impetus. The author ends with an acknowledgement that owners and contractors will be forced to rethink the traditional approach, thus creating knowledge that will improve quality and perhaps lead to innovation. However, he adds a cautionary note that greater risks for the contractor will result in higher prices, and that we don't know what proportion of contractor costs at present reflects their risks.

Villiers, C., Y. Mehta, G. Lopp, M. Tia, and R. Roque. Evaluation of Percent-Within-Limits Construction Specification Parameters. *International Journal of Pavement Engineering,* Vol. 4, No. 4, Dec. 2003, pp. 221–228.
This paper presents the findings from a study that evaluated 10 Superpave coarse mixtures used in the construction of four interstate highways in Florida. Two parameters were used to evaluate the mixtures: asphalt content and percent passing through a 2.36-mm sieve. The sensitivity of sampling frequency to the acceptable quality level (AQL) and rejectable quality level (RQL) is analyzed, to help in the development of more realistic percent-within-limits construction specifications. At the time of this study, the state of Florida used an AQL of 90 and RQL of 50.

Operation characteristic curves (probability of acceptance as a function of percent-within-limits) are created for various sampling frequencies. A conclusion was that 10 samples were required to attain the AASHTO recommendation of seller's risk of 1% and buyer's risk of 5%. The seller's risk is the probability that good quality will be rejected as unacceptable on the basis of test results. The minimum level of actual quality for the construction to be acceptable is AQL. The buyer's risk is the probability that what is accepted is of unacceptable quality based on test results. The maximum level of actual quality for the construction to be unacceptable is RQL.

The applicability of this study is contingent on development of operation characteristic curves based on historical data for the critical pay parameters.

Zhang, Z., and I. Damnjanovic. Quantification of Risk Cost Associated with Short-Term Warranty-Based Specifications for Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1946,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 3–11.
This paper begins with an acknowledgement of the concerns that state highway agencies have when deciding on the use of warranty specifications. Foremost among the concerns is the inability to quantify the risk cost or the warranty servicing cost. Other concerns include possible increase in the number of litigations and the potential elimination of small contractors from the bidding process because of surety requirements.

The scope of the analysis in this study is limited to short-term performance warranties in which a contractor performs only preventive maintenance, not rehabilitation, for the most vulnerable—burn-in—phase of pavement life cycle.

The authors' basis for the modeling presented in this paper is that, from the state agency's point of view, the objective is to find an upper bound on the risk costs that contractors would be allowed to include in a bid in addition to their nonwarranty bid. In other words, the agency will be willing to pay the risk costs reflected in the increased bid price as long as those costs are less than the savings from using the short-term warranty. From the contractor's point of view the objective is to design or build pavements for the minimum total cost, including maintenance cost during the warranty period. Through an example the paper supports the argument that with the application of performance warranties, contractors will be motivated to implement strict quality control measures during construction.

The modeling in this study is limited to "first-failure" after construction and is therefore based on reliability performance models. The sequence of failures that occur after the first-failure are also dependent on rehabilitation, are more appropriate for consideration in long-term warranties, and are therefore outside the scope of this study.

The paper comprises a notable effort to statistically model warranty risk costs for short-term warranties with a specific, empirical example. However, the extent to which the results can be applied to other scenarios remains questionable. In conclusion the authors also state the need to address issues related to differences in the effects of different pavement maintenance actions and the need for a warranty policy that addresses hidden defects early in the pavement life cycle.

APPENDIX E

Assessing the Value of Performance Specifications

Data Collection Approach

The Delphi technique was used to assess the actual or potential value of performance specifications. The method is particularly useful when empirical means are not suitable and study results must rely heavily on the subjective opinions of experts. In this study, the Delphi technique relied on the experience of experts in different fields within the highway industry to determine the added or lost value of using performance specification under a number of different scenarios (which considered different delivery methods and project characteristics).

Delphi Technique Background

Research shows that the Delphi technique is very useful when the judgment of individuals must be tapped and combined to address a lack of agreement or incomplete state of knowledge (Delbecq et al. 1975). Delphi is particularly valued for its ability to structure and organize group communication (Powell 2003). One of the major advantages of the Delphi technique is that it documents facts and opinions of the panelists, while avoiding the pitfalls of face-to-face interaction, such as group conflict and individual dominance (Gupta and Clarke 1996). It is an inexpensive research methodology involving experts without physically bringing them together. “Controlled feedback and anonymity through planned, rather than reactionary responses from experts helps panelists to revise their views without publicly admitting that they have done so, thus encouraging them to take up a more personal viewpoint rather than a cautious institutional position” (Masser and Foley 1987). The Delphi approach offers an additional advantage for situations in which defining areas of uncertainty or disagreement among experts is important. In those instances, Delphi can highlight topics of concern and evaluate uncertainty in a quantitative manner. Group evaluation of belief statements made by panel members is an explicit part of Delphi (Robinson 1991).

Linstone and Turoff (2002) documented some of the research attributes that warrant the use of Delphi in the data collection process of any given study. For example, they note that the use of Delphi is beneficial when the research problem does not lend itself to precise analytical techniques but can benefit from subjective judgments on a collective basis. Another condition for using Delphi is when the individuals needed to contribute to the examination of a broad or complex problem have no history of adequate communication and may represent diverse backgrounds with respect to experience or expertise. Or, when time and cost constraints make frequent group meetings infeasible, employing Delphi can prove valuable. Using Delphi is also appropriate when more individuals are needed than can effectively interact in a face-to-face exchange. Furthermore, Delphi helps preserve the heterogeneity of the participants to assure the validity of the results, that is, avoidance of domination by quantity or by strength of personality (“bandwagon effect”). All of these Delphi attributes were found to correspond with this research endeavor, which led the team to use the Delphi approach in the data collection process.

The number of survey rounds included in the data collection process is a critical aspect of Delphi technique. Studies show that some applications of the Delphi process have been accomplished in three and others in more rounds. The iterative nature of the procedure generates new information for panelists in each round, enabling them to modify their assessments and project them beyond their own subjective opinions. It can represent the best forecast available from a consensus of experts (Corotis et al. 1981). Typically three rounds of surveys are sent to a preselected expert panel, although the decision regarding the number of rounds is largely pragmatic (Jones et al. 1992). The Delphi method requires a minimum of two rounds beyond which the appropriate number of rounds is disputed (Thangaratinam and Redman 2005). "Repeated rounds may lead to fatigue by respondents and increased attrition" (Walker and Selfe 1996).

For this research, the experts participated in three rounds of surveys. Details on each round and the results of the rounds are discussed in the section Survey Results of this appendix.

Delphi Experts

The success of a Delphi study largely rests on the combined expertise of the participants who make up the expert panel (Powell 2003). Rowe (1994) suggests that experts be selected from varied backgrounds to guarantee a wide base of knowledge; Murphy et al. (1998) suggest that diversity in expert panel membership leads to better performance as it may allow for the consideration of different perspectives and a wider range of alternatives. However, considerable variation exists in the suggested panel size.

One recommendation for panel size is five to 20 experts with disparate knowledge (Rowe and Wright 2001). In a Delphi study related to thermal and transport science, reference was made to Clayton's rule of thumb that 15 to 30 people are an adequate panel size; 31 of 35 people agreed to be on that panel (Streveler et al. 2003). Guidance suggests that numbers of participants will vary according to the scope of the problem and the resources available (Delbecq et al. 1975). Some believe the more participants the better the results. However, there is very little empirical evidence on the effect of the number of participants on the reliability or validity of consensus processes as long as opinions of all stakeholders are taken into account (Murphy et al. 1998). Indeed, what is more important is the expertise of the panel members themselves.

The R07 study involved 11 participants, representing both public and private institutions and possessing a range of experience in delivery methods, use of warranties, and the development of specifications. The team was satisfied that the Delphi panel had the requisite expertise (relevant knowledge and years of experience with respect to the subject) to assess the perceived value of performance specifications under a number of different scenarios.

Experts were identified and considered for potential participation on the Delphi panel on the basis of three criteria:

- Affiliation (e.g., agency, contractor, consultant, academia);
- Experience with alternate project delivery approaches, warranties, and/or performance specifications; and
- Potential interest as determined by previous participation in research and other activities related to the application of performance specifications.

Twenty-eight agencies and organizations were identified, providing a list of 34 potential participants. Several of the potential participants were affiliated with the same agency or organization. Only one survey request was made for each agency or organization even if it had multiple potential participants. Of the 24 requests for participation in the Delphi effort, 13 participants represented departments of transportation (DOTs), five represented the construction industry, three represented firms that engaged in public-private partnerships (P3s), two were consultants, and one was from academia. Of the 24 requests, 14 agencies and organizations agreed to participate. Seven survey responses to the first round of the Delphi study were received. However, 11 professionals representing 10 agencies and organizations participated in the workshop and in Round 2 and Round 3 of the Delphi process. Table E.1 summarizes the participation of agencies and organizations in the Delphi study.

Survey Development

Once experts were identified, the next step in the Delphi process entailed preparing a survey to assess the perceived value of implementation of performance specifications by state highway agencies.

The survey was divided into three steps to guide the participants in inserting the necessary data in an organized and sequenced fashion. Step 1 of the survey asked respondents to describe a project in terms of the following six characteristics:

- Road class (local, state highway, interstate, toll);
- Type of construction (preservation, reconstruction, new construction);
- Traffic (low, moderate, or high average annual daily traffic—AADT);
- Location (urban, rural);
- Complexity (based on project phasing, right-of-way requirements, utilities, environmental issues, etc.); and
- Climate (based on moisture and temperature by region).

The objective of this step was to determine if certain project characteristics were likely to impart a larger influence than others on the perceived value added (or lost) of using performance specifications.

Given the project characteristics identified in Step 1, respondents were asked in Step 2 to evaluate the relative impact of moving from a method specification under a design-bid-build delivery approach (the benchmark case) to performance specifications under a variety of different delivery approaches (design-build, design-build-warrant, design-build-maintain, etc.). The value added or lost was to be evaluated (from the perspective of the owner) against the following criteria:

- *First cost (FC).* The relative percentage increase or decrease in the total costs incurred by the owner to complete the design and construction of a given project relative to the implementation of prescriptive (method) specifications.

Table E.1. Summary of the Participation of Agencies and Organizations in the Delphi Study

		Relevant Experience			Data Collection		
Affiliation	**Organization or Agency**	**Alternate Project Delivery**	**Warranties**	**Performance Specifications**	**Survey Requests**	**Survey Responses**	**Workshop Participation (No Participants)**
Department of transportation (DOT)	Florida DOT	√	√		√	√	√ (1)
	Virginia DOT	√		√	√		
	Washington State DOT	√			√		
	Michigan DOT	√	√		√		
	Ohio DOT	√	√		√		
	Mississippi DOT		√		√		
	Wisconsin DOT	√	√		√		
	North Carolina DOT	√	√	√	√		
	Missouri DOT	√		√	√		
	Caltrans	√		√			
	Texas DOT	√		√	√	√	√ (1)
	Minnesota DOT	√			√		
	Oklahoma DOT			√	√		
Contractor	Rieth-Riley	√	√	√		√	
	Kokosing	√	√		√	√	√ (1)
	Kiewit	√	√	√	√		
	Flatiron	√	√	√	√		
	Wagman	√	√		√		
P3	Colas			√	√		√ (1)
	Halcrow			√	√	√	√ (1)
	Cintra			√	√	√	√ (1)
	World Bank			√			
Consultant	HNTB	√	√		√		
	Transtec	√		√	√		√ (1)
	Trauner	√	√	√			√ (2)
Academia	University of Oklahoma	√		√	√	√	√ (1)
	Texas A&M	√	√	√			√ (1)
TOTAL	**28**				**22**	**7**	**11**

- *Life-cycle costs (LCC).* The relative percentage increase or decrease in the costs encountered during the life span of the project, resulting from implementation of performance specifications under the given delivery method, relative to implementation of prescriptive (method) specifications. A decrease or increase in LCCs of a given project is an indication of project quality. A decrease in LCC reflects high quality and an increase of LCC can be attributed to lower quality.
- *Construction inspection and administration costs.* The relative percentage increase or decrease in agency construction inspection and administration costs, resulting from implementation of performance specifications under the given delivery method, compared with implementation of prescriptive (method) specifications.
- *Innovation opportunity.* The opportunity for performance specifications, as implemented under the given delivery method, to create an incentive for innovation in executing design and/or construction works.
- *Schedule.* The relative percentage increase or decrease in total project duration, resulting from implementation of performance specifications under the given delivery method, compared with implementation of prescriptive (method) specifications.
- *Traffic disruption.* The relative decrease or increase in traffic disruption, resulting from implementation of performance specifications under the given delivery method, compared with implementation of prescriptive (method) specifications.

Finally, Step 3 of the survey provided a summary of the participants' input. In that step, participants were required to review a generated summary of their results for consistency and to make any necessary adjustments.

Survey Results

Round 1

The data presented below are the results from Round 1 of the Delphi survey. For this round, the research team chose 24 experts and requested their participation in the Delphi study through a formal e-mail invitation. Thirteen of the 24 agreed to participate; however, only seven completed the survey. Initial survey responses were received from the following owner and industry representatives:

Owners
Florida DOT (Dave Sadler)
Texas DOT (Jeff Seiders)
Industry
Ferrovial Agroman US Corporation (Cintra) (Fidel Saenz de Ormijana)
Halcrow (Joe Graff)
Kokosing Construction Company (John Householder)
Rieth-Riley Construction Company (Pete Capon)
Academia
Douglas Gransberg, University of Oklahoma

Thus, for Round 1, data was collected from a total of seven participants. One of the seven participants submitted an incomplete survey. That participant completed the survey for the design-build-maintain (DBM) delivery method only. Therefore, for consistency reasons, the team did not consider the participant's input in the Round 1 data analysis process. Thus, for Round 1 the data was analyzed from a total of six surveys.

The aggregate results for each comparison criteria are presented in the form of bar charts. The combinations of delivery methods and performance specifications under consideration included the following:

- Prescriptive (method) specifications, or benchmark;
- Design-bid-build, with some performance requirements, no warranty (DBB+P);
- Design-bid-build, with short-term warranty (DBB+STW);
- Design-build, no warranty (DB);
- Design-build, with short-term warranty (DB+STW); and
- Design-build-maintain (DBM).

First Cost

The data in Figure E.1 show that the participants felt that implementing performance specifications would result in an overall increase in first costs. However, one or two participants thought that a decrease in first cost was possible. They also believed that DBM leads to higher increases in first cost (5% to 15%) and that DBB+P mostly shows no impact or a small FC increase (0% to 5%). Furthermore, they expected FC increases for DBB+STW between 0% to 5% and 5% to 10%.

Life-Cycle Costs

The data show that there is a general decrease in LCC. DBM, DB+STW, and DBB+STW show a greater decrease in LCC compared with DBB+P. Meanwhile, DB seems to have no impact or to cause only a minor increase in LCC (see Figure E.2).

Construction Inspection and Administration Costs

The data show an overall trend of no impact or minimal decreases and increases in construction inspection and administration costs. However, DBM and DB+STW show greater decreases (see Figure E.3).

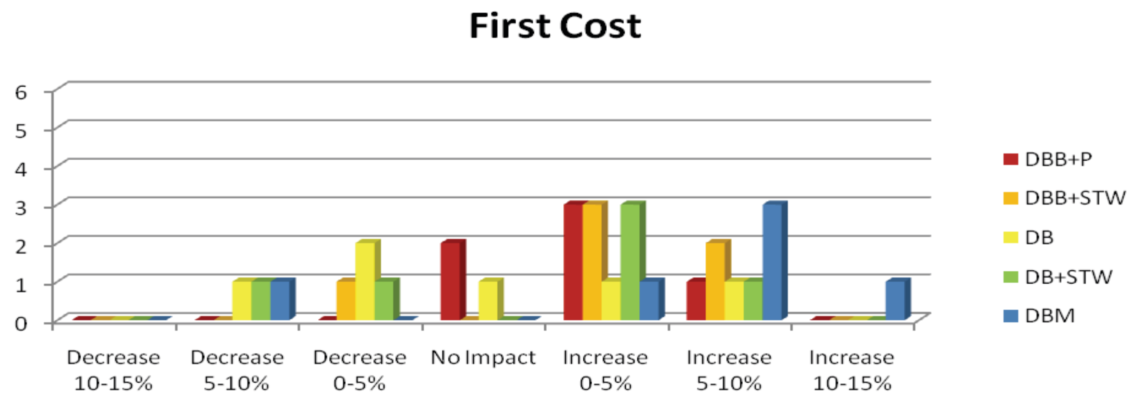

Figure E.1. Survey data related to first cost.

Schedule

The data show a general trend toward a decrease in schedule (see Figure E.4). The greatest decrease in project duration is under DBM (decrease 10% to 5%). A relatively smaller decrease in project duration occurs under DB and DB+STW (decrease 5% to 10%), and little impact on schedule occurs under DBB+P and DBB+STW.

Innovation Opportunity

The data show an overall greater incentive to innovate when using performance specifications. DBB+P is the only delivery method with no additional incentive to innovate. DBM, DB+STW, and DB each indicate a greater incentive to innovate; and for DBB+STW the incentive is almost the same (Figure E.5).

Traffic Disruption

The data show that all participants expected traffic disruption either to decrease or to stay the same. None felt that traffic disruption would increase under any delivery method. DBB+P and DBB+STW generally show no impact on traffic disruption. However, traffic disruption decreases with DBM, DB+STW, and DB (see Figure E.6).

Workshop

As a follow-up to the initial survey effort, the team conducted a face-to-face workshop with the survey respondents. The objective of the workshop was to reach a consensus on the survey results through subsequent rounds of the Delphi process and to further identify the benefits and risks associated with implementing performance specifications.

The experts involved in the workshop had a variety of different backgrounds and experiences in applying performance specifications in the highway industry. A total of 11 experts participated in the workshop (four additional participants in the workshop beyond those who completed the Round 1 survey). A few of the experts represented academia and the consulting industry, while other experts were from state highway agencies and contractors or developers.

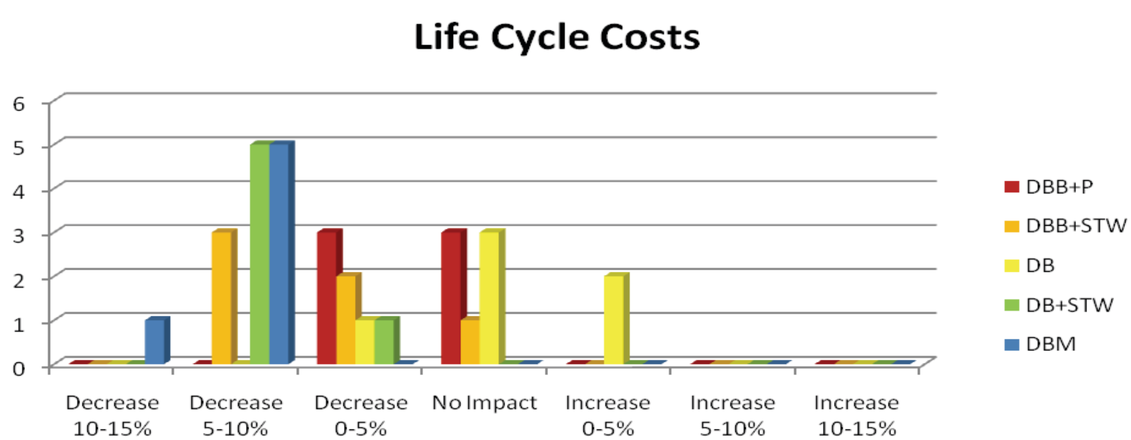

Figure E.2. Survey data related to life-cycle costs.

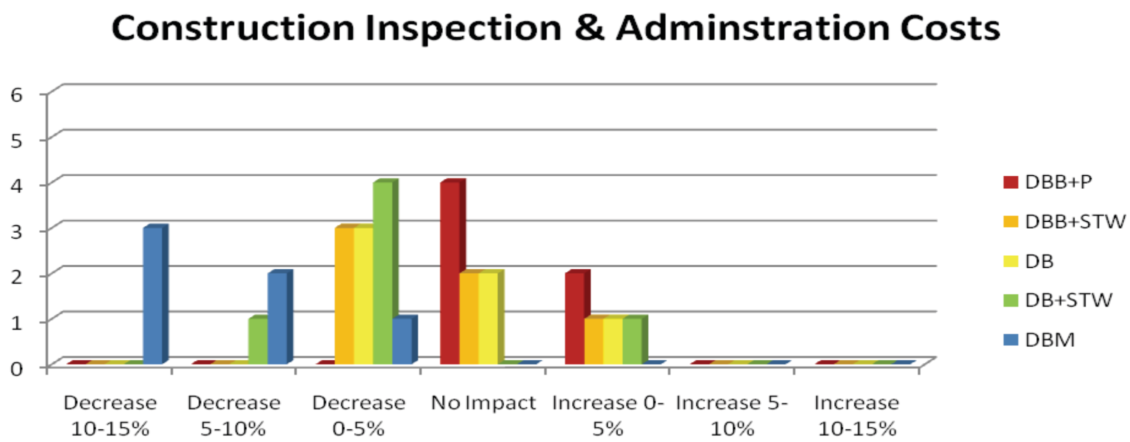

Figure E.3. Survey data related to construction inspection and administration costs.

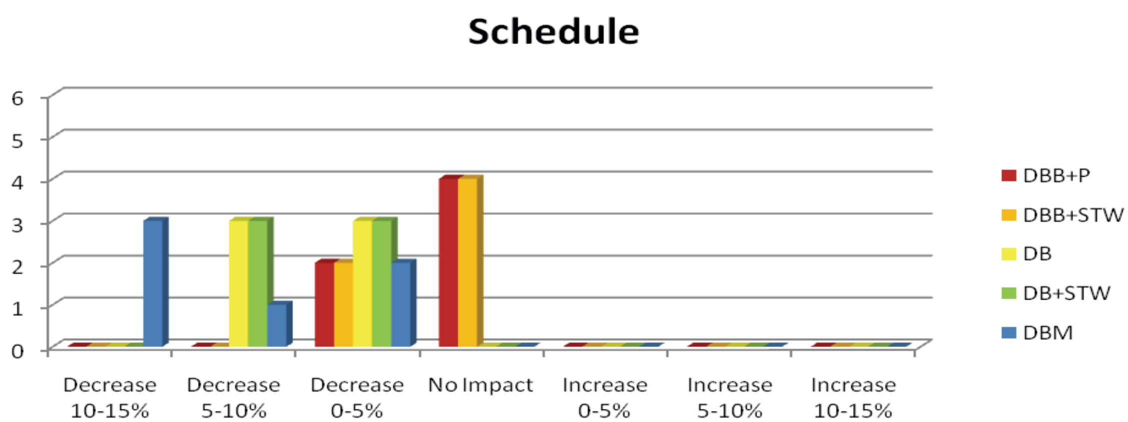

Figure E.4. Survey data related to schedule.

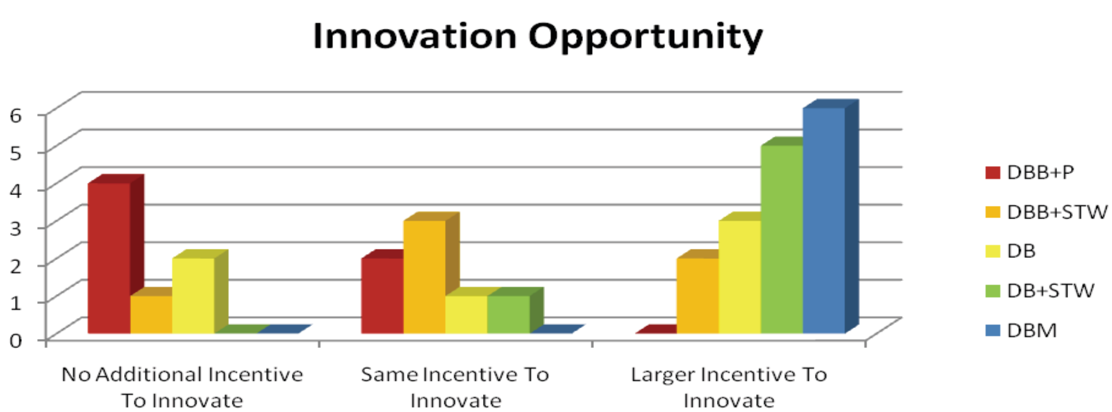

Figure E.5. Survey data related to incentive to innovate.

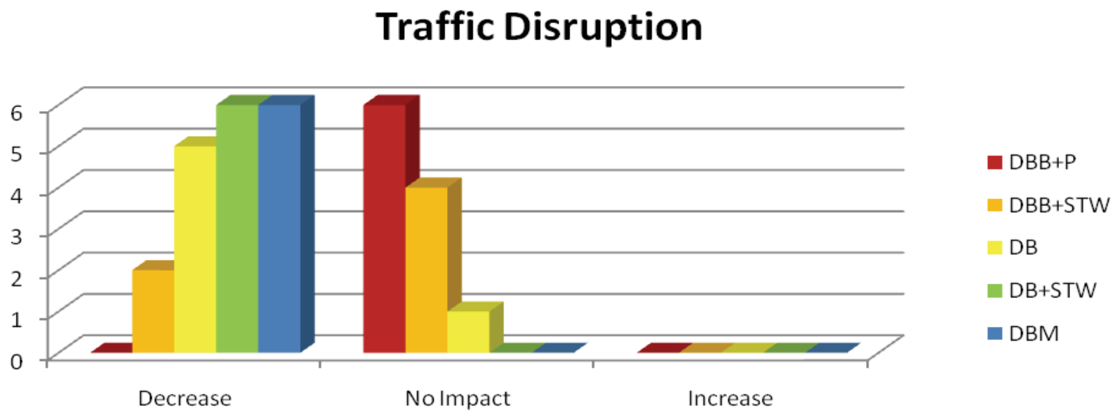

Figure E.6. Survey data related to traffic disruption.

The team began the workshop with a summary and discussion of the initial survey results. Note that for the initial survey, respondents based their answers on an *actual* project experience, which they described in terms of the six project characteristics identified in the survey tool (road class, location, etc.). Some general conclusions can be drawn from participants' initial responses:

- The use of performance specifications, particularly when used in conjunction with warranty or maintenance agreements, increases FCs and reduces LCCs. However, the use of DB without a warranty or maintenance option has no impact on FCs and slightly increases LCCs. These results indicate that quality (LCC) tends to be enhanced when using performance specifications with postconstruction warranty or maintenance options, but FC may increase slightly.
- The data related to construction inspection and administration costs show mixed results: no impact or minimal increases or decreases. But DB with warranties or maintenance agreements shows a greater decrease in those costs.
- In general, the use of performance specifications for all delivery methods results in a general decrease in schedule or project durations.
- Use of performance specifications under a DBB scenario has no impact on traffic, while the use of DB delivery by itself or in conjunction with warranties or maintenance options decreases traffic disruption.

Presentation of these results prompted discussion among the participants regarding any assumptions that were (or on reconsideration, should have been) built into their value assessments. These assumptions included the following:

- *First cost* refers to all costs incurred during the project development and delivery phases.
- First cost excludes any learning curve associated with the initial implementation of the specification.
- *Life-cycle cost* refers to all costs incurred during facility operations including resurfacing, rehabilitation, and reconstruction during the analysis period.
- The analysis period is considered to be 50 years.

The participants also discussed whether the project characteristics and value assessment criteria were appropriate and comprehensive. They agreed that the size (dollar value) of the project would have an effect on the results and should be added to the project characteristics; road class and weather could be eliminated, as the effect of these parameters would be minimal compared with the other characteristics. Also dropped was the use of innovation opportunity as a value comparison criterion. The participants felt that the ability to innovate was perhaps the leading driver behind the savings reflected in the other criteria; therefore, to evaluate savings associated with innovation itself would create double-counting problems.

The participants also discussed the applicability of the survey results (which focused on pavements) to other research areas such as bridges and geotechnical systems. The general consensus was that the results would be similar, with the possibility that the savings might be even more pronounced, particularly for the longer-term agreements.

Delphi Round 2

The group reconvened on Day 2 of the workshop to reevaluate their initial survey responses in light of the Day 1 discussions. This evaluation formed the second round of the Delphi process. In contrast to the initial survey, in this formal Delphi round, the participants were asked to evaluate the perceived value of implementing performance specifications under *each* project scenario that could be generated by combining the various project characteristics (i.e., project size, type, traffic, complexity, and location). After adjusting for the comments received on the first day, this meant evaluating 32 different project scenarios. Figure E.7 shows an example of one of the scenarios.

PROJECT COMBINATION 1					Same as Project Combination # :
Size	Type	Traffic	Complexity	Location	
Large	New Construction	High AADT	High	Urban	
	DBB + P	DBB + STW	DB	DB + STW	DBM
First Cost (FC)	No Impact	Increase 0-5%	Increase 0-5%	Increase 0-5%	Increase 0-5%
Life Cycle Cost (LCC)	Decrease 0-5%	Decrease 0-5%	Increase 0-5%	Decrease 0-5%	Decrease 5-10%
Inspection & Admin. Cost	No Impact	Decrease 0-5%	No Impact	Decrease 5-10%	Decrease 10-15%
Schedule	No Impact	Decrease 0-5%	Decrease 5-10%	Decrease 5-10%	Decrease 0-5%
Traffic	No Impact	No Impact	Decrease	Decrease	Decrease
The Same As:					

Figure E.7. Example of project scenario tables for Delphi Rounds 2 and 3.

The Round 2 Delphi survey distributed to the participants contained 32 tables similar to the one shown in Figure E.7. Each participant completed the Round 2 survey independently during the second day of the workshop. The results from this round were then analyzed in two different ways to better understand the data collected. The main objective of the data analysis was to better capture the participants' viewpoints regarding the application of various delivery methods and the effect on the defined performance criteria.

Aggregate Results

The number of participants for the second Delphi round was 11. Given the number of participants (11) and number of project combinations (32), the number of responses collected from the survey totaled 352. The responses were first combined to present the overall impact of each of the performance criteria, without considering different project scenarios. Appendix G presents the survey results in graphical form, in full color. The first section of the appendix presents the aggregated data, with five graphs each showing the combined data of all the participants for the five performance (comparison) criteria: first costs, life-cycle costs, inspection and administration costs, schedule, and traffic disruption.

Individual Project Combinations

The data collected from each participant in Delphi Round 2 were combined for each performance criterion (first costs, life-cycle costs, inspection and administration costs, schedule, and traffic disruption) according to project characteristic (traffic, complexity, size, type, and location). The second section of Appendix G presents in graphical form the combined results for each project characteristic when considered with each performance criterion.

The third section of Appendix G presents the results for each of the 32 project combinations. Each combination includes five bar charts, each representing the results when one of the five performance criteria is considered. An example of the data included in this section of the appendix is presented in Table E.2 and in Figures E.8 to E.12.

Table E.2 indicates that Project Combination 1 is a large, new construction project with high AADT traffic. This project is highly complex to construct and located in an urban area.

Figures E.8 to E.12 show the results of the 11 participants' input for this project combination (Project Combination 1) for the five comparison criteria: first cost, life-cycle cost, inspection and administration cost, schedule, and traffic disruption.

Delphi Round 3

For Round 3 of the Delphi effort, the participants were given the aggregate results of Delphi Round 2, as included in Appendix G, with the expectation that they would review their initial assessment and make changes as they saw fit given the aggregate group response and workshop discussions. The participants were also provided with a list of clarifications regarding some issues related to the data collection approach that were discussed at the workshop. The list of clarifications follows:

1. *Life-cycle cost* refers to all costs incurred during facility operations including resurfacing, rehabilitation, and reconstruction during the analysis period.
2. Analysis period is considered to be 50 years.
3. *First cost* refers to all costs incurred during project development and delivery phases.
4. The impacts (first cost, schedule, life-cycle costs, etc.) should be assessed independently of the point of view. In other words, what will be the impact, not what would I want to see.
5. *Design-build* implies that the contractor has some level flexibility in deciding on design parameters.

Table E.2. Project Criteria for Project Combination 1

Project Combination 1				
Size	Type	Traffic	Complexity	Location
Large	New Construction	High AADT	High	Urban

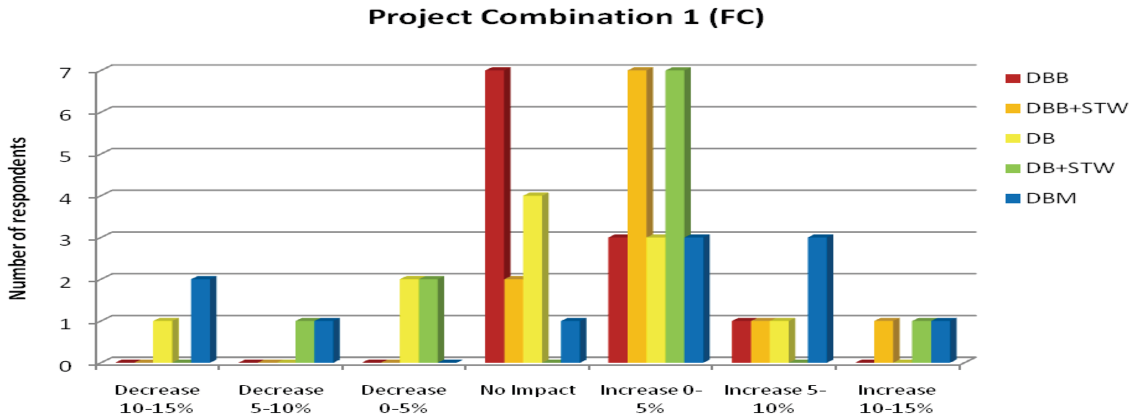

Figure E.8. First cost comparison results under Project Combination 1.

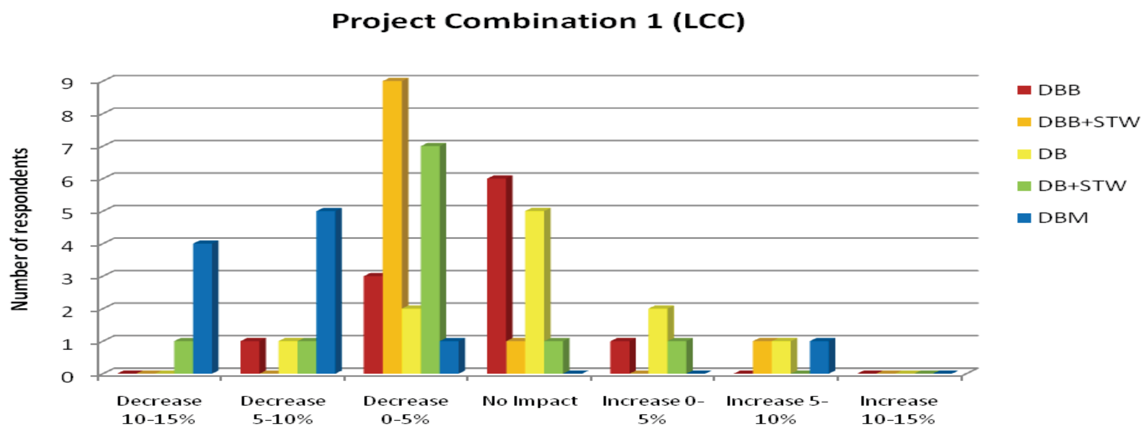

Figure E.9. Life-cycle cost comparison results under Project Combination 1.

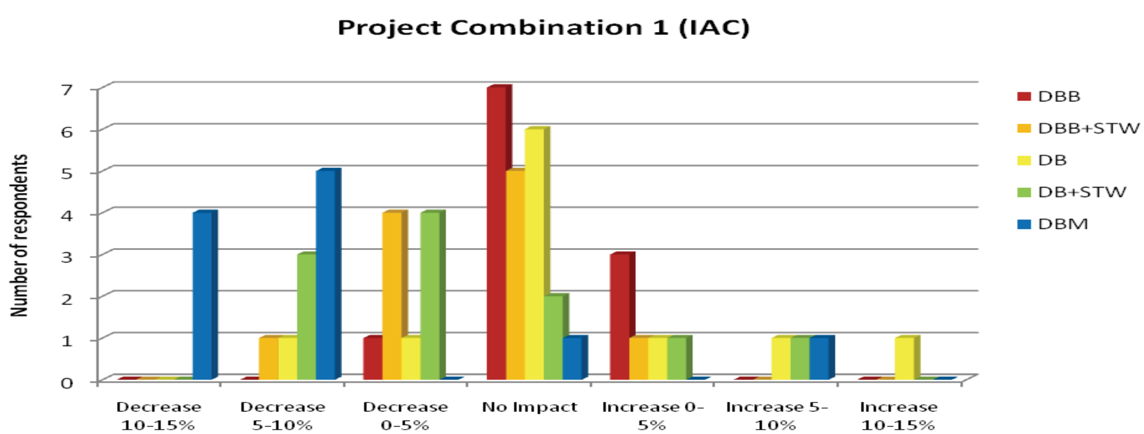

Figure E.10. Inspection and administration cost comparison results under Project Combination 1.

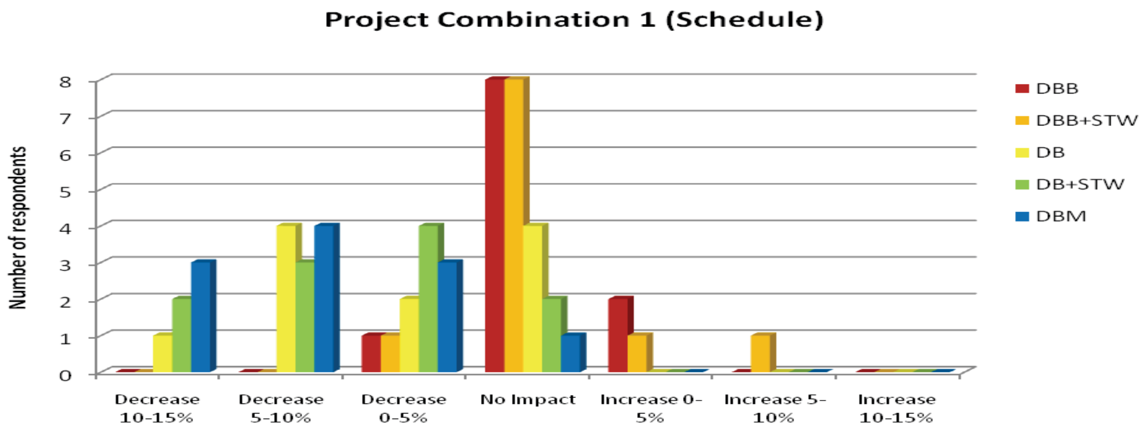

Figure E.11. Schedule comparison results under Project Combination 1.

The participants were asked to consider these clarifications when completing the third round of the Delphi effort.

Six of the 11 experts sent back a reply to the e-mail message with their changes, and the remaining five did not wish to make any changes to their Round 2 inputs. The team aggregated the data provided by the experts in Round 3 and assessed how the responses changed from Round 2. The assessment shows that apart from some minor changes, the aggregate results generated in Round 3 are almost identical to those in Round 2.

The aggregate first cost results show an expected trend as shown in Figure E.13. DBB+P may result in a slight FC increase, while DBB+STW will most likely increase first costs. The results for the other three levels of performance specifications are less conclusive. DB shows a significant variance across the responses. This results from a lack of clarity about the objective of using DB. Is it used simply to accelerate project delivery, or does it give contractors the design flexibility to maximize project efficiency as well? DBM is another method that shows significant variance. In fact, the results are contradictory. As this method is quite new, such results are not surprising. The experts who have experience in DBM typically report great FC savings.

The results for life-cycle cost value gains are intuitive. As the level of performance specifications increases, the LCCs decrease. Again, DB shows significant variation in responses. As DB gives contractors no contractual responsibility for performance, many experts believed that this could jeopardize quality. This is reflected in the results (see Figure E.14).

Much like for life-cycle cost, inspection and administrative costs decrease with higher levels of performance specification (see Figure E.15). DBM shows the largest decrease, while DBB+P and DBB+STW show no impact.

The results related to schedule impact are largely split (see Figure E.16). DBM, DB+STW, and DB show decreases, while DBB methods show no impact or an increase. These results are again expected as DB and its variants integrate project delivery across different delivery phases (e.g., design, construction, maintenance).

Finally, the results presented in Figure E.17 show that the effect of the various approaches on traffic is largely the same, except for higher levels of performance specifications. As

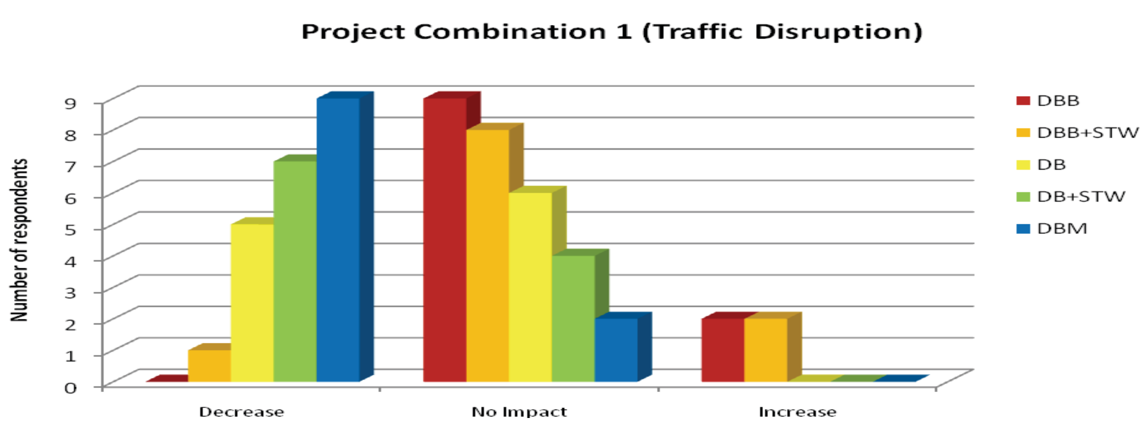

Figure E.12. Traffic disruption comparison results under Project Combination 1.

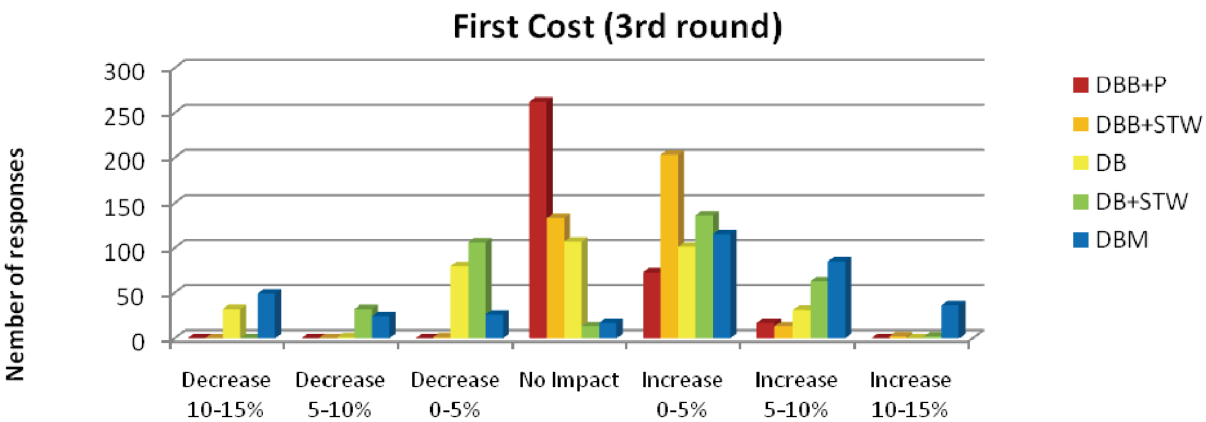

Figure E.13. Round 3 first cost comparison histogram.

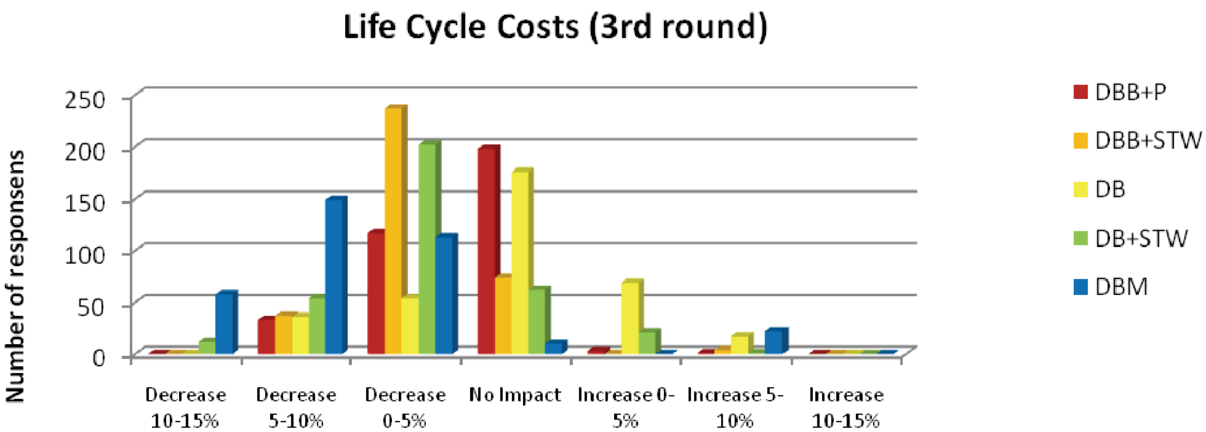

Figure E.14. Round 3 life-cycle cost histogram.

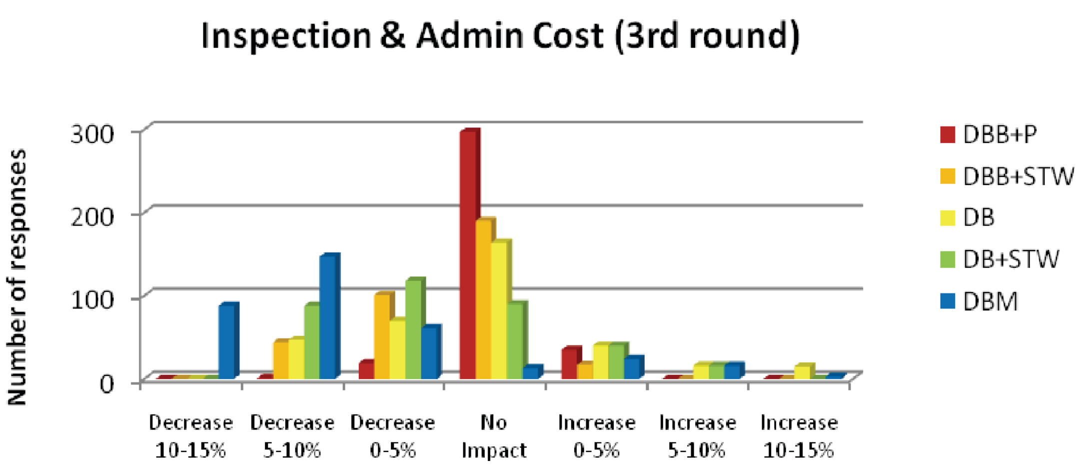

Figure E.15. Round 3 inspection and administration cost histogram.

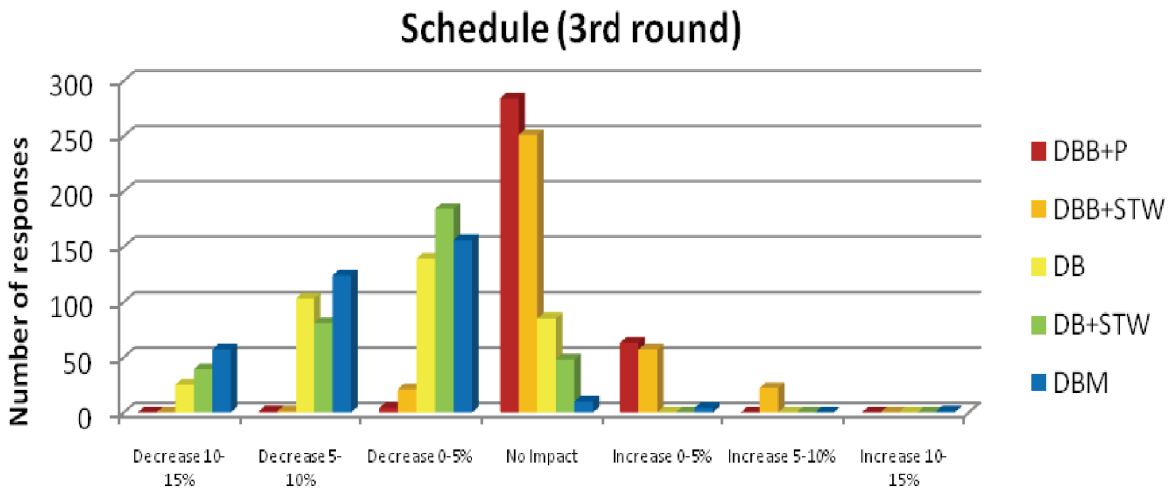

Figure E.16. Round 3 schedule histogram.

contractors receive incentives to manage traffic under performance criteria, shortened schedules are expected.

Summary of Results

The general trends derived from the Round 3 surveys concerning added or lost value are presented in Table E.3. The table presents the general trends seen in the histograms with respect to the delivery methods and the comparison criteria included in the Round 3 survey. Performance specifications implemented under DBB delivery (i.e., the DBB+P delivery scheme) show the least added value of all the delivery methods. No impact was evident on most of the comparison criteria except for some decrease in life-cycle cost.

The results show that implementing performance specifications under the DBB+STW delivery method will have minor impacts on the project. That approach will likely lead to small decreases in life-cycle cost and inspection and administration costs, and a slight increase in first cost.

Performance specifications implemented under the DB delivery method show the greatest variability. DB shows consistent decreases in both schedule and inspection and administration costs but shows mixed results for both first cost and life-cycle cost. The surveyed experts responded that DB leads to an increase or a decrease of 0% to 5% in first cost and an increase or decrease of 0% to 10% in life-cycle cost. This variability can be attributed in part to how DB is implemented by agencies and the extent to which performance specifications are used.

For DB+STW, the results show an effect on the life-cycle cost, inspection and administration cost, and schedule comparison criteria similar to DB. In addition, DB+STW decreases traffic disruption, an added value attributed only to DB+STW and DBM (see Table E.3). However, the DB+STW delivery method increases first cost as much as 10%.

Finally, performance specifications implemented under the DBM delivery method show the most significantly consistent decreases in life-cycle cost, inspection and administration cost, schedule, and traffic disruption relative to the other delivery methods. However, these decreases come with an increase (up to 10%) in the highway project's first cost (see Table E.3).

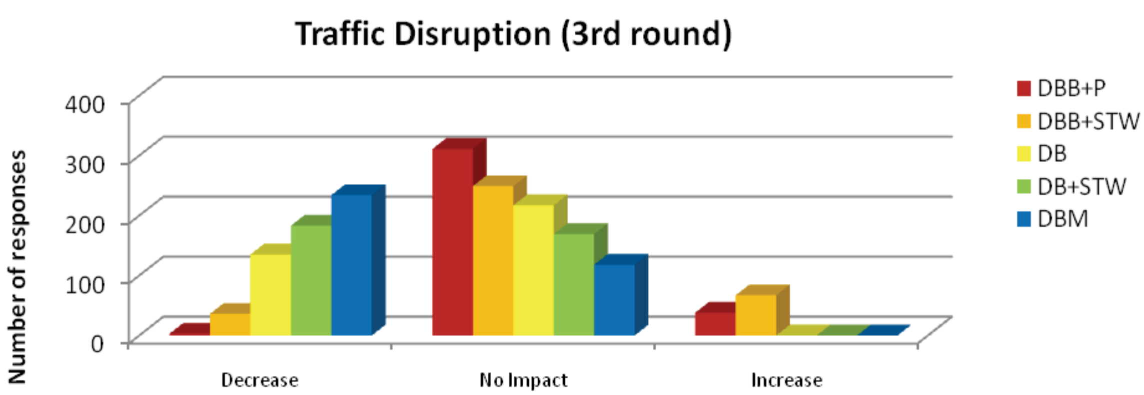

Figure E.17. Round 3 traffic disruption histogram.

Table E.3. General Trends Extracted from Round 3 Results

	First Cost	Life-Cycle Cost	Inspection and Administration Cost	Schedule	Traffic Disruption
DBB+P	No impact	No impact and decrease 0–5%	No impact	No impact	No impact
DBB+STW	No impact and increase 0–5%	Decrease 0–5%	No impact and decrease 0–5%	No impact	No impact
DB	No impact and increase 0–5%[a]	No impact and increase 0–10%[b]	No impact and decrease 0–5%	Decrease 0–10%	No impact
DB+STW	Increase 0–10%[c]	No impact and decrease 0–10%	No impact and decrease 0–10%	Decrease 0–10%	Decrease
DBM	Increase 0–10%	Decrease 0–15%	Decrease 5–10%	Decrease 0–10%	Decrease

[a] Some responded that DB leads to a decrease of 0% to 5% in first cost.
[b] Some responded that DB leads to a decrease of 0% to 10% in life-cycle cost.
[c] Some responded that DB+STW leads to a decrease of 0% to 5% in first cost.

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APPENDIX F

Lake Anna Demonstration Project, Virginia Department of Transportation

Introduction

Current department of transportation (DOT) specifications for hydraulic cement concrete bridge decks are generally of the prescriptive type. In the design of the concrete mixtures, minimum cementitious material and maximum water–cementitious materials ratios (w/cm) are specified. Materials used in the mixtures are also covered in the specifications and are required to comply with the appropriate ASTM or AASHTO standards. The mixtures have a specified range of air content and slump, a maximum temperature tested at the fresh state, and a minimum design compressive strength of the hardened concrete tested at 28 days using standard curing. DOTs typically perform the tests. Decks with test results within the specification limits are paid for in full.

Performance (or end-result) specifications require the contractor to assume more responsibility for supplying a product or an item of construction. The highway agency's responsibility is either to accept or to reject the final product or to apply a pay adjustment commensurate with the degree of compliance with the specifications. Specifications that focus on the end-result properties of the product are more efficient and cost-effective than the prescriptive type of specification that places limits on the materials and proportions used.

The objective of the Lake Anna Demonstration Project was to demonstrate a performance shadow specification for a hydraulic cement concrete bridge deck using construction parameters that relate to performance, including portland cement concrete (PCC) deck permeability, cracking, joint condition, skid, smoothness, and thickness and cover depth. A percent within limits (PWL) was developed for construction parameters (e.g., cover depth, thickness, strength, and permeability), and pass-fail criteria were used for others (e.g., cracking, joint condition, and cross slope). The performance specification was shadowed to compare results with the Virginia Department of Transportation's (VDOT) end-result specification, which incorporates a PWL with pay adjustments for strength and permeability.

Overview

During the Lake Anna Bridge Rehabilitation Project on Route 208, the deck was replaced with high-performance concrete with low permeability and corrosion resistant steel (MMFX2, low carbon chromium steel). Figure F.1 shows the bridge.

The bridge has 13 spans and two lanes. The total length of the bridge is 929 ft 3 ⅜ in. The length of each span is a little over 71 ft with the two end spans closer to 73 ft. In late 2011 the westbound lane (WBL) and in mid 2012 the eastbound lane (EBL) were replaced. Because of the traffic control requirements, concrete was placed at night to allow one lane in both directions to be open to traffic at alternating times during the day.

Westbound Lane

Materials and Proportions

The concrete mixture is given in Table F.1. Type II cement and slag cement were used as the cementitious material. Coarse aggregate was siliceous crushed rock, and fine aggregate was natural sand. Commercially available air entraining and water reducing admixtures were used in the mix. Mix2 was placed beginning with the second day of pumped concrete after the first three loads. Mix2 has 5% less coarse aggregate, compensated for by the addition of sand. The contractor requested the change to facilitate pumping. Pumping was done by the slick lines (10-ft-long steel pipes) laid on the deck. For the last day's placement, the slick line had to cross the four spans already placed on the previous placement day. To accommodate the long line, the change in the mix was made to improve the workability.

Placement

Traffic was allowed to use the EBL during the reconstruction of the WBL. The concrete placement started on November 8, 2011,

Figure F.1. Route 208 bridge over Lake Anna.

Table F.1. Mixture Proportions for WBL (lb/ft³)

Ingredient	Mix 1	Mix 2
Cement	381	381
Slag	254	254
Fine aggregate	1052	1105
Coarse aggregate	1857	1802
Water	286	286

and was completed in 4 days, as shown in Table F.2. Ready-mixed concrete trucks delivered the concrete in 10-yd³ loads from the plant, which was located about 15 miles away.

Each span used about four truckloads of concrete. During the first 2 days, the concrete was placed by the chute of the truck stopped on the EBL. Concrete barriers separated the lanes. During the last 2 days of placement, concrete was pumped from the approach slab on the east end. On Days 1 and 2, the placement was made using the full extension of the chutes of the trucks. However, the chutes could not reach the whole width, and the deposited concrete had to be spread to the far side. Thus, loads had to be placed on the side closer to the EBL where the truck was located and then spread across toward the parapet. This method prolonged the placement, and the EBL had to be closed to traffic for about 15 minutes for each load. The traffic interruption was more than anticipated. Therefore, the second day, placement was done at night when fewer vehicles were on the road. Placement took a long time because of the need to spread the load to the outer edge with a "come-along" tool (a tool that looks like a hoe and has a long straight-edged blade). Concrete lost slump with time, so to facilitate finishing, water was

Table F.2. Dates and Fresh Concrete Properties for WBL

Day	Batch	Date	Slump (in.)	Air (%)	Density (lb/ft³)	Mix Temperature (°F)	Evaporation Rate (lb/ft²/hr)
1	1	11/8/2011	7.0	7.5	140.8	62	0.02
	2	11/8/2011	6.5	6.5	144.0	65	0.02
	3	11/8/2011	6.0	5.3	145.6	72	0.02
2	1	11/14/2011	5.8	6.2	143.2	70	0.06
	2	11/14/2011	6.5	7	142.8	69	0.05
	3	11/14/2011	7.0	6.7	142.8	70	0.07
3	1	12/1/2011	7.0	7.6	142.0	65	0.06
	1P	12/1/2011	2.5	6.7	144.0		
	2	12/1/2011	5.5	6.3	144.8	65	0.06
	2P	12/1/2011	5.5	11.5	135.2		
	3	12/1/2011	7.0	6.8	143.6	68	0.06
	3P	12/1/2011	5.5	4.5	146.8		
	4	12/1/2011	7.0	6.7	144.0	67	0.03
	4P	12/1/2011	7.0	7	142.4		
4	1	12/13/2011	7.0	7.5	143.2	63	0.03
	1P	12/13/2011	6.0	7.5	142.8	64	0.05
	2	12/13/2011	7.0	7.2	144.8	63	0.02
	2P	12/13/2011	5.5	7.9	142.6	65	0.03
	3	12/13/2011	6.8	6.9	144.0	69	0.03
	3P	12/13/2011	5.0	7.3	143.2	70	0.03
	4	12/13/2011	6.8	7.3	142.8	66	0.03
	4P	12/13/2011	7.0	6.8	143.6	61	0.02

Note: P indicates tested after pumping.

Figure F.2. Water sprayed on concrete using the truck hose.

sprayed on the concrete that was not yet finished, as shown in Figure F.2.

In addition to the use of come-along tools, vibrators also were used to spread the concrete. Vibration was done in a random manner as the load was deposited on deck. Because vibration can cause segregation, the contractor was notified that a regular grid pattern should be used, with attention to the radius of action of the vibrators. The slump of the concrete was high as delivered (see Table F.2).

Vibration tended to bring the paste to the surface, and the screed moved the fine material to the inside edge. Initially the extra paste was worked into the surface (Figure F.3), but later an attempt was made to pull the paste to the middle of the placement.

Figure F.3. Extra paste worked into the surface.

Figure F.4. Water ponding along the edge and hand finishing.

After screeding, concrete was left uncovered for an extended period to accommodate the prolonged hand finishing along the edges. The contractor tried to keep the surface wet by fog misting. However, rather than misting, the water was sprayed and it ponded along the edge (see Figure F.4).

Right after screeding, water was also sprayed to close the surface blemishes. The contractor was informed that cut grooves would hide such blemishes and surface should not be sprayed. It was apparent that due to mishandling the concrete could have properties that would provide poor performance.

Recommended Improvements for Placement

On the basis of observations during placement, the following improvements were recommended:

- Deposit concrete where it is going to be used. Do not move concrete around, as that can cause segregation.
- Do not overvibrate concrete, especially concrete that has high slump (>5 in.). Concretes with high slump have a tendency to segregate and settle when vibrated.

- Do not spray water in front of or behind the screed. Water increases the water-cementitious materials ratio and causes a weak layer at the surface. When fog misting, the nozzle should be directed upward; mist should fall down to increase the relative humidity (RH) on the surface and not wash the surface. Spraying concrete after the screed to aid in closing small blemishes as the pan moves is not necessary. Grooving will make those small blemishes unnoticeable. At no time should water be sprayed on concrete that has not been screeded.
- Hand finishing should be minimized. Hand finishing brings fine material to the surface, and overfinishing removes air entrained voids near the surface. Time spent in hand finishing also delays the curing process.
- Concrete should be covered with wet burlap immediately after screeding. Wet burlap laid on top of fresh concrete is not going to harm the surface. Walking or dropping heavy objects on fresh concrete can mar the surface and should be avoided. Wet burlap should be drained ahead of time so that water does not drip on the fresh concrete surface.

Testing for Concrete Properties

Concretes were tested randomly with a frequency of one sample per sublot, and each sublot was four loads, totaling 40 yd^3. Each sample was tested at the fresh state from the truck as it arrived at the jobsite for air content, slump, density, and concrete temperature. For pumped concrete, samples were obtained and tested after pumping as well. Cylinders were cast for testing at the hardened state for compressive strength and permeability. (The results from the hardened concrete tests are given in the section, Method of Statistical Assessment.) Table F.2 summarizes the fresh concrete test results. The slump values were within the specifications for the concrete tested from the truck. However, the concrete tested after pumping did not meet the slump requirement of 4 in. to 7 in. on one occasion and the air content requirement of 5% to 8% on another occasion.

Eastbound Lane

Materials and Proportions

For the EBL, concrete placement started on June 20, 2012, and was completed in 3 days—as shown in Table F.3. Concrete from the same plant, using the materials and proportions listed in Table F.1 for Mix1, were used. Ready-mixed concrete trucks delivered the concrete in 10-yd^3 loads as in the earlier placement for the WBL. Concretes were tested randomly with the same frequency as in WBL both from the truck as it arrived and after pumping. The concrete tested from the truck met the fresh concrete requirements. However, when tested after pumping, the values did not meet the requirements for slump on four occasions and air content on five occasions.

Placement

Concrete placement started on June 20, 2012, and five spans were completed. A week later, a second day of placement occurred, and six more spans were completed. The remaining two spans were placed on July 3, 2012.

A small pump truck, as shown in Figure F.5, was used. The width of the lane did not permit a large pump truck.

Recommended Improvements for Placement

The following observations relate to the recommendations for placing concrete that were made after the EBL experience:

- *Deposit concrete where it is going to be used*. The pump truck enabled depositing concrete where it was needed. However, because of the short pump lines of the small pump truck, the truck had to be moved several times to deliver the concrete.
- *Do not overvibrate concrete.* Concrete was vibrated in a grid pattern. However, overvibration did occur. The slump values were high, and vibration brought the fine material to the surface—as shown in Figure F.6. The screed moved the paste to the side which was pulled manually into the middle.
- *Do not spray water in front of or behind the screed.* Spraying of water on the surface before and after screeding continued as shown in Figure F.7.
- *Hand finishing should be minimized.* Hand finishing continued as shown in Figure F.8. Minimal time and effort should be spent covering the surface immediately. Prolonged finishing delays curing and causes low spots that can collect water.
- *Concrete should be covered with wet burlap immediately after screeding*. In this phase, burlap was placed sooner than in the earlier phase. However, by further minimizing hand finishing, wet burlap can be used to cover the surface right after the screed. In this project the rate of evaporation was minimal, which helped with the curing process. However, if the rate of evaporation was high, cracking would be an issue. Covering the surface with burlap immediately to avoid loss of surface moisture is the recommended procedure.

Thus, in the placement of the EBL, improvements in depositing concrete and curing occurred. However, spraying water on the surface and overvibrating of the concrete continued. Hand finishing was still an issue. The deficiency and

Table F.3. Dates and Fresh Concrete Properties for EBL

Batch	Date	Slump (in.)	Air (%)	Density (lb/ft³)	Mix Temperature (°F)	Evaporation Rate (lb/ft²/hr)
Before Pumping						
1	6/20/2012	6.50	5.4	145.6	82	0.01
2	6/20/2012	4.50	5.4	146.4	80	0.01
3	6/20/2012	6.50	5.0	147.6	79	0.01
4	6/20/2012	7.00	6.1	143.6	76	0.02
5	6/20/2012	6.75	5.2	144.8	75	0.01
6	6/27/2012	5.50	5.6	148.0	81	0.03
7	6/27/2012	8.00	7.6	144.8	80	0.02
8	6/27/2012	5.00	6.3	147.6	78	0.02
9	6/27/2012	5.75	6.9	146.8	79	0.02
10	6/27/2012	6.75	7.0	146.0	75	0.02
11	6/27/2012	6.00	7.5	145.2	81	0.03
12	7/3/2012	7.00	5.4	149.2	82	0.02
13	7/3/2012	5.75	4.9	141.6	84	0.05
After Pumping						
Batch	**Date**	**Slump (in.)**	**Air (%)**	**Density (lb/ft³)**	**Mix Temperature (°F)**	**Evaporation Rate (lb/ft²/hr)**
1	6/20/2012	4.25	4.2	146.4	82	0.01
2	6/20/2012	3.50	4.7	146.4	83	0.02
3	6/20/2012	5.50	5.6	143.6	80	0.01
4	6/20/2012	7.00	6.5	142.8	76	0.01
5	6/20/2012	6.25	5.2	144.0	74	0.01
6	6/27/2012	2.0	4.6	146.4	86	0.04
7	6/27/2012	7.3	7.9	140.4	84	0.03
8	6/27/2012	5.5	7.1	141.2	81	0.03
9	6/27/2012	4.8	7.1	141.6	80	0.03
10	6/27/2012	6.0	6.2	144.0	80	0.03
11	6/27/2012	4.0	6.5	143.6	82	0.03
12	7/3/2012	2.0	4.9	146.4	82	0.02
13	7/3/2012	1.0	4.1	145.6	87	0.07

Figure F.5. Pump truck.

Figure F.6. Vibration brought fine material to the surface.

Figure F.7. Water being sprayed on surface.

Figure F.8. Hand finishing.

issues in the placement operation prompted the preparation of an inspection checklist (see Attachment D).

Method of Statistical Assessment

As part of the performance specification being developed, the performance parameters given in Table F.A.1 of Attachment A were evaluated. Two approaches were used to develop pay factors for the measured parameters. The VDOT approach is designed to measure compressive strength and permeability but was applied to all parameters. The other approach was developed by the R07 team for implementation under the design-build delivery approach. The SHRP 2 methodology features a higher reward to contractors for excellent work and a steeper penalty for poor quality work.

Developing Pay Factors Using VDOT Approach

This section presents VDOT's current process for end-result specifications (ERS). (See Ozyildirim, C. 2011. *End-Result Specifications for Hydraulic Cement Concrete: Phase II*. VCTIR 12-R2. Virginia Center for Transportation Innovation and Research, Charlottesville, Va.)

Acceptance Criteria

Acceptance for compressive strength and permeability is based on the Quality Index (Q). The Q uses both the average and the standard deviation within each lot to estimate the population parameters and determine the percentage of the lot within specification limits. The acceptable quality level (AQL) is that quality of concrete for which the contractor will receive 100%.

The rejectable quality level (RQL) is that quality of concrete requiring removal and replacement by the contractor or for which the contractor will provide remedial action. The AQL has been established at 90 percent within limits (PWL) and the RQL at 50 PWL. If the rejectable product can be corrected, it may be accepted upon correction, at the engineer's discretion.

The Q is calculated using the following equations:

$$Q_L = (\bar{X} - \mathrm{LSL})/s \qquad Q_U = (\mathrm{USL} - \bar{X})/s$$

where

Q_L = Lower Quality Index;
Q_U = Upper Quality Index;
$\bar{X}$ = average;
s = standard deviation;
LSL = lower specification limit shown in Table F.4; and
USL = upper specification limit shown in Table F.4.

Q_L is used for strength and Q_U shall be used for permeability.

Q_L and Q_U are used for the estimation of the lot PWL from tables. The PWL, in turn, is used to determine the pay factor through the appropriate pay factor equation.

Basis of Payment

a. When the PWL for the 28-day minimum design compressive strength and design maximum permeability of the lot is equal to or exceeds 50, the pay factor shall be determined by the following equation:

$$\text{Pay factor for individual properties} = 82 + 0.2(\text{PWL})$$

b. The lot pay factor is an average of the individual pay factors or can be a weighted average if any of the parameters need more emphasis.
c. To receive a pay factor greater than 100%, all individual properties shall be 90 PWL or more for all lots in the project.

The total pay quantity is determined by multiplying the average pay factor by the unit bid price and adding the price adjustment for deck thickness and ride quality.

Table F.4. Lower and Upper Specification Limits

Class of Concrete	LSL for Strength (psi)	USL for Permeability (coulombs)	USL for Permeability Over Tidal Water (coulombs)
A5 (prestressed)	5500	1200	1200
A4 (bridge)	4500	2200	1700
A3 (substructure)	3800	3200	1700

Table F.5. Pay Factors for SHRP 2 (%)

Percentage Within Limits (PWL)	Pay Factor
91–100	[0.006 * (PWL – 90)]
85–90	0.0
55–84	–0.9 + 0.01 * PWL

Developing Pay Factors Using SHRP 2 Approach

The SHRP 2 approach is also based on the PWL determined for each lot. The research team recommends that payments be based on pay adjustments determined by PWL calculations for each pay item. Pay factor adjustments reward the contractor for providing superior product and penalize the contractor for providing product that is of lower quality than specified. Pay adjustments can be calculated using the multipliers given below. For example, if 100% of the product is within limits, the pay adjustment is 0.06 = 6%.

Table F.5 lists the equations used to generate the pay factors on the basis of a given parameter's PWL.

Analysis of WBL

In the development of the performance specification for SHRP 2, construction parameters summarized in Table F.A.1 of Attachment A were included alongside material parameters (strength and permeability). The VDOT approach uses only the material properties of strength and permeability. For SHRP 2, the PWL approach was also applied to some of the construction parameters. In some cases, acceptance was based on pass/fail without the price adjustment.

Cracking. The concrete deck over every other pier had a formed joint; the concrete deck over the remaining piers (between the ones with formed joints) had continuous joints. Cracking was found on the deck over the joints that were continuous. The specification limit for cracking is a pass/fail parameter, requiring that no cracks be wider than 0.008 in. If cracks exceed the allowable width, repairs are to be made either by epoxy injection or gravity fill. Table F.6 shows the maximum cracks recorded above the piers without formed joints after placement. Because cracking is a pass/fail parameter, no distinction was made between the VDOT and SHRP 2 methods.

Cover Depth. Cover depth measurements were performed on hardened deck in December 2011. *Cover depth* refers to the depth of concrete above reinforcement. The distance from the concrete surface to the center of the reinforcing bar is specified as 2.75 in. Therefore, the cover depth, which is also the

Table F.6. Crack Data over Piers Without Formed Joints

Pier	Crack Width (in.)	Pass/Fail
12	0.0197	Fail
10	0.0158	Fail
8	0.0169	Fail
6	0.0091	Fail
4	none	Pass
2	0.0059	Pass

lower specification limit, is 2.4375 in., for No. 5 bars with ⅝-in. diameter used in the deck. The upper specification limit is the cover depth plus 1 in., which is 3.4375 in. Table F.7 shows the resulting pay factors for each span of the bridge using the VDOT approach, and Table F.8 shows the results using the SHRP 2 approach. Both methods indicate a penalty (<100% pay) for cover depth when both the USL and LSL are used in calculating the pay factors.

Rebar Location. Rebar location was inspected before the placement of concrete. The team decided that inspection is necessary and sufficient; and pay factor calculations using PWL are not needed.

Table F.7. Pay Factors for Cover Depth Using VDOT ERS Approach (%)

Span	LSL Pay Factor	USL Pay Factor	USL and LSL Pay Factor
1	102.00	101.83	101.83
2	101.99	98.82	98.80
3	101.93	100.26	100.20
4	102.00	101.95	101.95
5	101.91	101.08	100.99
6	101.98	101.98	101.96
7	100.26	101.95	100.21
8	100.73	101.41	100.14
9	99.39	102.00	99.39
10	96.79	102.00	96.78
11	97.54	102.00	97.54
12	95.34	102.00	95.34
13	101.04	102.00	101.04
Average	**100.22**	**101.48**	**99.71**

Table F.8. Pay Factors for Cover Depth Using SHRP 2 Approach (%)

Span	LSL Pay Factor	USL Pay Factor	USL and LSL Pay Factor
1	106.00	105.48	105.48
2	105.96	100.00	94.02
3	105.80	100.79	100.00
4	106.00	105.85	105.85
5	105.73	103.25	102.98
6	105.93	105.93	105.87
7	100.79	105.84	100.63
8	102.20	104.24	100.00
9	100.00	106.00	100.00
10	83.93	105.99	83.92
11	87.70	106.00	87.80
12	76.72	106.00	76.72
13	103.11	106.00	103.11
Average	**99.22**	**104.72**	**97.41**

Deck Thickness. Deck thickness measurements were taken during the placement of the deck concrete at the fresh state. The analysis was performed by determining the difference between the measured deck thickness and the target thickness at the ends, midspan, and quarter points at both sides of the beams. The lower specification limit for the difference between the two was -0.125 in. The upper limit was +0.25 in. Table F.9 shows the resulting pay factors, organized by span using the VDOT approach, and Table F.10 shows the results using the SHRP 2 approach. The pay factors indicate a penalty.

Compressive Strength. Compressive strength calculations were divided into two subgroups: samples collected before pumping from the truck on arrival and samples collected after pumping, immediately before consolidation. The lower specification limit for the 28-day compressive strength was 4500 psi. Table F.11 outlines the pay factor results using the VDOT approach, and Table F.12 shows the results using the SHRP 2 approach. The results were divided into four batches, one for each day of placement. The first two batches involved no pumping, so no pay factors after pumping are associated with those days. Pay factors for compressive strength using the VDOT ERS approach are given in Table F.11 and using the SHRP 2 approach in Table F.12. The pay factors provide for a bonus.

Permeability. Permeability calculations were divided into before-pumping and after-pumping subgroups, as for the

Table F.9. Pay Factors for Deck Thickness Using VDOT ERS Approach (%)

Span	LSL Pay Factor	LSL and USL Pay Factor
1	98.25	86.68
2	94.86	88.66
3	95.37	89.65
4	93.49	89.00
5	92.71	89.18
6	96.29	88.40
7	100.40	85.85
8	100.67	85.73
9	99.85	85.65
10	100.49	85.75
11	100.43	86.49
12	99.51	86.88
13	100.88	85.38
Average	**97.65**	**87.30**

compressive strength analysis. The upper specification limit for 28-day permeability is 2200 coulombs. Similar to the strength results, the permeability tests were divided into four batches, one for each day of placement. The first two batches involved no pumping, so no pay factors after pumping are associated with those days. Pay factors for permeability using the VDOT ERS approach are given in Table F.13 and using the SHRP 2 approach in Table F.14. The pay factors provide for a bonus.

Table F.10. Pay Factors for Deck Thickness Using SHRP 2 Approach (%)

Span	LSL Pay Factor	LSL and USL Pay Factor
1	91.25	33.42
2	74.31	43.42
3	76.84	48.24
4	67.46	45.00
5	63.55	45.89
6	81.44	41.99
7	101.19	29.25
8	102.00	28.63
9	100.00	28.24
10	101.48	28.73
11	101.29	32.47
12	99.51	34.40
13	102.64	26.91
Average	**89.459**	**35.88**

Table F.11. Pay Factors for Compressive Strength Using VDOT ERS Approach (%)

Before Pumping		After Pumping	
Batch	LSL Pay Factor	Batch	LSL Pay Factor
1	102	1	NA
2	102	2	NA
3	102	3	102
4	102	4	102
Average	**102**	**Average**	**102**

Air Content. Air content was measured as the truck arrived. The results were divided into two subgroups, before and after pumping. The lower specification limit for air content was 5%, and the upper specification limit was 8%. Pay factors for air content using the VDOT ERS approach are given in Table F.15 and using the SHRP 2 approach in Table F.16. The pay factors indicate a bonus based on as-delivered concrete but a penalty based on as-placed into the deck.

Smoothness. To be assessed.

Skid Resistance. To be assessed.

Cross Slope. Cross slope is difficult to measure and include in statistical analysis, especially in cases with super elevation. The team decided to consider it a pass/fail parameter. Result: pass. Cross slope in the middle (screed finished areas) portion of the placement was within the tolerances, as expected. However, along the edges where extensive hand finishing was performed, high and low spots were evident. High areas were ground. Low areas should be filled with epoxy mortar. Low

Table F.12. Pay Factors for Compressive Strength Using SHRP 2 Approach (%)

Before Pumping		After Pumping	
Batch	LSL Pay Factor	Batch	LSL Pay Factor
1	106	1	NA
2	106	2	NA
3	106	3	106
4	106	4	106
Average	**106**	**Average**	**106**

Table F.13. Pay Factors for Permeability Using VDOT ERS Approach (%)

Before Pumping		After Pumping	
Batch	**USL Pay Factor**	**Batch**	**USL Pay Factor**
1	102	1	NA
2	102	2	NA
3	102	3	102
4	102	4	102
Average	**102**	**Average**	**102**

Table F.14. Pay Factors for Permeability Using SHRP 2 Approach (%)

Before Pumping		After Pumping	
Batch	**USL Pay Factor**	**Batch**	**USL Pay Factor**
1	106	1	NA
2	106	2	NA
3	106	3	106
4	106	4	106
Average	**106**	**Average**	**106**

Table F.15. Pay Factors for Air Content Using VDOT ERS Approach (%)

Before Pumping		After Pumping	
Batch	**USL and LSL Pay Factor**	**Batch**	**USL and LSL Pay Factor**
1	102	1	NA
2	102	2	NA
3	102	3	88.868
4	102	4	101.130
Average	**102**	**Average**	**95.00**

Table F.16. Pay Factors for Air Content Using SHRP 2 Approach (%)

Before Pumping		After Pumping	
Batch	**USL and LSL Pay Factor**	**Batch**	**USL and LSL Pay Factor**
1	106	1	NA
2	106	2	NA
3	106	3	66.604
4	106	4	103.40
Average	**106**	**Average**	**85.00**

areas are shown as dips in attachment tables F.B.1, F.B.2, and F.C.1. Dips were measured at three locations—at each of the joints, middle, and quarter points—and recorded if they were ¼ in. or more.

Joint Condition. Joint condition is a pass/fail parameter. Result: pass.

Analysis of EBL

Cracking. As in the WBL, the concrete deck over every other pier had a formed joint; the concrete deck over the remaining piers (between the ones with formed joints) had continuous joints. Very limited cracking was found in the deck at the joints that were continuous. Table F.17 shows the maximum cracks recorded above the piers without the formed joints after placement.

Cover Depth. Cover depth measurements were performed on the hardened deck in August and September 2012. The lower specification limit is 2.4375 in., and the upper specification limit is 3.4375 in. for this deck. Table F.18 shows the resulting pay factors for each span of the bridge using the VDOT approach, and Table F.19 shows the results using the SHRP 2 approach.

Rebar Location. Rebar location was inspected and approved before the placement of concrete.

Deck Thickness. Deck thickness measurements were not calculated for the EBL.

Compressive Strength. Pay factors for compressive strength are given in Table F.20 for the VDOT approach and Table F.21 for the SHRP 2 approach. All pay factors indicate a bonus.

Permeability. Pay factors for permeability are given in Table F.22 for the VDOT approach and Table F.23 for the SHRP 2 approach. All pay factors indicate a bonus.

Table F.17. Crack Data over Piers Without Formed Joints

Pier	Crack Width (in.)	Pass/Fail
12	none	Pass
10	none	Pass
8	none	Pass
6	.0098	Fail
4	.0098	Fail
2	none	Pass

Table F.18. Pay Factors for Cover Depth Using VDOT ERS Approach (%)

Span	LSL Pay Factor	USL Pay Factor	LSL and USL Pay Factor
1	101.19	101.06	100.25
2	92.39	102.00	92.39
3	94.69	102.00	94.69
4	95.56	101.79	95.35
5	0.00	102.00	91.30
6	100.49	101.86	100.36
7	100.46	101.73	100.20
8	95.84	102.00	95.84
9	97.30	101.70	96.99
10	94.91	101.91	94.81
11	97.78	101.46	97.24
12	95.91	101.06	94.97
13	100.01	101.46	99.47
Average	**89.73**	**101.69**	**96.45**

Table F.19. Pay Factors for Cover Depth Using SHRP 2 Approach (%)

Span	LSL Pay Factor	USL Pay Factor	LSL and USL Pay Factor
1	103.57	103.19	100.76
2	61.95	106.00	61.95
3	73.43	106.00	73.43
4	77.79	105.38	76.75
5	56.49	106.00	56.49
6	101.48	105.59	101.07
7	101.39	105.20	100.00
8	79.20	106.00	79.20
9	86.48	105.09	84.96
10	74.54	105.72	74.07
11	88.90	104.37	86.19
12	79.55	103.19	74.86
13	100.00	104.37	100.00
Average	**83.44**	**105.08**	**82.29**

Table F.20. Pay Factors for Compressive Strength Using VDOT ERS Approach (%)

Before Pumping		After Pumping	
Batch	USL Pay Factor	Batch	USL Pay Factor
1		1	
2		2	
3	102	3	102
4		4	
5		5	
6		6	
7	102	7	102
8		8	
9		9	
10		10	
11	102	11	102
12		12	
13		13	
Average	**102**	**Average**	**102**

Table F.21. Pay Factors for Compressive Strength Using SHRP 2 Approach (%)

Before Pumping		After Pumping	
Batch	USL Pay Factor	Batch	USL Pay Factor
1		1	
2		2	
3	106	3	106
4		4	
5		5	
6		6	
7	106	7	106
8		8	
9		9	
10		10	
11	106	11	106
12		12	
13		13	
Average	**106**	**Average**	**106**

Table F.22. Pay Factors for Permeability Using VDOT ERS Approach (%)

Before Pumping		After Pumping	
Batch	**LSL Pay Factor**	**Batch**	**LSL Pay Factor**
1		1	
2		2	
3	102	3	102
4		4	
5		5	
6		6	
7	102	7	102
8		8	
9		9	
10		10	
11	102	11	102
12		12	
13		13	
Average	**102**	**Average**	**102**

Table F.23. Pay Factors for Permeability Using SHRP 2 Approach (%)

Before Pumping		After Pumping	
Batch	**LSL Pay Factor**	**Batch**	**LSL Pay Factor**
1		1	
2		2	
3	106	3	106
4		4	
5		5	
6		6	
7	106	7	106
8		8	
9		9	
10		10	
11	106	11	106
12		12	
13		13	
Average	**106**	**Average**	**106**

Table F.24. Pay Factors for Air Content Using VDOT ERS Approach (%)

Before Pumping		After Pumping	
Batch	**USL and LSL Pay Factor**	**Batch**	**USL and LSL Pay Factor**
1		1	
2		2	
3	98.79	3	94.61
4		4	
5		5	
6		6	
7	102	7	95.93
8		8	
9		9	
10		10	
11	98	11	94.53
12		12	
13		13	
Average	**98.60**	**Average**	**95.03**

Air Content. Pay factors for air content are given in Table F.24 for the VDOT approach and Table F.25 for the SHRP 2 approach. All pay factors indicate a penalty.

Smoothness. To be assessed.

Skid Resistance. To be assessed.

Cross Slope. Cross slope is a pass/fail parameter. Result: pass. Cross slope in the middle (screed finished areas) portion of the placement was within the tolerances, as expected. However, along the edges where extensive hand finishing was performed, high and low spots were evident. High areas were ground. Low areas should be filled with epoxy mortar. Low areas are shown as dips in attachment tables F.B.1, F.B.2, and F.C.1. Dips were measured at three locations—at each of the joints, middle, and quarter points—and recorded if they were ¼ in. or more.

Joint Condition. Joint condition is a pass/fail parameter. Result: pass.

Summary of WBL and EBL Analyses

Tables F.26 and F.27 outline the average pay factor for each category. The single-tail analyses of cover depth and deck thickness are less restrictive than the two-tailed analyses.

Table F.25. Pay Factors for Air Content Using SHRP 2 Approach (%)

Before Pumping		After Pumping	
Batch	USL and LSL Pay Factor	Batch	USL and LSL Pay Factor
1	93.93	1	73.07
2		2	
3		3	
4		4	
5		5	
6	106	6	79.67
7		7	
8		8	
9		9	
10	90	10	72.67
11		11	
12		12	
13		13	
Average	**96.64**	**Average**	**75.14**

All of the pumping-dependent parameters fully met the requirements before pumping. As previously mentioned, the rewards are higher and the penalties steeper with the SHRP 2 approach. The SHRP 2 approach proved especially harsh when assessing deck thickness, giving a pay factor of only 35.88%.

Table F.26. Pay Factor Averages for WBL and EBL Using VDOT ERS Approach (%)

Parameter	LSL and USL Pay Factor	
Cover depth	98.08	
Deck thickness	87.30	
Average	**92.69**	
Parameter	**Before Pumping**	**After Pumping**
Compressive strength	102	102
Permeability	102	102
Air content	100.3	95.02
Average	**101.43**	**99.67**

Table F.27. Pay Factor Averages for WBL and EBL Using SHRP 2 Approach (%)

Parameter	LSL and USL Pay Factor
Cover depth	89.85
Deck thickness	35.88*
Average	**62.87**

*Either rejected or accepted at 50%.

Parameter	Before Pumping	After Pumping
Compressive strength	106	106
Permeability	106	106
Air content	101.32	80.07
Average	**105.06**	**100.81***

*Air content is weighted 0.5.

Conclusion

The research team drew the following conclusions from the examination of the SHRP 2 performance specification as a shadow specification for the Lake Anna bridge project:

- Cover depth, thickness, compressive strength, and air content after pumping resulted in a disincentive using both the VDOT and SHRP 2 approaches. The penalty for cover depth and thickness was more severe but the compressive strength after pumping was less severe using the SHRP 2 approach.
- Compressive strength and air content before pumping resulted in an incentive using both the VDOT and SHRP 2 approaches. The bonus was larger for the SHRP 2 approach.
- The bonus and penalty will depend on the equations chosen for the pay factors.
- Pay factors can be used to encourage contractors to do better quality work.

One important lesson drawn from these conclusions is that agencies interested in implementing performance specifications, particularly for the first time, should exercise care in setting limits for parameters and adjusting payment formulas to balance targeted performance with what industry can reasonably achieve.

Another important lesson learned from this demonstration project was that workmanship issues can have a large effect on performance outcomes, and such issues may not necessarily be addressed or identified through the use of performance parameters measured through end-result testing. The team developed a checklist, included in Attachment D—which addresses transportation and handling, preplacement and placement inspection, and postplacement inspection—for use as a companion document with the guide specification.

Attachment A: Performance Parameters

Table F.A.1. Performance Parameters

Parameter	Measurement Procedure	Target/Lot Requirements	Tolerance/Quality Acceptance Limits
Cracking	Cracks measured at 3-ft intervals on the surface of the deck in the 3 hours after sunrise at a concrete age ≥ 28 days.	No crack wider than 0.008 inches	Repair wider cracks. Pattern: gravity fill Linear: epoxy injection
Cover depth	Probing fresh concrete or calibrated NDT (e.g., pacometer, GPR).	≥ specified cover depth (CD) Measure on 10 ft grid	PWL 85% full payment LQL = CD UQL = CD + 1.0-in.
Rebar location	Measure from reference surface	± 0.5-inch on rebar placement Measure on 10 ft grid	Pass/Fail
Thickness (fresh)	Probe	ACI recs. + ¼-in. to –⅛ in. Measure on 10-ft grid	PWL 85% full payment LQL = T – ⅛ in. UQL = T + ¼ in.
Compressive strength (design)	Cylinders: ASTM C39 (Consider accommodating referee testing from cores.)	Design strength:. min. of 5 tests per lot. At least one sublot per day. Note: more tests may be requested (and are desirable). One test = three 4-in. by 8-in. cylinders or two 6-in. by 12-in. cylinders	PWL: 85% = full payment LQL = DS + 300 psi
Compressive strength (opening to traffic)	Maturity: ASTM C1074 (or field-cured specimens)	Specified strength (min.): min. five tests per lot, at least one sublot per day Specimens: One test = three 4-in. by 8-in. cylinders or two 6-in. by 12-in. cylinders	Pass or apply lane rental penalties
Permeability (job-site testing)	ASTM C1202 (accelerated test) Referee testing from cores	2000 coulombs (max.) at 28 days Min. five tests per lot, at least one sublot per day One test = three cylinders (2-in. high by 4-in. diameter cut from 4-in. by 4-in. or 4-in. by 8-in. cylinders)	PWL: 85% = full payment UQL = 2000 PWL: <80% = penalty or apply sealer PWL: <70% = penalty or apply epoxy overlay PWL: <50% = reject or apply concrete overlay
Permeability (mix design submittal)	ASTM C1202 (accelerated test)	1500 coulombs (max.) at 28 days	Pass or resubmit mix design
Air content	ASTM C231	Specified	PWL: 85% = full payment LQL and UQL specified
Smoothness	Profilometer-based specification (continuous IRI)	80 in./mi with 100-ft base length	PWL: 85% = full payment (see histogram from ProVAL Smoothness Assurance Module) UQL = 80 in./mi#
Skid resistance	ASTM E274, ASTM E524	FN40S ≥ 40 Average per lane	PWL: 85% = full payment LQL = 40
Cross slope	Elevation	Plans ± ⅛ in.	Pass/fail
Joint condition	Vertical setting (depth) Gap vs temperature (width) Visual/survey	Plans ± ⅛ in. Plans ± ⅛ in. Proper installation	Pass/fail Pass/fail Pass or replace

Attachment B: WBL

Table F.B.1. Cover Depth Data

Parapet	Dips[a] (in.)	Beam 1/A	Beam 2/B	Beam 3/C	Dips[a] (in.)	Barrier	
		3.05	**2.85**	**3.10**		**Pier**	**Abut. B**
	0.250	2.75	3.05	2.80		Q 2	
	0.750	3.05	2.90	3.05	0.250	M	
	0.875	3.25	3.05	2.90	0.625	Q 1	
		3.10	3.40	3.30		Joint 0	**Pier 12**
	0.875				0.375	Joint	
		3.20	3.25	3.15	1.000	Q 2	
		2.85	2.90	3.00	0.500	M	
		3.50	2.90	2.80	0.500	Q 1	
		3.60	**3.60**	**2.95**		Pier	**11**
	0.250	**3.35**	**3.55**	**3.10**		Pier	
	0.250	3.35	3.20	2.75	0.250	Q 2	
		3.00	3.20	2.80	0.625	M	
	0.250	3.30	3.20	2.70	0.250	Q 1	
					0.250	Joint 0	**Pier 10**
	0.250	2.70	3.15	2.85	0.375	Joint	
	0.250	3.05	3.00	2.90	0.375	Q 2	
	0.500	3.05	2.90	2.90	1.000	M	
	0.500	2.85	3.00	2.95	0.375	Q 1	
		2.90	**3.40**	**3.30**	0.500	Pier	**9**
		3.25	**3.30**	**3.15**		Pier	
		3.20	3.20	3.10		Q 2	
		3.25	3.20	3.05	0.250	M	
		2.80	3.05	2.95	0.500	Q 1	
						Joint 0	**Pier 8**
	0.250	2.45	2.85	2.60	0.375	Joint	
		3.10	2.95	2.80		Q 2	
		3.25	3.05	2.95	0.250	M	
		2.75	3.00	2.75		Q 1	
		2.50	**3.00**	**2.75**	0.250	Pier	**7**
		2.95	**2.65**	**2.50**		Pier	
		3.00	3.15	2.50		Q 2	

(continued on next page)

Table F.B.1. Cover Depth Data (continued)

Parapet	Dips[a] (in.)	Beam 1/A	Beam 2/B	Beam 3/C	Dips[a] (in.)	Barrier	
	0.375	2.35	2.95	2.45	0.250	M	
	0.625	2.90	3.00	2.75		Q 1	
						Joint 0	**Pier 6**
		2.65	3.20	2.85		Joint	
		3.00	3.00	2.85		Q 2	
		3.00	3.10	2.90		M	
		2.95	3.00	2.75		Q 1	
		2.00	**3.35**	**2.75**	0.250	Pier	**5**
		2.35	**2.75**	**2.35**		Pier	
	0.375	2.70	2.95	2.90		Q 2	
	0.500	2.75	2.50	2.65		M	
	0.625	2.65	2.40	2.70		Q 1	
						Joint 0	**Pier 4**
	0.375	2.60	2.60	2.75		Joint	
	0.750	2.70	2.20	2.45	0.250	Q 2	
		2.80	2.55	2.50		M	
	0.250	2.60	2.70	2.05		Q 1	
		2.65	**3.25**	**2.85**		Pier	**3**
	0.250	**2.75**	**2.85**	**2.50**		Pier	
		2.60	2.80	2.40		Q 2	
		2.85	2.65	2.40		M	
		2.55	2.90	2.30		Q 1	
						Joint 0	**Pier 2**
		2.70	2.75	2.15		Joint	
		2.20	2.75	2.15		Q 2	
	0.250	2.80	2.85	2.30		M	
		2.95	2.75	2.35		Q 1	
		2.55	**2.75**	**2.40**		Pier	**1**
		2.70	**3.15**	**2.75**		Pier	
		2.55	2.95	2.95		Q 2	
		2.90	2.85	2.65	0.500	M	
		2.65	2.70	2.70		Q 1	
		3.05	2.65	2.35		Joint 0	**Abut. A**

[a] Dips are low spots on deck with a depth of ¼ in. or more.

Table F.B.2. Average, Standard Deviation, and the Number of Dips

Span	Average	Standard Deviation	No. < 2.4375 in.	No. of Dips
13	3.04	0.182	0	5
12	3.17	0.270	0	5
11	3.08	0.267	0	7
10	2.99	0.180	0	9
9	3.03	0.252	0	2
8	2.85	0.224	0	4
7	2.79	0.263	1	3
6	2.89	0.304	1	1
5	2.64	0.180	3	3
4	2.62	0.276	2	4
3	2.61	0.223	4	1
2	2.56	0.275	6	1
1	2.77	0.206	1	1
Sum			18	46
Average	**2.849**	**0.239**	**1.38**	**3.538**

Note: N = 15, Specified cover depth = 2.4375 in.

Table F.B.3. Pay Factors for Cover Depth Using Only LSL and Using Both LSL and USL (%)

QUL	USL PWL	USL Pay Factor	QLL	LSL PWL	LSL + USL – 100	Pay Factor
2.18	99.13	101.83	3.30	100.00	99.13	101.83
1.00	84.09	98.82	2.70	99.93	84.02	98.80
1.34	91.31	100.26	2.41	99.67	90.98	100.20
2.47	99.75	101.95	3.09	100.00	99.75	101.95
1.63	95.42	101.08	2.34	99.55	94.97	100.99
2.62	99.89	101.98	1.84	99.89	99.78	101.96
2.46	99.74	101.95	1.34	91.31	91.05	100.21
1.80	97.06	101.41	1.49	93.66	90.72	100.14
4.42	100.00	102.00	1.12	86.95	86.95	99.39
2.98	99.99	102.00	0.65	73.93	73.92	96.78
3.71	100.00	102.00	0.77	77.70	77.70	97.54
3.19	100.00	102.00	0.44	66.72	66.72	95.34
3.24	100.00	102.00	1.61	95.19	95.19	101.04
Average	**97.41**	**101.48**		**91.12**	**88.53**	**99.71**

Table F.B.4. Analysis of Compressive Strength and Permeability

Batch	Data		Average				Standard Deviation			
			Before Pumping		After Pumping		Before Pumping		After Pumping	
	Strength	Perm.	Strength	Perm.	Strength	Perm.	Strength	Perm.	Strength	Perm.
1	6190	1129	6040	1197	N/A	N/A	132.3	66.1	N/A	N/A
2	5990	1261								
3	5940	1202								
1	6190	1030	6087	1166	N/A	N/A	179.0	118.8	N/A	N/A
2	5880	1248								
3	6190	1221								
1	6540	1010	6110	1247	5683	1123	563.2	158.3	746.7	119.8
1P	4790	1099								
2	5460	1331								
2P	5920	1026								
3	6620	1309								
3P	6560	1070								
4	5820	1337								
4P	5460	1297								
1	5130	1136	5533	967	5420	890	296	128.5	273.8	46.3
1P	5185	920								
2	5610	970								
2P	5320	879								
3	5840	825								
3P	5815	931								
4	5550	938								
4P	5360	829								

Attachment C: EBL

Table F.C.1. Cover Depth Data

Parapet	Dips[a] (in.)	Beam 1/A	Beam 2/B	Beam 3/C	Dips[a] (in.)	Barrier	
	0.2500	2.70	3.10	2.85		Joint	**Abut. B**
	0.2500	2.80	2.80	3.45	0.1875	Q 2	
	0.2500	2.75	2.50	3.10	0.2500	M	
	0.3125	2.25	2.70	3.05	0.1875	Q 1	
	0.2500	2.40	3.25	3.00	0.3125	Pier	**Pier 12**
	0.2500	**2.40**	**3.25**	**3.00**	**0.3125**	Pier	
	0.1250	2.55	2.75	2.65	1.0000	Q 2	
	0.2500	1.90	2.35	2.95	0.7500	M	
	0.2500	1.80	2.55	3.15	0.1250	Q 1	
	0.2500	2.40	3.25	3.25	0.1250	Joint 0	**11**
	0.1250	2.60	3.15	3.20	0.2500	Joint	
	0.2500	2.60	2.90	3.30	0.2500	Q 2	
	0.1250	2.50	2.45	3.15	0.5000	M	
	0.1875	2.30	2.65	2.75	0.7500	Q 1	
	0.1875	1.90	2.80	2.90	0.1250	Pier	**Pier 10**
	0.1875	**1.90**	**2.80**	**2.90**	**0.1250**	Pier	
	0.2500	2.10	2.70	2.65	0.0625	Q 2	
	0.3125	1.85	2.55	2.75	0.0625	M	
	0.3750	2.35	2.65	2.85	0.2500	Q 1	
	0.2500	2.60	3.00	3.00	0.1250	Joint 0	**9**
	0.2500	2.95	3.15	2.65	0.2500	Joint	
	0.4375	2.85	2.85	3.20	0.3750	Q 2	
	0.2500	2.10	2.80	2.60	0.1875	M	
	0.3125	2.05	2.85	2.90	0.1250	Q 1	
	0.3125	2.20	3.00	2.40	0.0625	Pier	**Pier 8**
	0.3125	**2.20**	**3.00**	**2.40**	**0.0625**	Pier	
	0.5000	2.45	2.85	2.85	0.3750	Q 2	
	0.3125	2.15	2.65	2.70		M	
	0.3125	2.20	2.60	2.80	0.1875	Q 1	
	0.2500	2.30	2.90	2.65	0.1875	Joint 0	**7**
	0.2500	3.00	3.15	2.75	0.1250	Joint	
	0.2500	2.45	2.95	2.65	0.1250	Q 2	
	0.1875	2.65	2.75	2.85	0.1875	M	
	0.3125	2.40	3.05	3.05	0.1250	Q 1	

(continued on next page)

Table F.C.1. Cover Depth Data (continued)

Parapet	Dips[a] (in.)	Beam 1/A	Beam 2/B	Beam 3/C	Dips[a] (in.)	Barrier	
	0.3750	2.50	3.45	3.00	0.3750	Pier	**Pier 6**
	0.3750	**2.50**	**3.45**	**3.00**	**0.3750**	Pier	
	0.5000	2.50	3.00	2.80	0.5000	Q 2	
		2.80	2.60	2.60		M	
	0.3750	2.80	2.90	2.55		Q 1	
		2.90	3.25	2.70	0.1250	Joint 0	**5**
	0.5000	2.50	3.10	2.50	0.2500	Joint	
	0.2500	2.20	2.65	2.45	0.2500	Q 2	
	0.3125	2.25	2.35	2.50	0.3125	M	
	0.1875	2.15	2.60	2.60	0.2500	Q 1	
	0.3125	1.80	2.55	1.95	0.1875	Pier	**Pier 4**
	0.3125	**1.80**	**2.55**	**1.95**	**0.1875**	Pier	
	0.3125	2.50	2.70	2.75	0.2500	Q 2	
	0.2500	2.65	2.40	2.50	0.5000	M	
	0.2500	2.80	2.80	2.65	0.1875	Q 1	
	0.1250	3.00	3.40	2.80	0.2500	Joint 0	**3**
		2.50	2.75	2.75	0.2500	Joint	
	0.1250	2.50	2.90	2.45	0.1250	Q 2	
	0.1875	2.25	2.55	2.55	0.3125	M	
	0.2500	2.10	2.60	2.45	0.3750	Q 1	
	0.1250	2.35	2.80	2.25	0.2500	Pier	**Pier 2**
	0.1250	**2.35**	**2.80**	**2.25**	**0.2500**	Pier	
	0.1250	2.25	2.55	2.35	0.0625	Q 2	
	0.1250	2.00	2.65	2.40	0.3125	M	
	0.2500	2.10	2.80	2.00	0.1875	Q 1	
	0.5000	2.70	3.10	2.50	0.1875	Joint 0	**1**
	0.1250	2.65	3.60	2.85	0.1250	Joint	
	0.3125	2.60	3.10	2.90	0.1250	Q 2	
	0.3125	2.65	2.85	2.75	0.1875	M	
	0.3125	3.05	3.00	2.85	0.1250	Q 1	
	0.1250	3.50	3.20	2.65		Joint 0	**Abut. A**

[a] Dips are low spots on deck with a depth of ¼ in. or more.

Table F.C.2. Analysis of Compressive Strength and Permeability

			Before Pumping		After Pumping		Before Pumping		After Pumping	
	Data		Average				Standard Deviation			
Span	Strength	Perm.	Strength	Perm.	Strength	Perm.	Strength	Perm.	Strength	Perm.
1	7150	720	6908.00	833.40	6866.00	828.60	497.21	97.23	325.32	51.08
1P	7210	808								
2	7130	959								
2P	7150	844								
3	7310	905								
3P	6900	904								
4	6060	808								
4P	6490	822								
5	6890	775								
5P	6580	765								

Note: Number of sublots = 5: one set from truck and the second set after the pump (P).

6	6650	649	6527.50	700.25	6520.00	754.00	395.84	86.53	521.47	122.22
6P	7170	623								
7	5940	610								
7P	6320	682								
8	6730	800								
8P	5940	886								
9	6790	742								
9P	6650	825								

Note: Number of sublots = 4: one set from truck and the second set after the pump (P).

10	6770	551	7342.50	694.25	7352.50	673.25	450.29	110.73	613.32	73.45
10P	6620	586								
11	7390	663								
11P	7670	656								
12	7340	776								
12P	7110	688								
13	7870	787								
13P	8010	763								

Note: Number of sublots = 4: one set from truck and the second set after the pump (P).

Attachment D: Inspection Checklist Hydraulic Cement Concrete Deck

Part 1: Preplacement Inspection					
Issue	**Yes**	**No**	**N/A**	**Comments**	**Initials**
A. Forms					
i. Are forms tight, sturdy, and clean?					
ii. Are the joints formed with compressible material? *Use of incompressible material may cause delaminations due to the restraint of the incompressible material kept too long in the joint.*					
B. Reinforcement					
i. Are the bar size and spacing correct?					
ii. Is the reinforcement properly supported?					
iii. Are bar splices correct?					
iv. Is the reinforcement clean (i.e., no rust other than mill scale; no oil, concrete, or other materials)?					
v. Is the type of reinforcement correct? *Is it black steel or corrosion-resistant reinforcement?*					
C. Shear Studs					
i. Are the shear stud spacing and height as specified?					
D. Equipment (Verify the following are on site and in working condition.)					
i. Are the trucks clean with blades in good condition, and is there proof of inspection for each truck?					
ii. Is the screed set properly to provide the specified crown and grade?					
(a) Does the screed have a vibrating unit complying with the specs?					
(b) Is there a burlap drag attached to the screed? *Burlap shall be kept wet during placement.*					
iii Are there backup vibrators onsite?					
(a) Do the frequency and amplitude of vibrators comply with the specs?					
iv. Does the pump have enough clean lines?					
v. Is the mobile mixer calibrated?					
vi. Does the concrete testing equipment comply with the specs, and is it calibrated?					
vii. Is there a curing box with a recording thermometer? *Continuous temperature data that can be printed are needed to ensure that short spikes because of opening the lid do not invalidate the result.*					
E. Aggregate Storage					
i. Is there an individual stockpile for each aggregate? *To achieve the specified gradation and minimize segregation individual stockpiles are needed.*					
ii. Are aggregates stored on concrete slabs to prevent mixing with soil? *Mixing with soil is an unacceptable practice (UP) because the soil will leave mud holes in the concrete.*					
iii. Are the aggregates kept moist by sprinklers? *Aggregates must be maintained in a moist condition to control the water content and temperature of the concrete.*					

(continued on next page)

Attachment D (continued)

Issue	Yes	No	N/A	Comments	Initials
iv. Is the aggregate moisture content checked daily at least once by the gravimetric method? *If the moisture condition of aggregates is not properly controlled, fresh and hardened concrete properties can be adversely affected.*					
F. Contingency Plan: Is there a contingency plan for equipment breakdown and inclement weather?					
G. Trial Batches: Are trial batches completed, and are the results submitted and approved?					
Part 2: Placement Inspection					
A. Light: Is there sufficient light in the work area?					
B. Certified Personnel					
i. Is there a certified technician responsible for placement?					
ii. Is there a certified technician responsible for admixture adjustments in the field?					
iii. Is there a certified technician responsible for sampling and testing the concrete?					
C. Formwork: Is the formwork surface treated? *Forms should be wetted or oiled since dry forms can remove water from the mixture, affecting workability and hydration.*					
D. Concrete Transportation and Handling					
i. Is the concrete deposited using a chute? *If deposited using other than a chute, indicate how (bucket, pump, belt). Aluminum chutes or lines are not permitted due to the formation of gas.*					
ii. Does the first load of concrete have the proper documentation? *VDOT requires Form TL-28a.*					
iii. Is concrete protected against wind, rain, hot and cold conditions?					
iv. Is water added after batching? *Extra water during transit or at the jobsite beyond the design amount adversely affects strength and durability.*					
v. Is the concrete delivered within the allowable time and mixing revolution? *The time limit can be waived if the proper admixtures are used. The maximum number of revolutions can be waived if the concrete is workable and sound aggregates are used.*					
E. Inspection of Concrete Placement and Consolidation					
i. Is concrete placed as close as possible to the final location in the structure? *Moving concrete can cause segregation.*					
ii. Is the concrete distributed evenly rather than piling up in any area of the form? *Moving piles of concrete can cause segregation.*					
iii. Is concrete placed against a previously placed fresh concrete batch? *If concrete is deposited as separate piles, trying to combine them would require moving the concrete, which can cause segregation. In addition, leaving the surface of the concrete uncovered for a long time could cause drying of the surface, leading to cold joints.*					

(continued on next page)

Attachment D (continued)

Issue	Yes	No	N/A	Comments	Initials
iv. Is the concrete free from segregation? *Segregation causes aggregates to pile up in an area, leading to lower strength. The areas rich in paste and mortar shrink more, which can cause cracking.*					
v. Is concrete prevented from hitting reinforcing bars and segregating? *Segregation adversely affects strength and durability.*					
vi. Is concrete dropped more than 5 feet? *Significant drops can cause segregation.*					
vii. If concrete is dropped, are there drop chutes or tremie to direct the fall? *Dropping concrete on reinforcement can cause segregation.*					
viii. Is there an undue time delay in depositing the concrete? *A time delay can cause cold joints, which may separate and facilitate infiltration of harmful solutions.*					
ix. Is the concrete covered when delays occur? *Covering with wet burlap and plastic is needed to prevent drying. Drying results in reduced workability, requiring that water be added or sprayed on the surface.*					
x. Is concrete moved by vibrators? *Moving would cause segregation.*					
xi. Are vibrators inserted in a grid pattern? *Full coverage and insertion within 1.5 times the radius of action of the vibrator in a grid pattern are needed.*					
xii. Is vibration causing segregation (excessive mortar brought to the surface)? *Excessive mortar provides a weak layer prone to wear and cracking.*					
xiii. Are vibrators inserted vertically?					
Vertical insertion is needed except in thin slabs where vibrators can be inserted at an angle or horizontally.					
xiv. Is concrete spaded or vibrated along forms and joints? *Proper consolidation in those areas is needed.*					
xv. Is free fall prevented during pumping? *Free fall should be avoided, and concrete should be pumped continuously to minimize loss in air content and slump.*					
F. Inspection of Leveling and Screeding Operations					
i. Is the screed support sufficient to maintain line and grade?					
ii. Is there enough concrete rolling in front of the rollers? *Concrete must be rolling in front of the rollers to ensure correct profile and vibration.*					
iii. Is there only a moderate amount of paste or mortar on the surface of the concrete after screeding? *Excess mortar reduces strength and durability.*					
G. Inspection of Finishing Operations					
i. Is water sprayed on the concrete surface before the screed? *Water sprayed before the screed as a finishing aid is an UP. Extra water sprayed will increase the water-cementitious material ratio, reducing strength and durability.*					

(continued on next page)

Attachment D (continued)

Issue	Yes	No	N/A	Comments	Initials
ii. Is any hand finishing moderate? *Extensive hand finishing is an UP. It brings fine material to the surface, reduces air voids, changes the profile (low spots), and delays the curing operation.*					
iii. Are low areas present? *Low areas will hold water, reduce surface traction, and increase freeze-thaw deterioration.*					
H. Inspection of Curing					
i. Is concrete surface after the screeding sprayed with water? *Too much water can increase the water-cementitious material ratio, reducing strength and durability. Fog misting is encouraged to reduce the rate of evaporation.*					
ii. Is the burlap wet and applied in a timely manner? *Right after screeding, wet (but not dripping) burlap should be placed. Delay in burlap application increases the chance of surface drying that can lead to cracking.*					
iii. Is the burlap kept wet during the curing period? *After the setting of the concrete, burlap should be kept wet with a soaker hose or plastic or should be ponded with water to prevent loss of surface moisture that may lead to cracking.*					
iv. Are specimens placed in a curing box immediately after casting?					
v. In cold weather, are the forms prewarmed? *The concrete temperature should be kept above a particular temperature for proper hydration.*					
vi. Are the aggregates kept from freezing? *Frozen aggregates stick together and cause a temperature differential within the concrete, leading to cracking.*					
vii. In hot weather, are the ingredients cooled? *High concrete temperatures accelerate concrete hydration, adversely affecting workability.*					
viii. Is flaked or shaved ice used? *Flaked or shaved ice should be used since large ice particles could leave voids within the concrete.*					
ix. Is the rate of evaporation within the spec limit? *High evaporation rates cause great loss of surface moisture, leading to cracking.*					
Part 3: Post-placement Inspection					
A. Inspection of Concrete Moist Curing					
i. Are there daily checks to ensure that the wet burlap stays wet? *Keeping concrete wet during the curing period is essential for the development of concrete properties and for minimizing the dimensional changes that can cause cracking.*					
ii. Is the curing compound used properly? *Approved curing compound must be applied immediately and with good coverage as the water sheen is disappearing in order to retain the moisture and reflect the sunlight.*					
iii. Is the concrete temperature monitored during the curing period? *A favorable temperature is essential for the hydration reaction and to minimize volumetric changes caused by a temperature differential that may cause cracking.*					

(continued on next page)

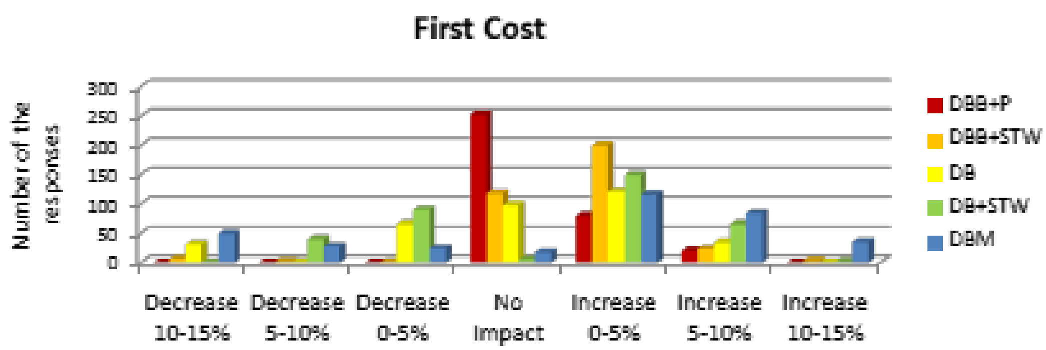
Attachment D (continued)

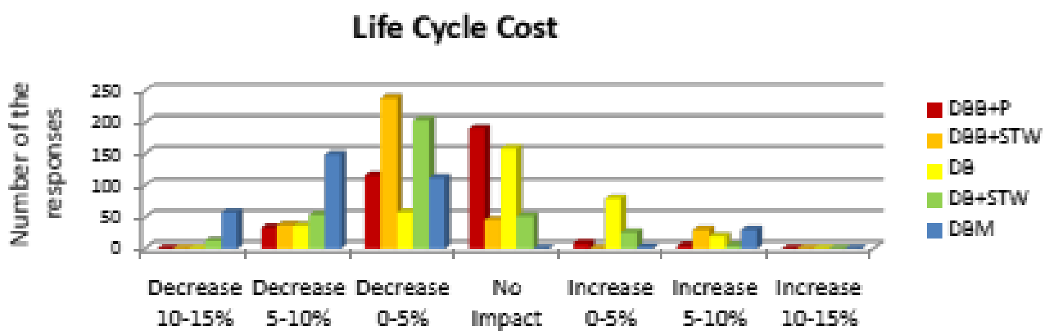
Issue	Yes	No	N/A	Comments	Initials
B. Checking of Joints: Is each joint checked for alignment, removal of temporary formwork, and workmanship? *Joints are critical locations that require proper placement and consolidation; after hardening, the temporary formwork must be removed promptly so that the expanding concrete has room to expand and does not delaminate the joint area.*					
C. Checking for Low Spots: Is the surface checked for low spots? *Low spots hold water and keep concrete saturated, which adversely affects durability and traction.*					
D. Freeze Protection: Is the concrete protected against freezing? *Concrete frozen at the fresh state will have voids; concrete frozen at the hardened state will have freeze/thaw cracking.*					

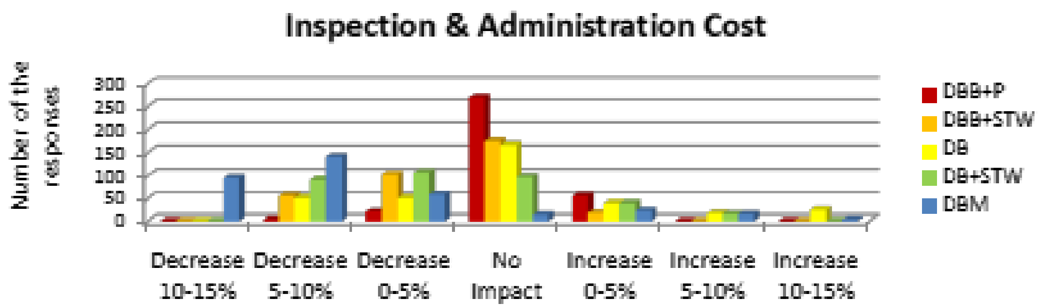
APPENDIX G

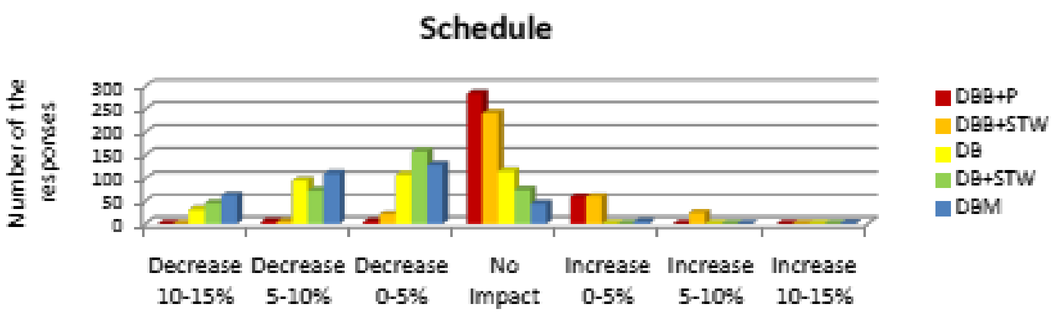
Delphi Survey Round 2 Results

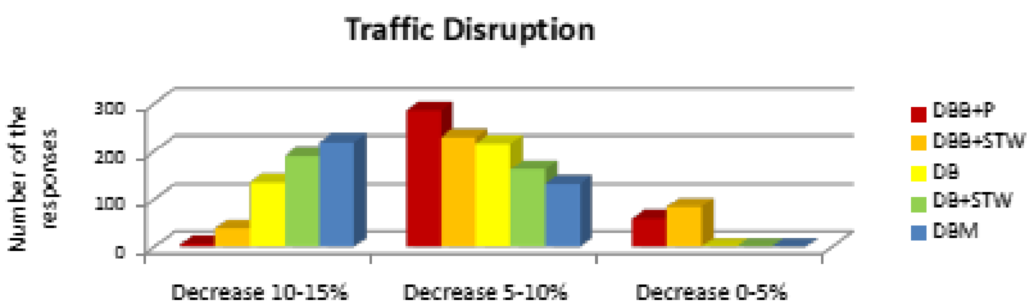
Round 2 Survey Results: Aggregate Results






Inspection & Administration Cost
Number of the responses
300
250
200
150
100
50
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB+P
DBB+STW
DB
DB+STW
DBM

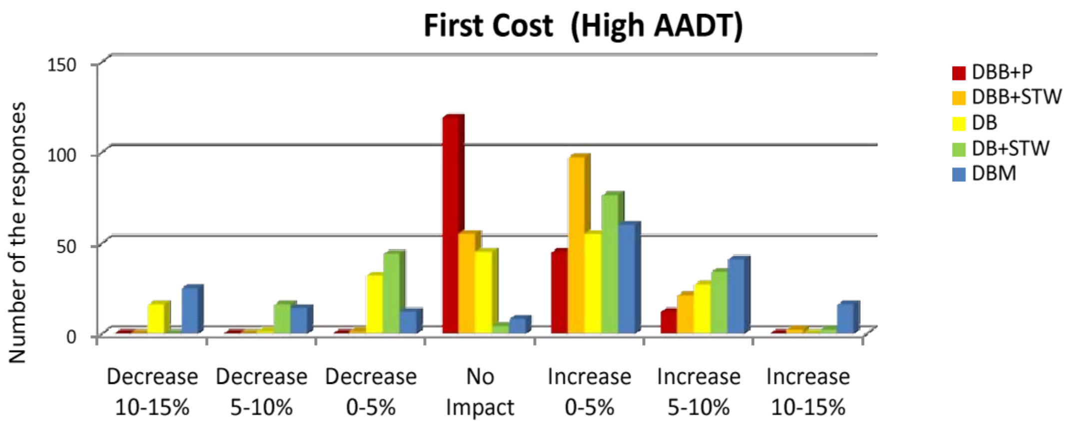

Schedule
Number of the responses
300
250
200
150
100
50
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB+P
DBB+STW
DB
DB+STW
DBM


Traffic Disruption
Number of the responses
300
200
100
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
DBB+P
DBB+STW
DB
DB+STW
DBM

Round 2 Survey Results: Results for Each of the Performance Criteria

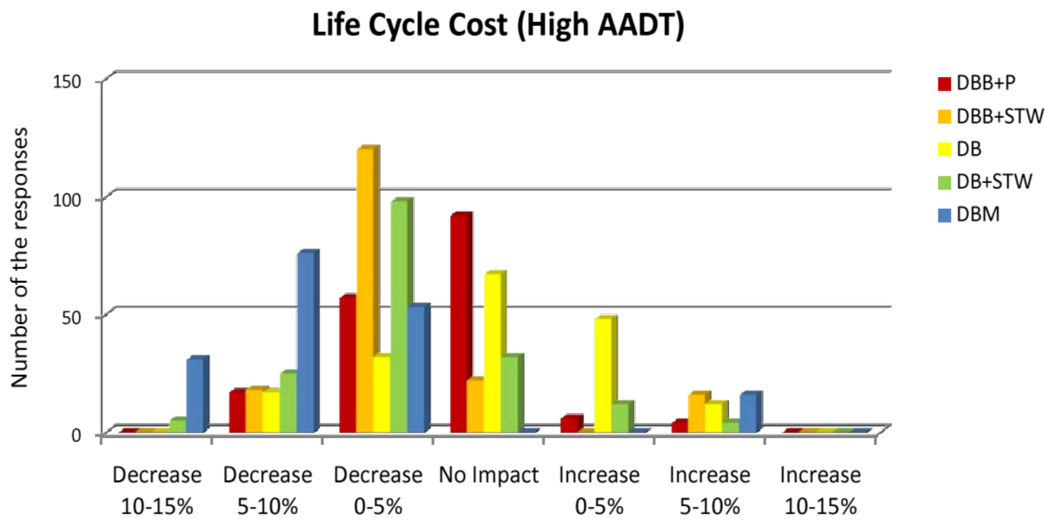
Project Characteristic: Traffic

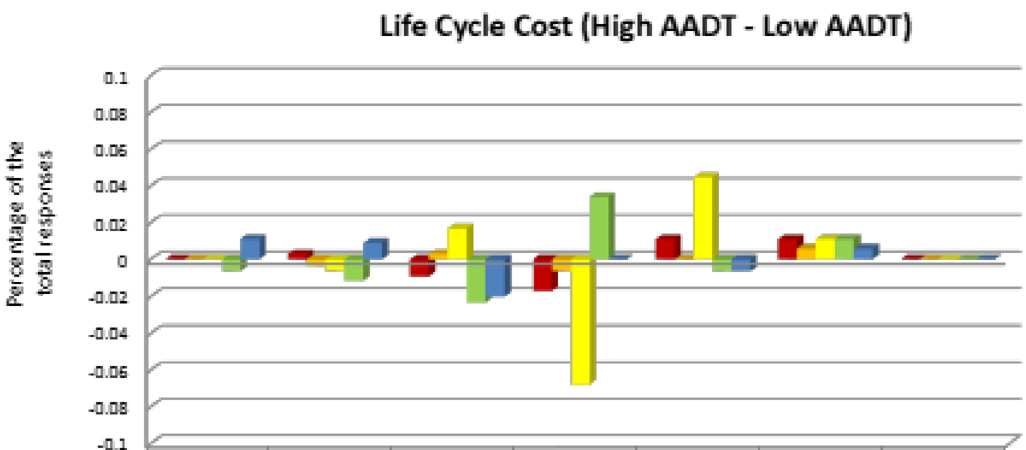
First Cost (FC)



	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0	-0.043	0.031	0.011	0
DBB+STW	-0.017	-0.006	0.003	-0.02	-0.017	0.054	0.003
DB	0	0.003	-0.006	-0.023	-0.028	0.054	0
DB+STW	0	-0.023	-0.006	0.009	0.009	0.006	0.006
DBM	0.003	0	0	-0.003	0.014	-0.003	-0.011

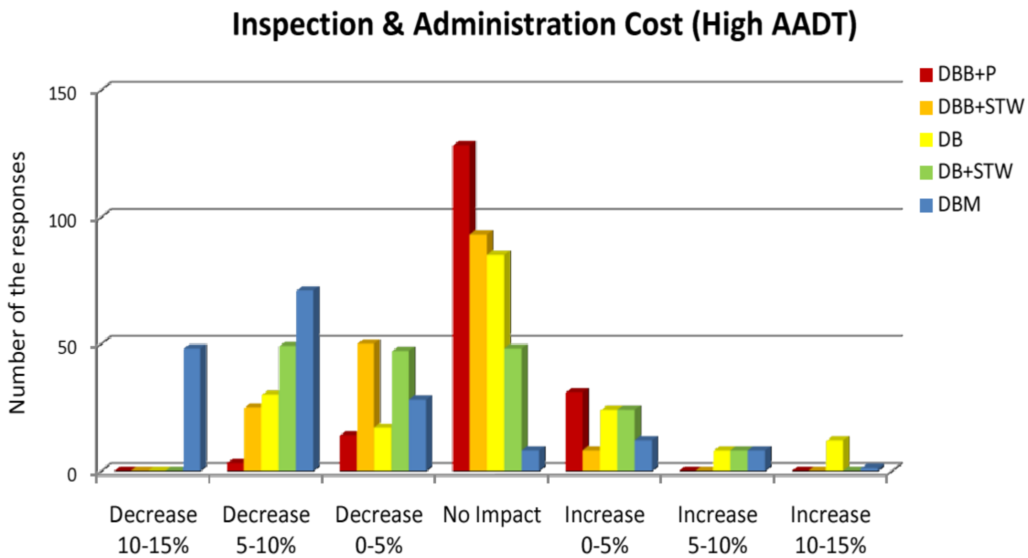
Life-Cycle Cost (LCC)

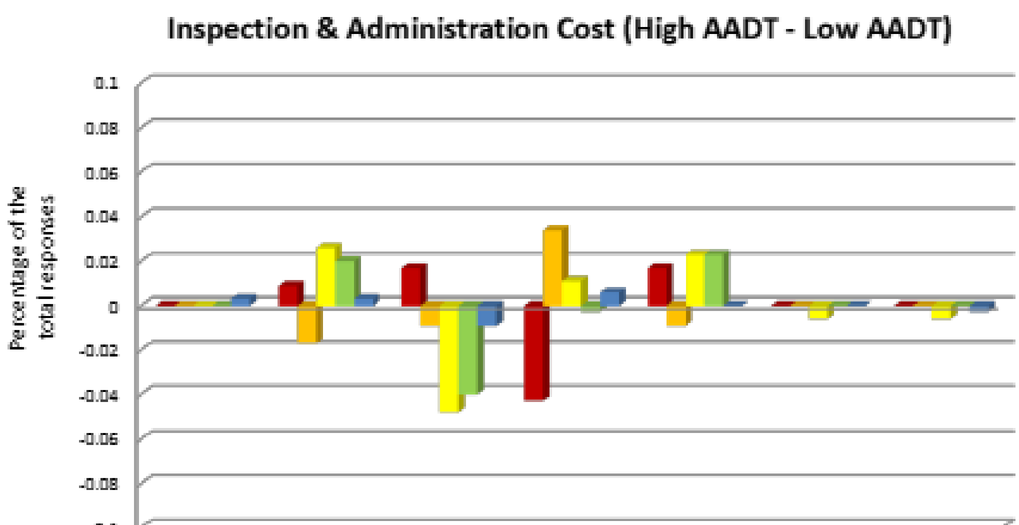




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0.003	-0.009	-0.017	0.011	0.011	0
DBB+STW	0	-0.003	0.003	-0.006	0	0.006	0
DB	0	-0.006	0.017	-0.068	0.045	0.011	0
DB+STW	-0.006	-0.011	-0.023	0.034	-0.006	0.011	0
DBM	0.011	0.009	-0.02	0	-0.006	0.006	0

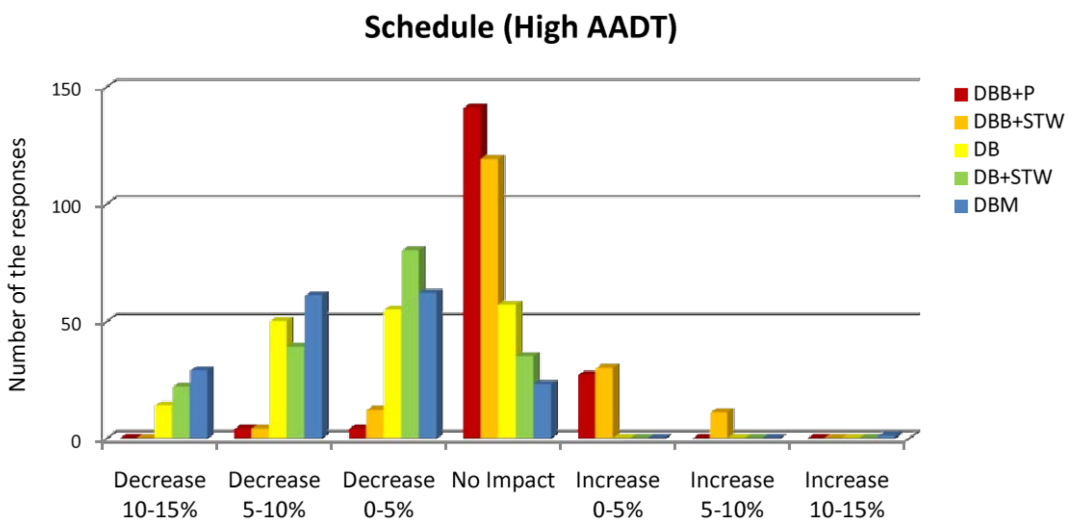
Inspection and Administration Cost (IAC)

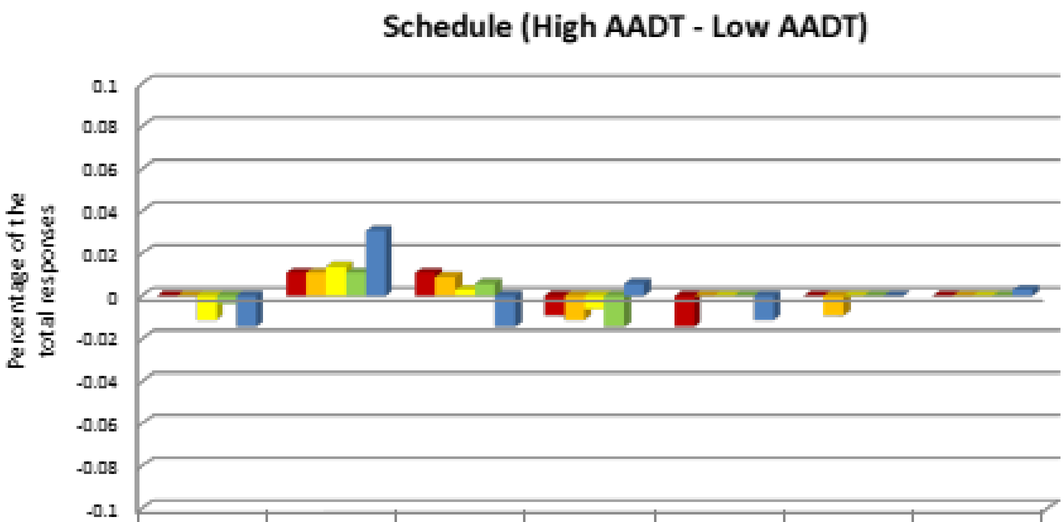




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0.009	0.017	-0.043	0.017	0	0
DBB+STW	0	-0.017	-0.009	0.034	-0.009	0	0
DB	0	0.026	-0.048	0.011	0.023	-0.006	-0.006
DB+STW	0	0.02	-0.04	-0.003	0.023	0	0
DBM	0.003	0.003	-0.009	0.006	0	0	-0.003

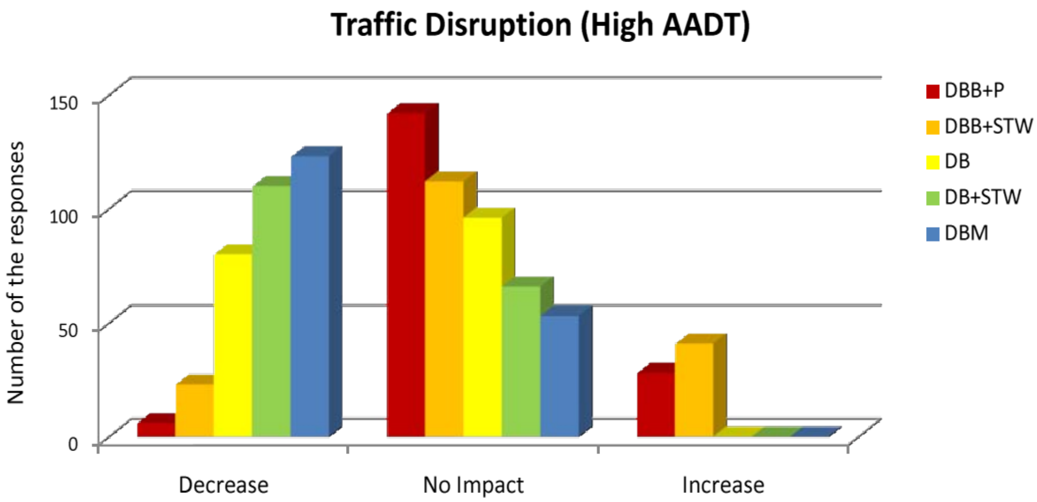
Schedule

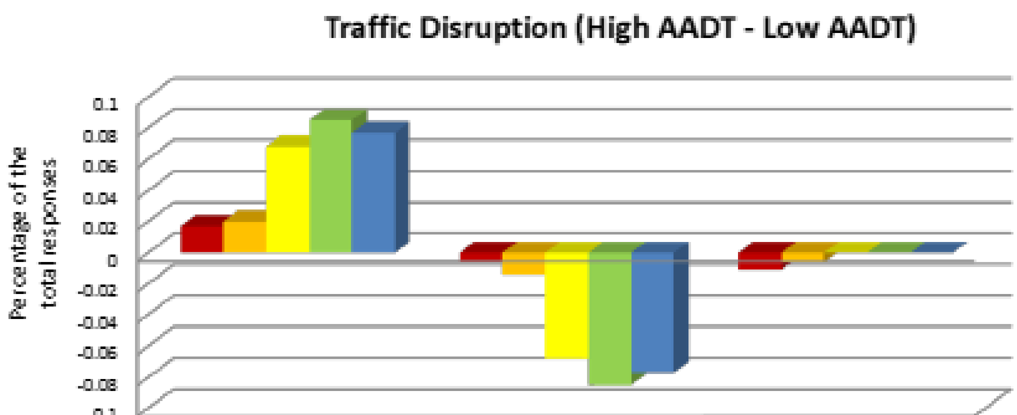




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0.011	0.011	-0.009	-0.014	0	0
DBB+STW	0	0.011	0.009	-0.011	0	-0.009	0
DB	-0.011	0.014	0.003	-0.006	0	0	0
DB+STW	-0.003	0.011	0.006	-0.014	0	0	0
DBM	-0.014	0.031	-0.014	0.006	-0.011	0	0.003

Traffic Disruption

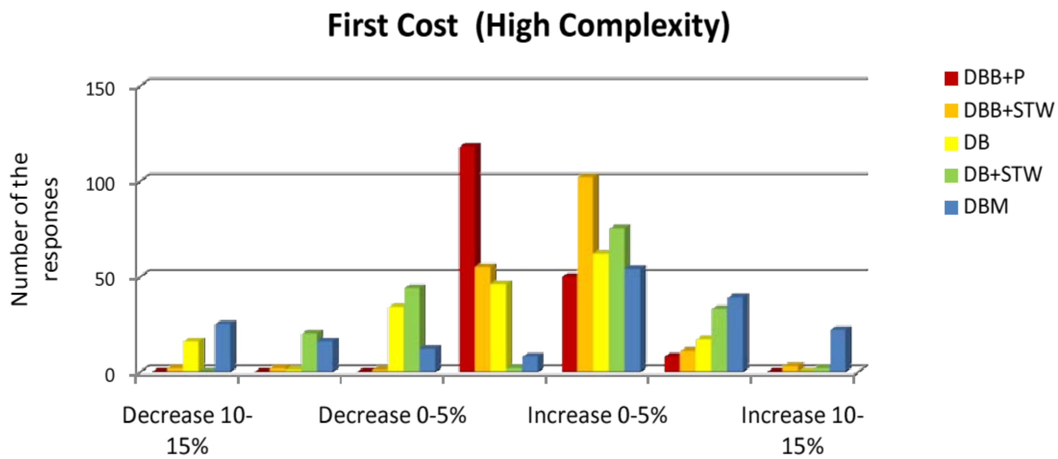


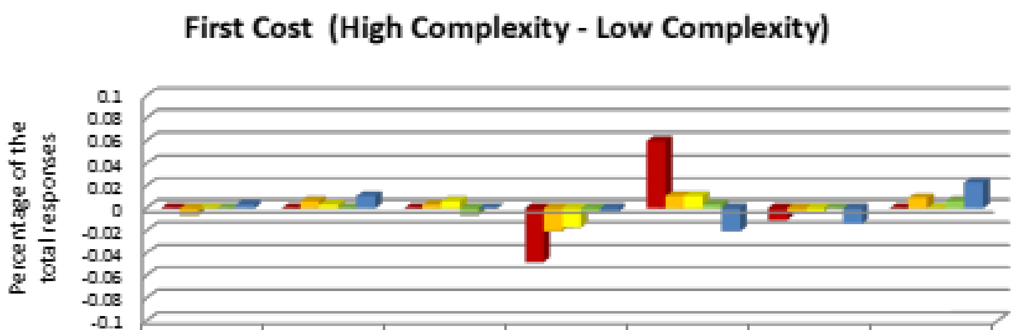


	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%
DBB+P	0.017	-0.006	-0.011
DBB+STW	0.02	-0.014	-0.006
DB	0.068	-0.068	0
DB+STW	0.085	-0.085	0
DBM	0.077	-0.077	0

Project Characteristic: Complexity

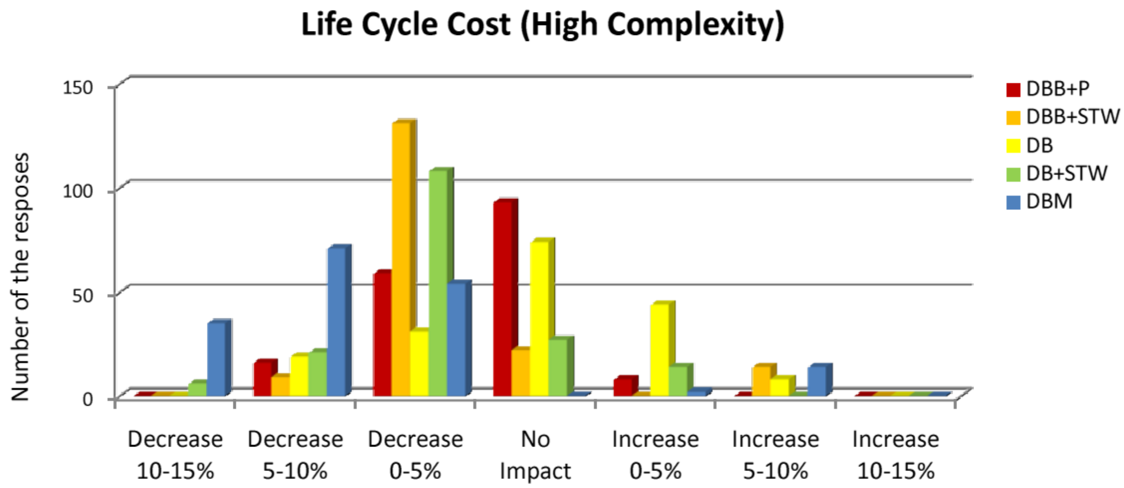
First Cost

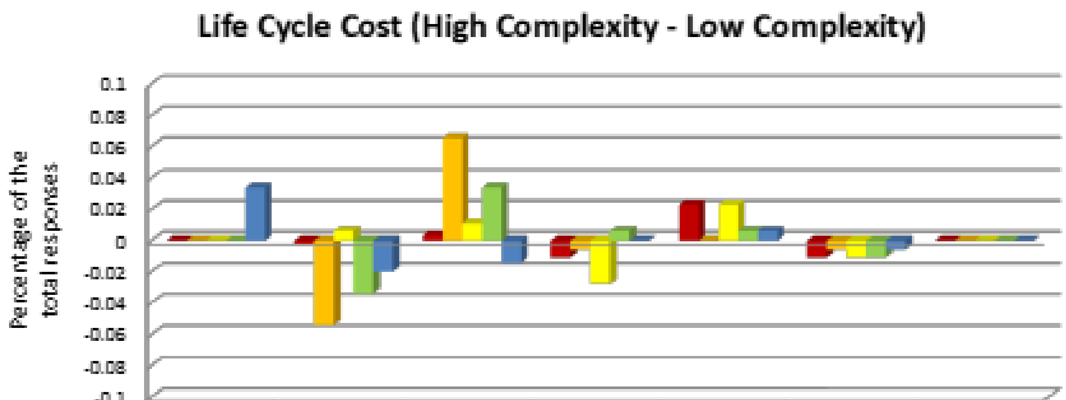




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0	-0.048	0.06	-0.011	0
DBB+STW	-0.006	0.006	0.003	-0.02	0.011	-0.003	0.009
DB	0	0.003	0.006	-0.017	0.011	-0.003	0
DB+STW	0	0	-0.006	-0.003	0.003	0	0.006
DBM	0.003	0.011	0	-0.003	-0.02	-0.014	0.023

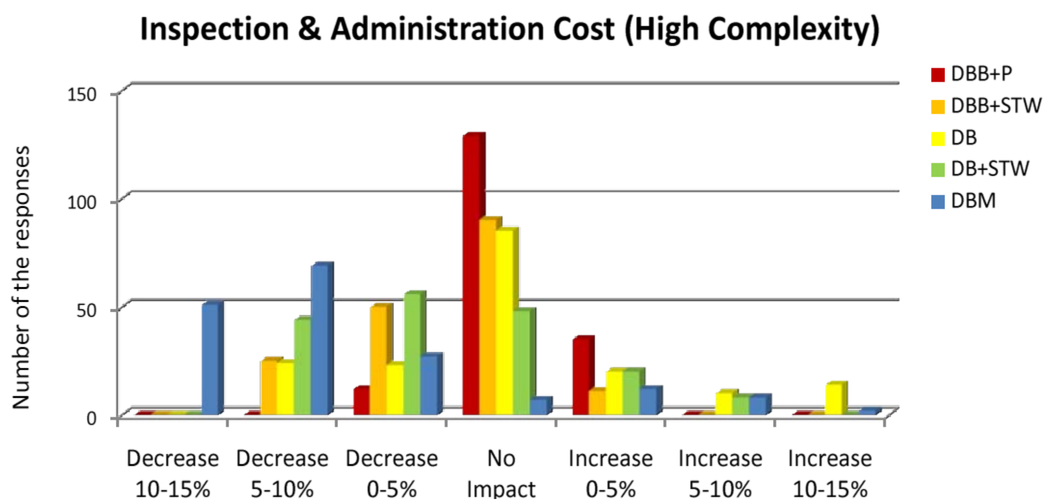
Life-Cycle Cost

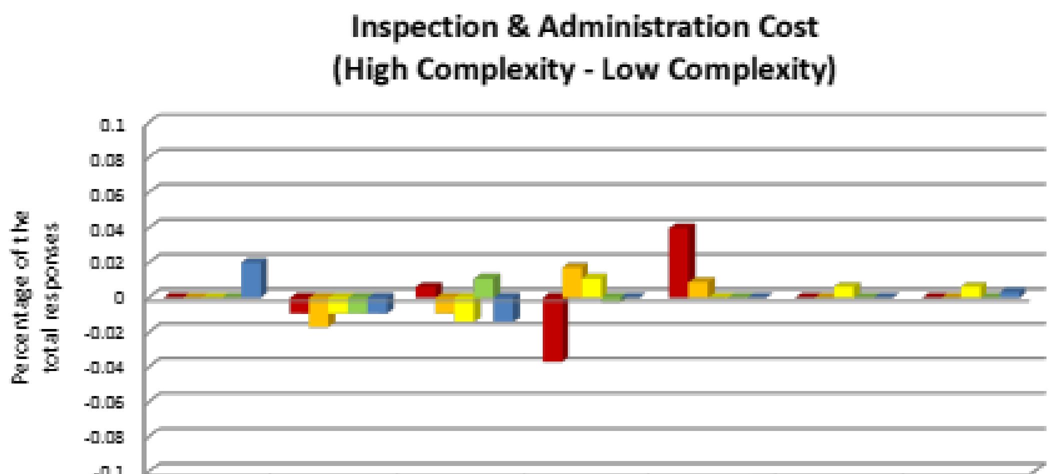




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.003	0.003	-0.011	0.023	-0.011	0
DBB+STW	0	-0.054	0.065	-0.006	0	-0.006	0
DB	0	0.006	0.011	-0.028	0.023	-0.011	0
DB+STW	0	-0.034	0.034	0.006	0.006	-0.011	0
DBM	0.034	-0.02	-0.014	0	0.006	-0.006	0

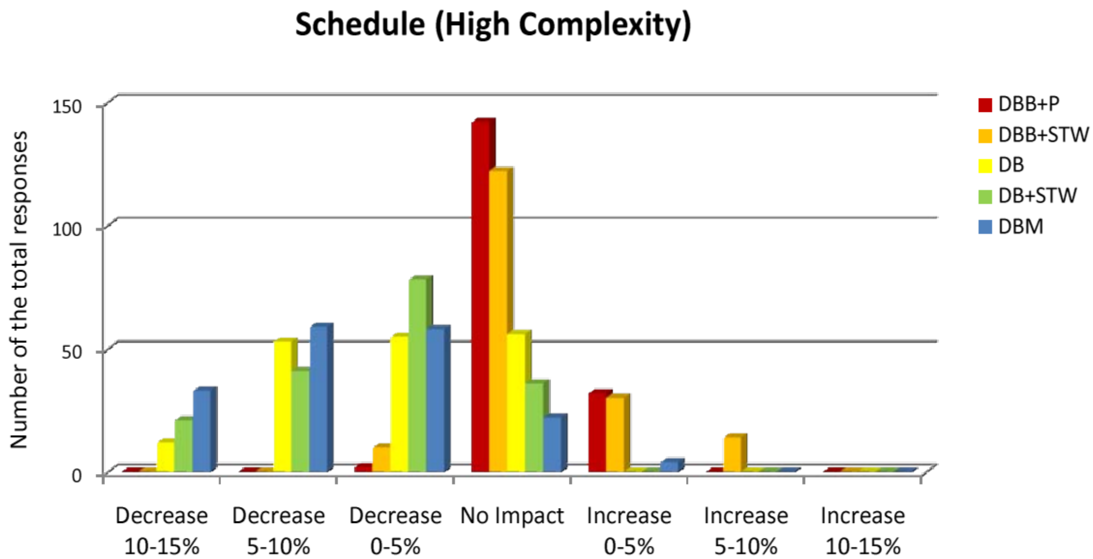
Inspection and Administration Cost

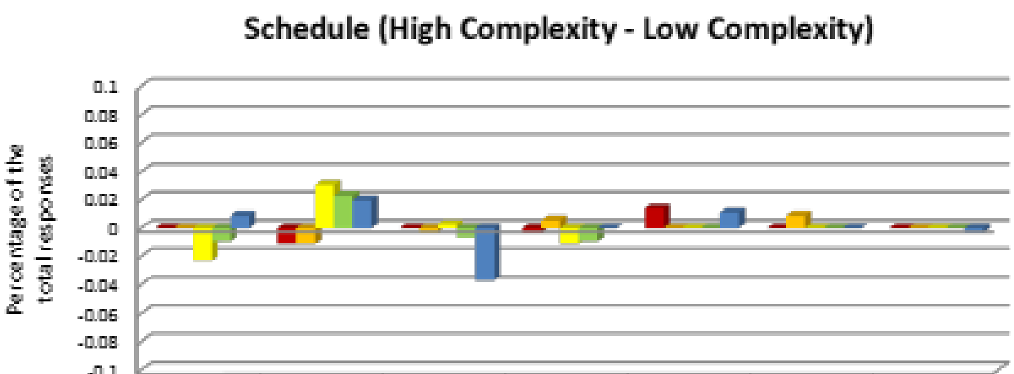




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.009	0.006	-0.037	0.04	0	0
DBB+STW	0	-0.017	-0.009	0.017	0.009	0	0
DB	0	-0.009	-0.014	0.011	0	0.006	0.006
DB+STW	0	-0.009	0.011	-0.003	0	0	0
DBM	0.02	-0.009	-0.014	0	0	0	0.003

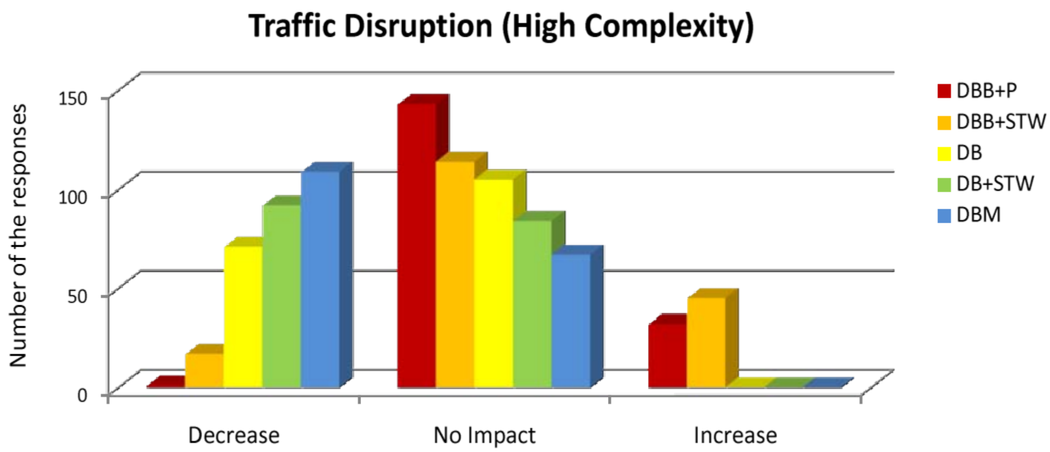
Schedule

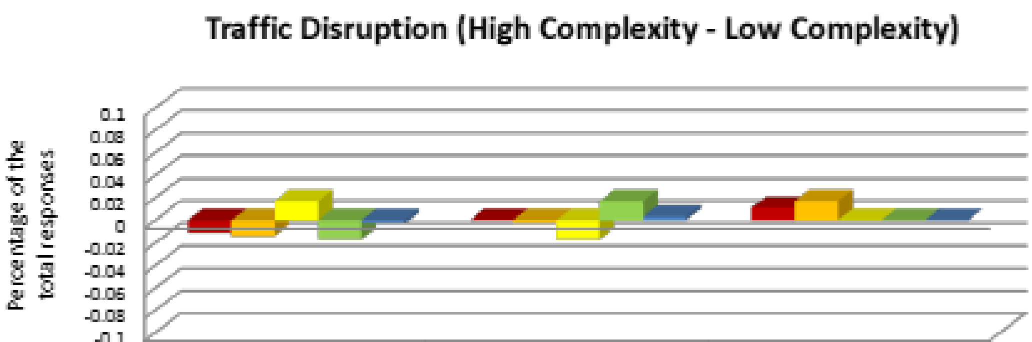




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.011	0	-0.003	0.014	0	0
DBB+STW	0	-0.011	-0.003	0.006	0	0.009	0
DB	-0.023	0.031	0.003	-0.011	0	0	0
DB+STW	-0.009	0.023	-0.006	-0.009	0	0	0
DBM	0.009	0.02	-0.037	0	0.011	0	-0.003

Traffic Disruption

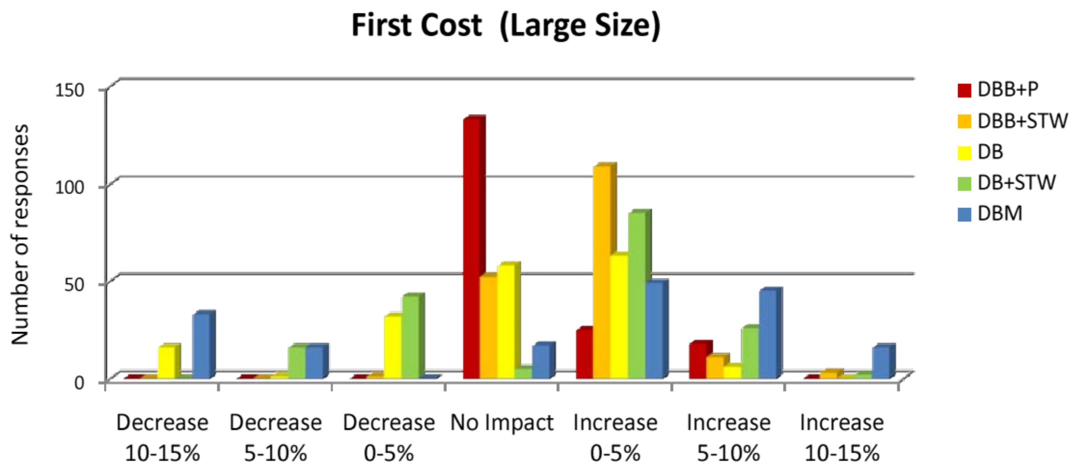


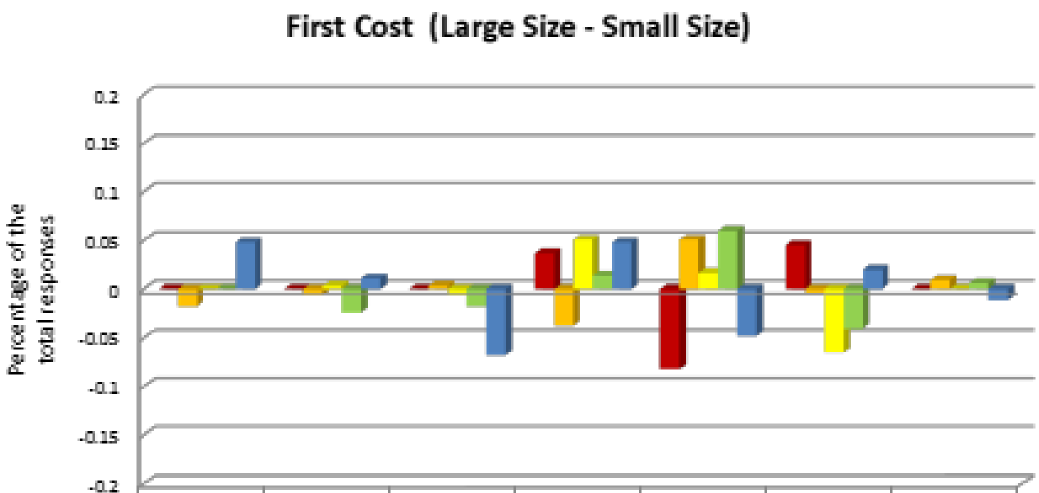


	Decrease	No Impact	Increase
DBB+P	-0.011	0	0.011
DBB+STW	-0.014	-0.003	0.017
DB	0.017	-0.017	0
DB+STW	-0.017	0.017	0
DBM	-0.003	0.003	0

Project Characteristic: Size

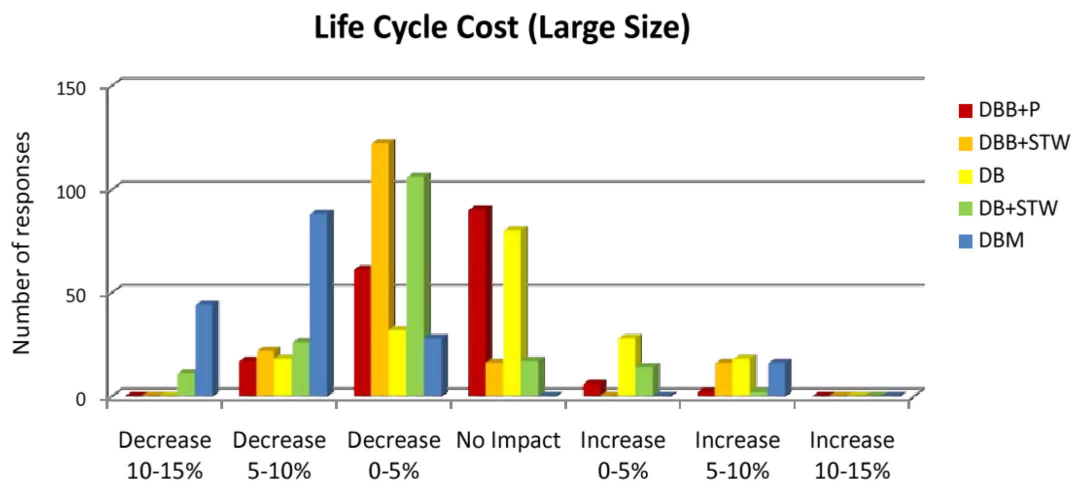
First Cost

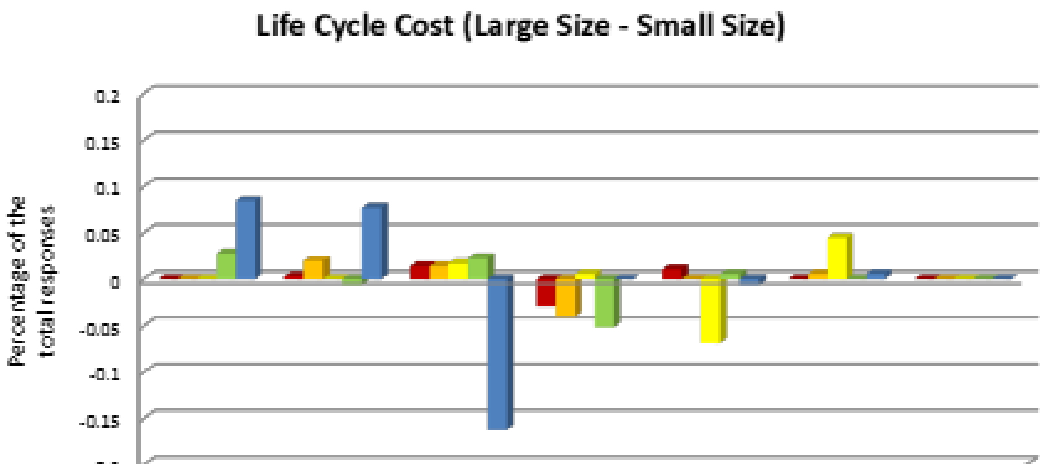




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0	0.037	-0.082	0.045	0
DBB+STW	-0.017	-0.006	0.003	-0.037	0.051	-0.003	0.009
DB	0	0.003	-0.006	0.051	0.017	-0.065	0
DB+STW	0	-0.023	-0.017	0.014	0.06	-0.04	0.006
DBM	0.048	0.011	-0.068	0.048	-0.048	0.02	-0.011

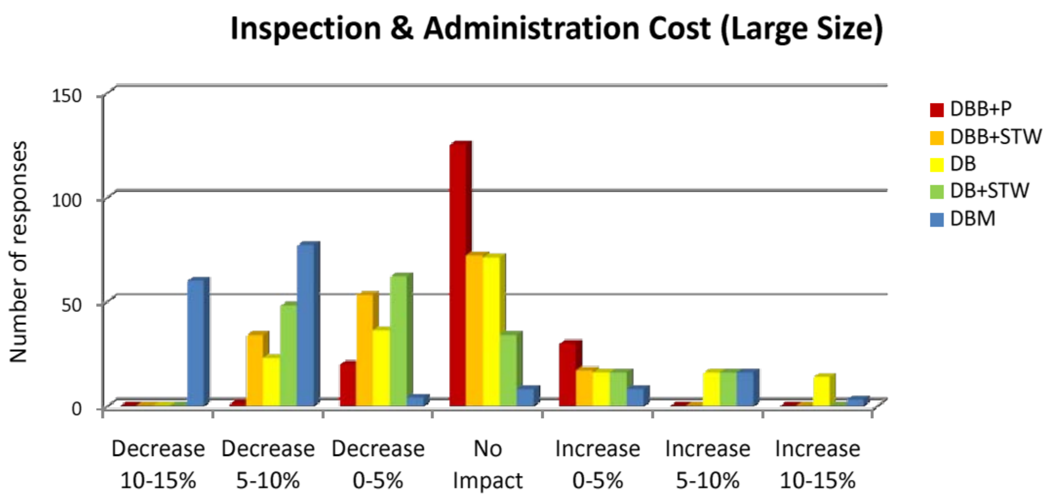
Life-Cycle Cost

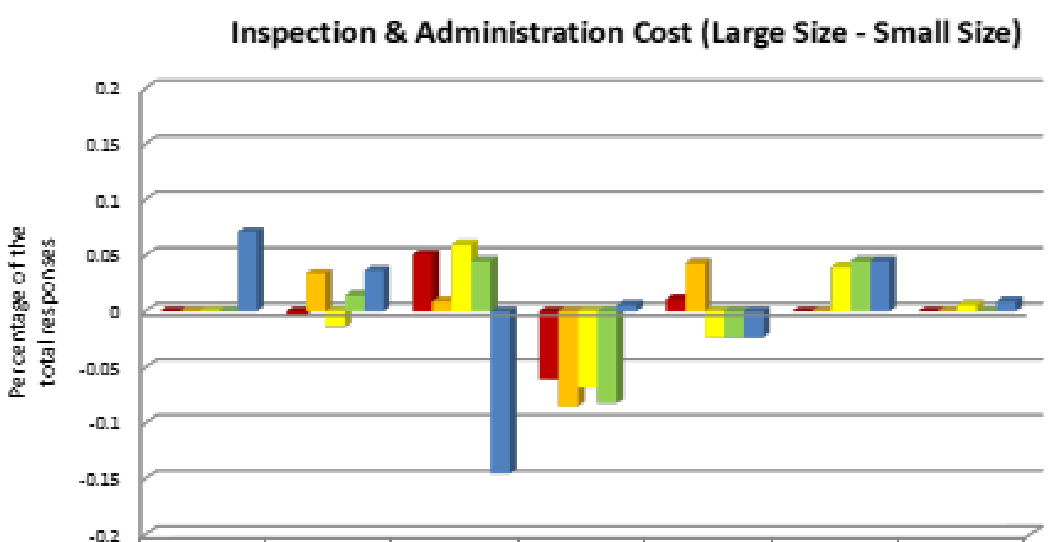




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0.003	0.014	-0.028	0.011	0	0
DBB+STW	0	0.02	0.014	-0.04	0	0.006	0
DB	0	0	0.017	0.006	-0.068	0.045	0
DB+STW	0.028	-0.006	0.023	-0.051	0.006	0	0
DBM	0.085	0.077	-0.162	0	-0.006	0.006	0

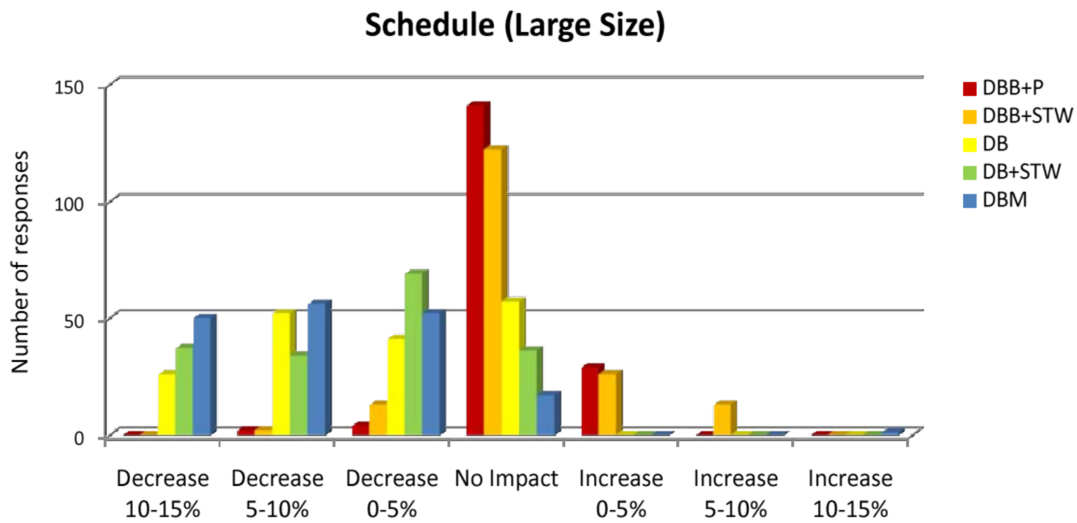
Inspection and Administration Cost

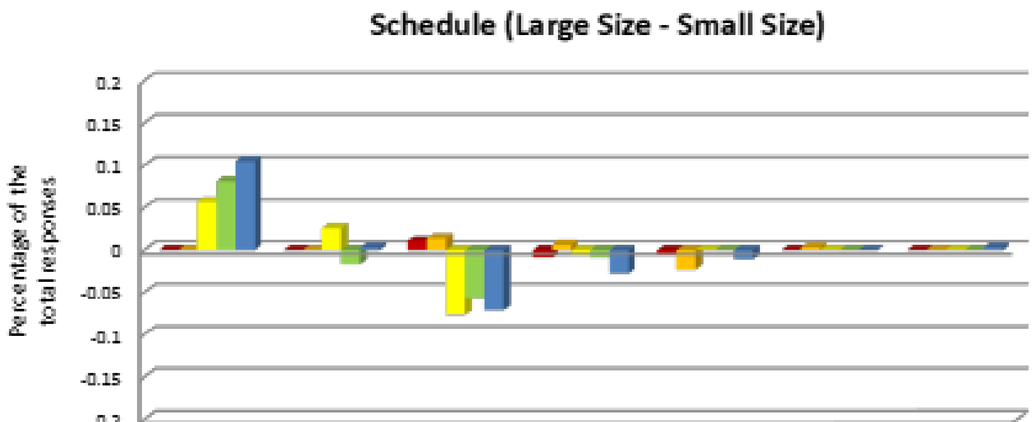




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.003	0.051	-0.06	0.011	0	0
DBB+STW	0	0.034	0.009	-0.085	0.043	0	0
DB	0	-0.014	0.06	-0.068	-0.023	0.04	0.006
DB+STW	0	0.014	0.045	-0.082	-0.023	0.045	0
DBM	0.071	0.037	-0.145	0.006	-0.023	0.045	0.009

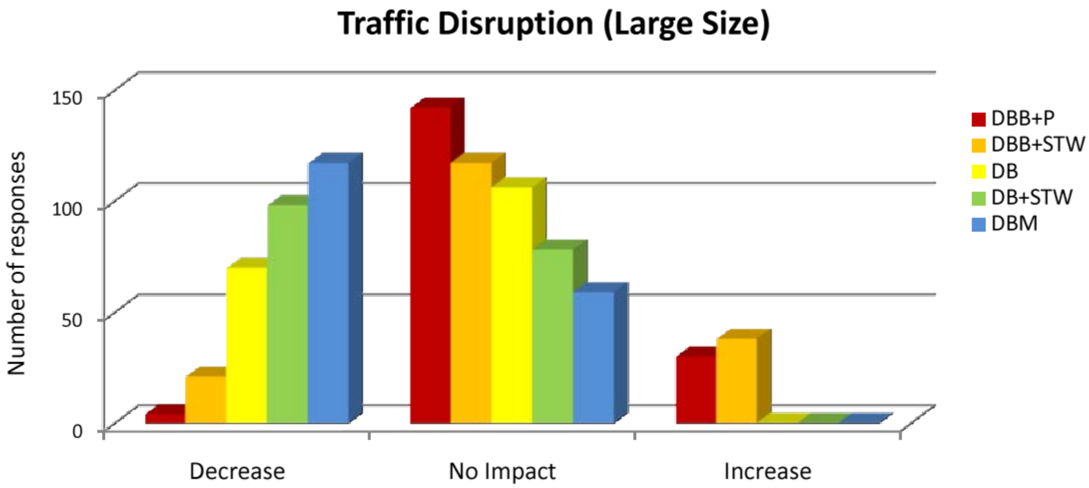
Schedule

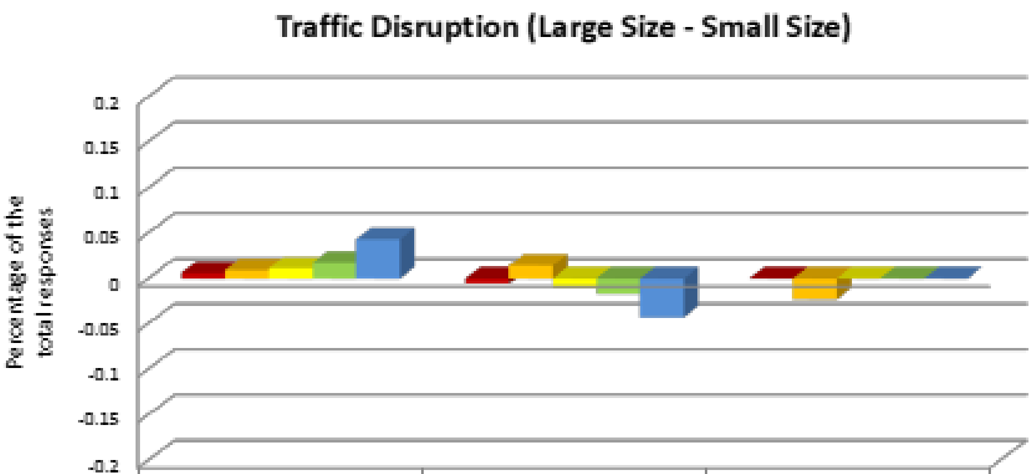




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0.011	-0.009	-0.003	0	0
DBB+STW	0	0	0.014	0.006	-0.023	0.003	0
DB	0.057	0.026	-0.077	-0.006	0	0	0
DB+STW	0.082	-0.017	-0.057	-0.009	0	0	0
DBM	0.105	0.003	-0.071	-0.028	-0.011	0	0.003

Traffic Disruption

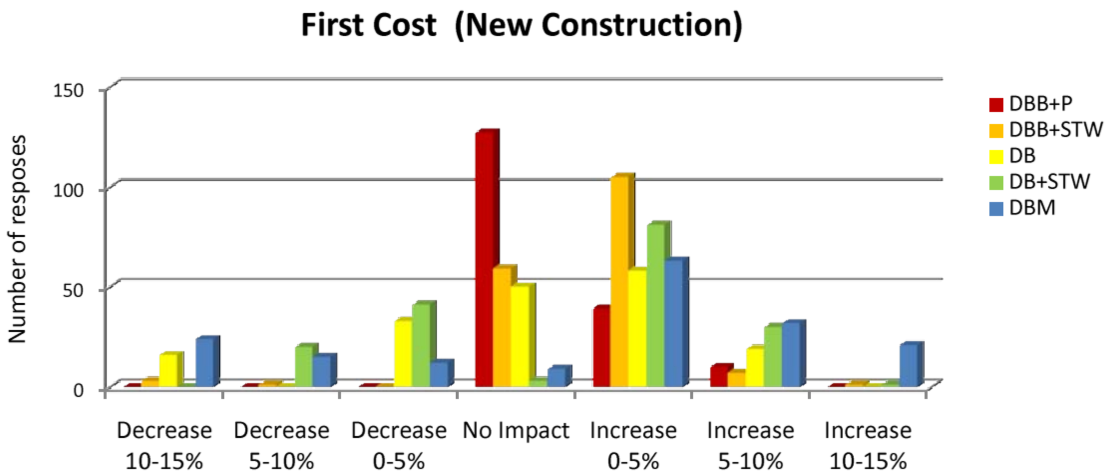




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%
DBB+P	0.006	-0.006	0
DBB+STW	0.009	0.014	-0.023
DB	0.011	-0.011	0
DB+STW	0.017	-0.017	0
DBM	0.043	-0.043	0

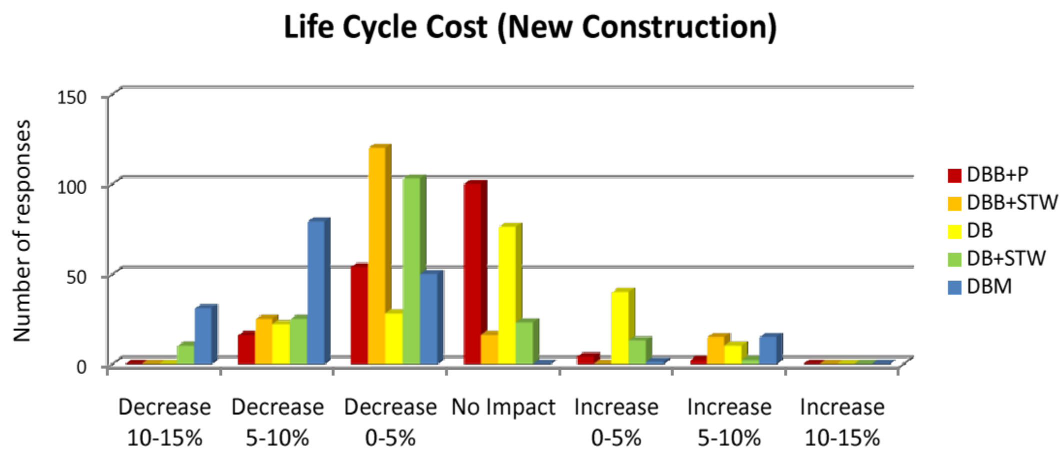
Project Characteristic: Type

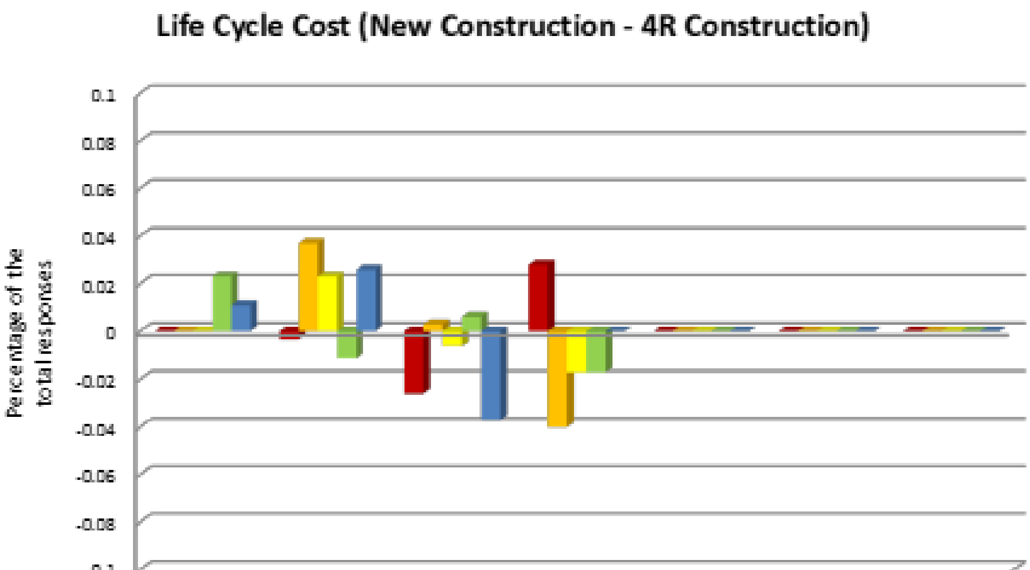
First Cost



	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0	0.003	-0.003	0	0
DBB+STW	0	0	-0.003	0.003	0.028	-0.026	-0.003
DB	0	-0.003	0	0.006	-0.011	0.009	0
DB+STW	0	0	-0.023	0.003	0.037	-0.017	0
DBM	-0.003	0.006	0	0.003	0.031	-0.054	0.017

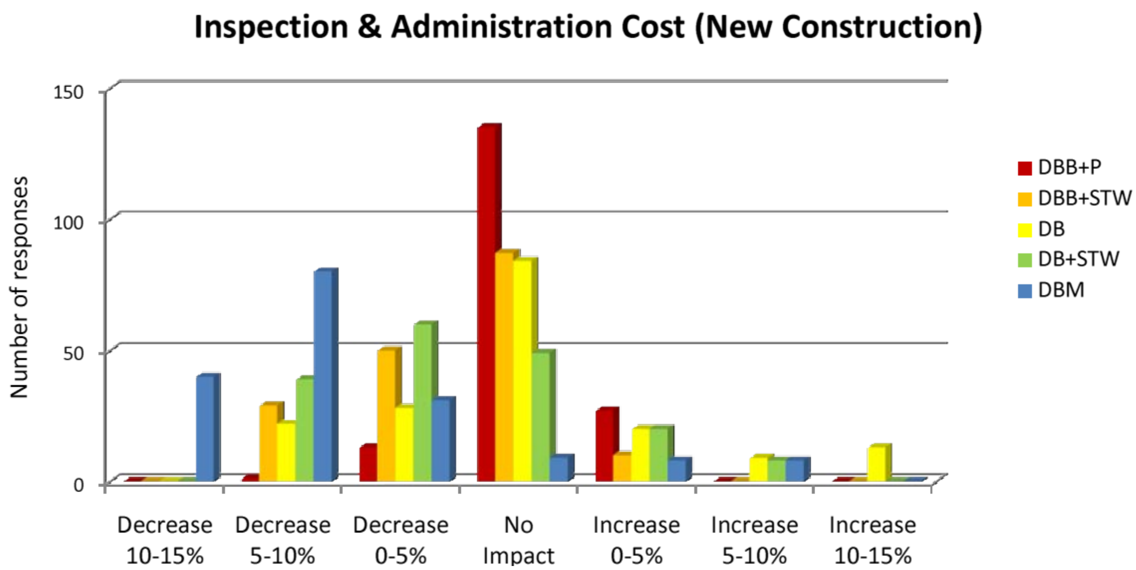
Life-Cycle Cost

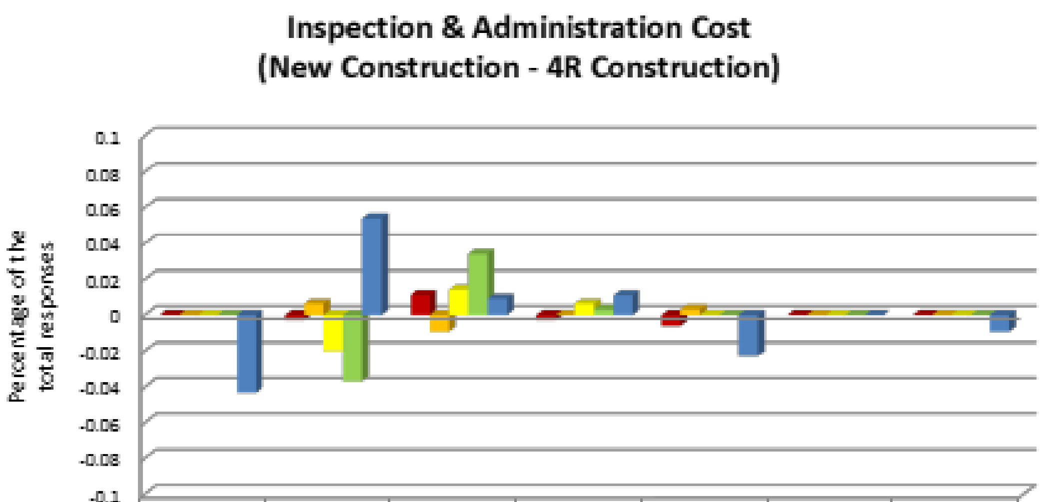




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.003	-0.026	0.028	0	0	0
DBB+STW	0	0.037	0.003	-0.04	0	0	0
DB	0	0.023	-0.006	-0.017	0	0	0
DB+STW	0.023	-0.011	0.006	-0.017	0	0	0
DBM	0.011	0.026	-0.037	0	0	0	0

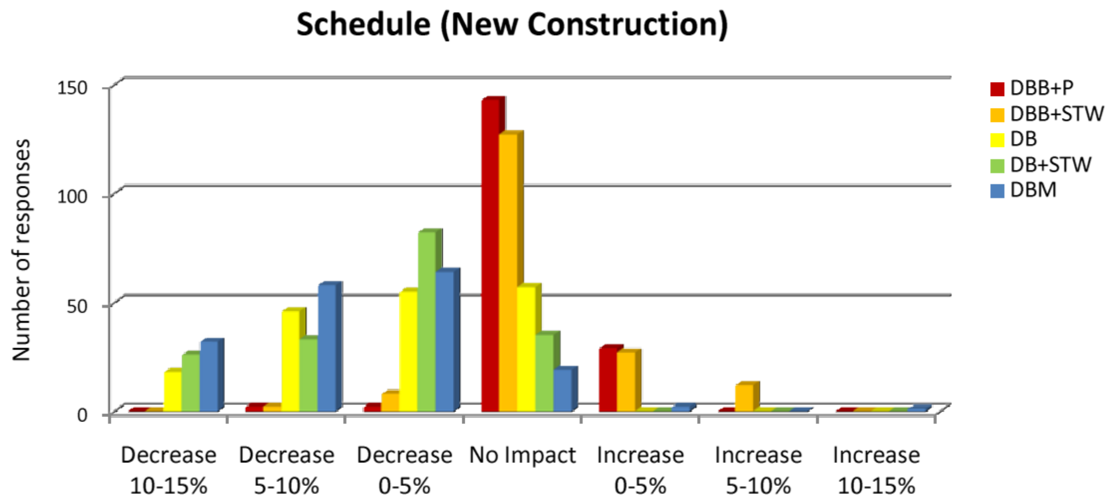
Inspection and Administration Cost

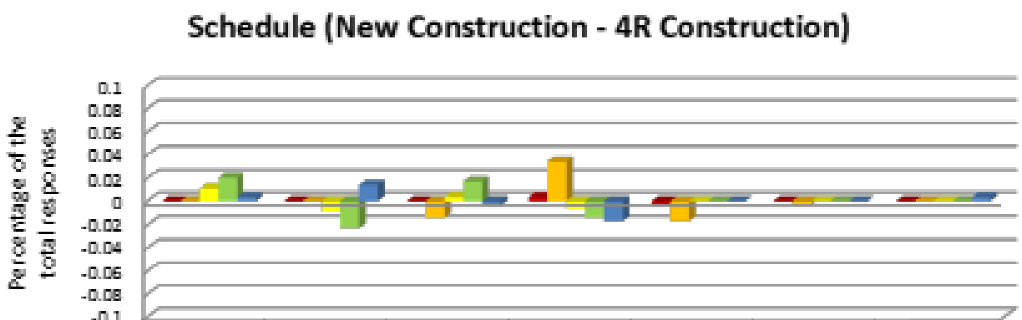




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.003	0.011	-0.003	-0.006	0	0
DBB+STW	0	0.006	-0.009	0	0.003	0	0
DB	0	-0.02	0.014	0.006	0	0	0
DB+STW	0	-0.037	0.034	0.003	0	0	0
DBM	-0.043	0.054	0.009	0.011	-0.023	0	-0.009

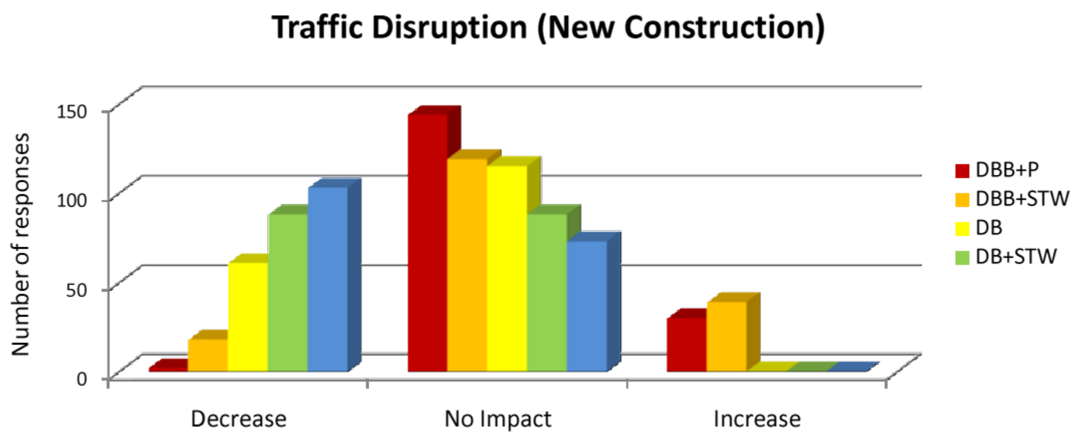
Schedule

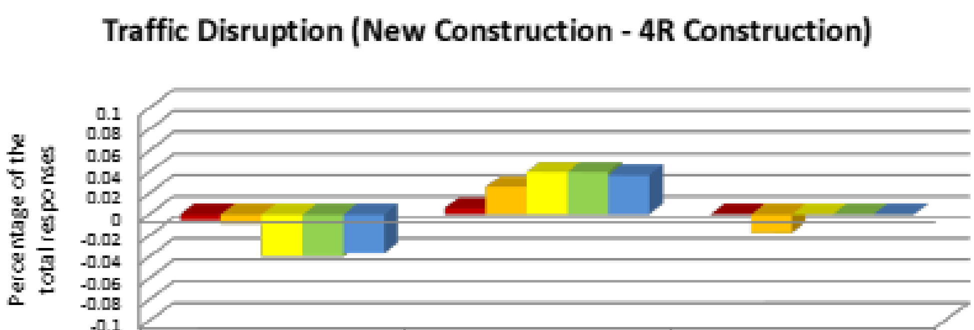




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0	0.003	-0.003	0	0
DBB+STW	0	0	-0.014	0.034	-0.017	-0.003	0
DB	0.011	-0.009	0.003	-0.006	0	0	0
DB+STW	0.02	-0.023	0.017	-0.014	0	0	0
DBM	0.003	0.014	-0.003	-0.017	0	0	0.003

Traffic Disruption

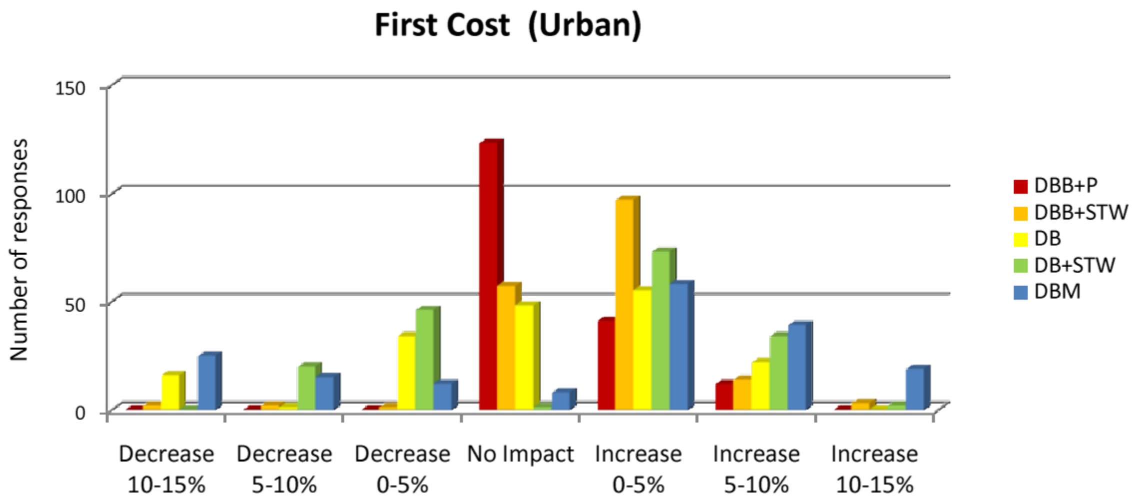


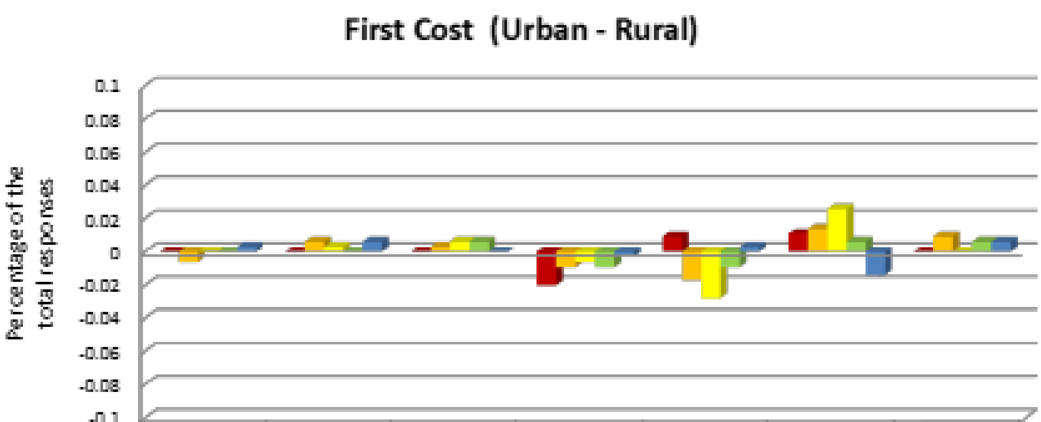


	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%
DBB+P	-0.006	0.006	0
DBB+STW	-0.009	0.026	-0.017
DB	-0.04	0.04	0
DB+STW	-0.04	0.04	0
DBM	-0.037	0.037	0

Project Characteristic: Location

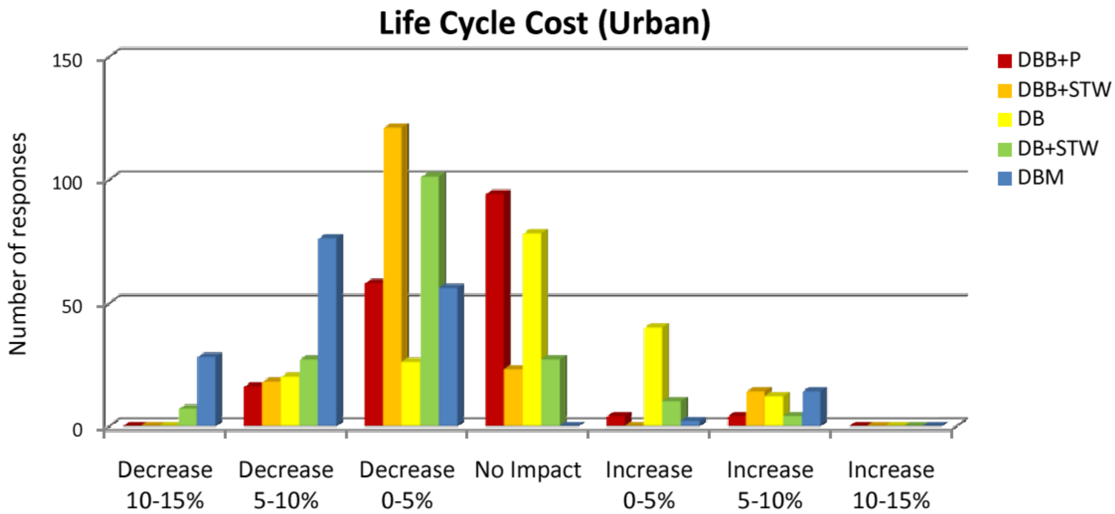
First Cost

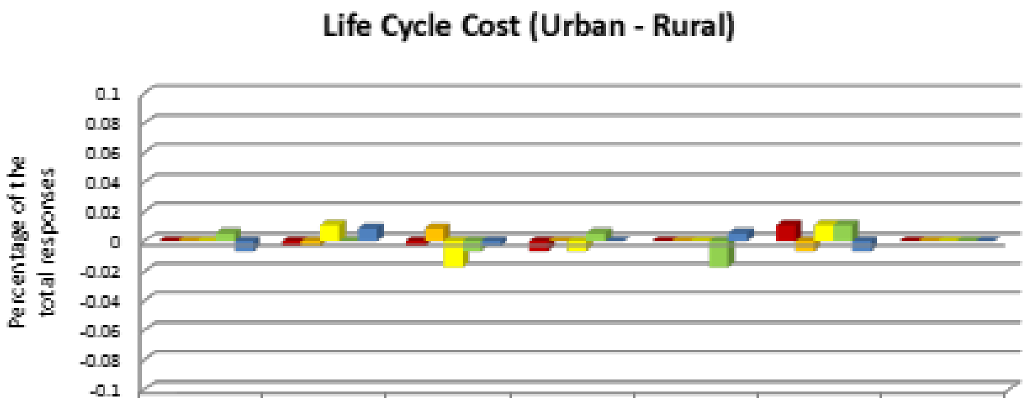




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0	0	-0.02	0.009	0.011	0
DBB+STW	-0.006	0.006	0.003	-0.009	-0.017	0.014	0.009
DB	0	0.003	0.006	-0.006	-0.028	0.026	0
DB+STW	0	0	0.006	-0.009	-0.009	0.006	0.006
DBM	0.003	0.006	0	-0.003	0.003	-0.014	0.006

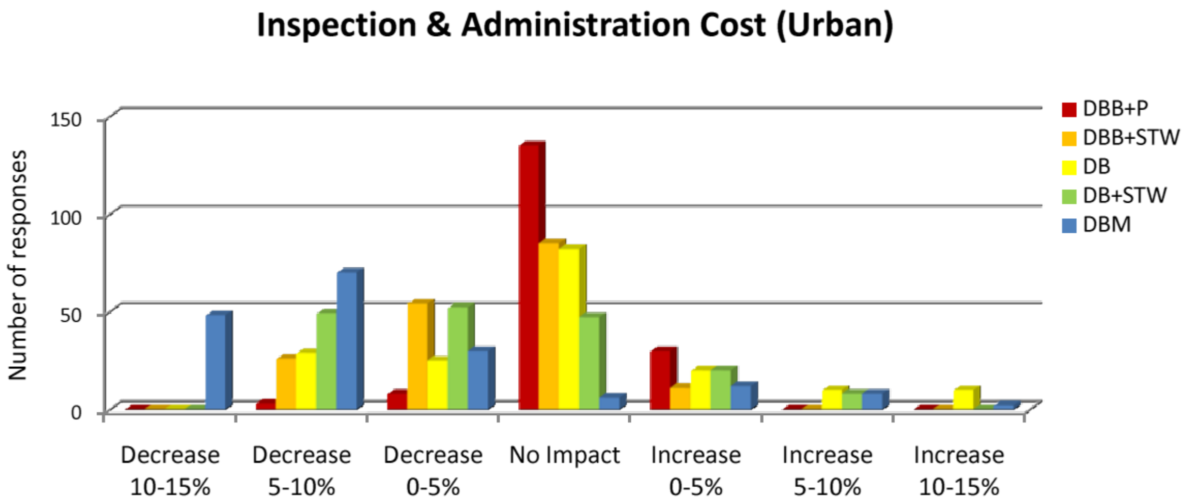
Life-Cycle Cost

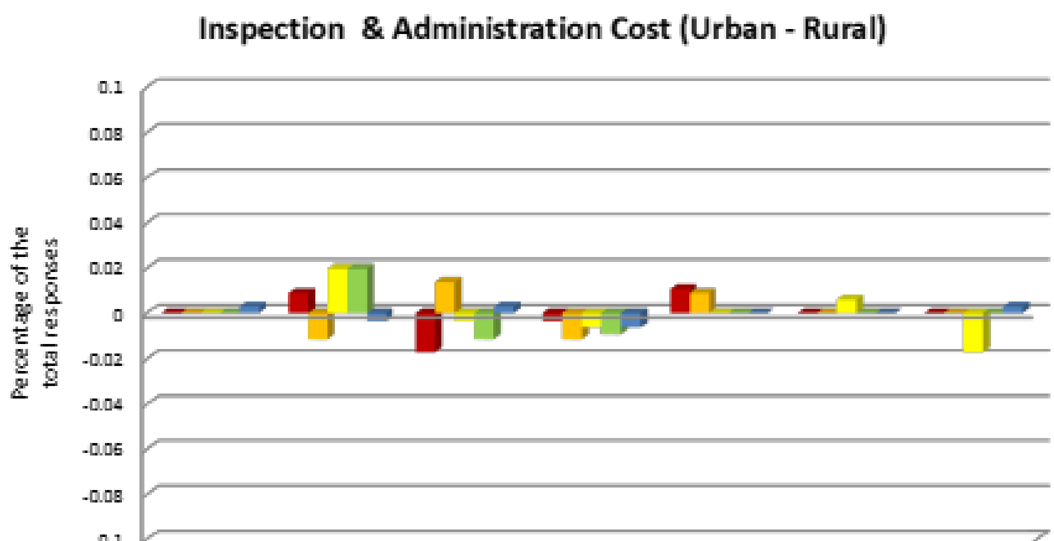




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	-0.003	-0.003	-0.006	0	0.011	0
DBB+STW	0	-0.003	0.009	0	0	-0.006	0
DB	0	0.011	-0.017	-0.006	0	0.011	0
DB+STW	0.006	0	-0.006	0.006	-0.017	0.011	0
DBM	-0.006	0.009	-0.003	0	0.006	-0.006	0

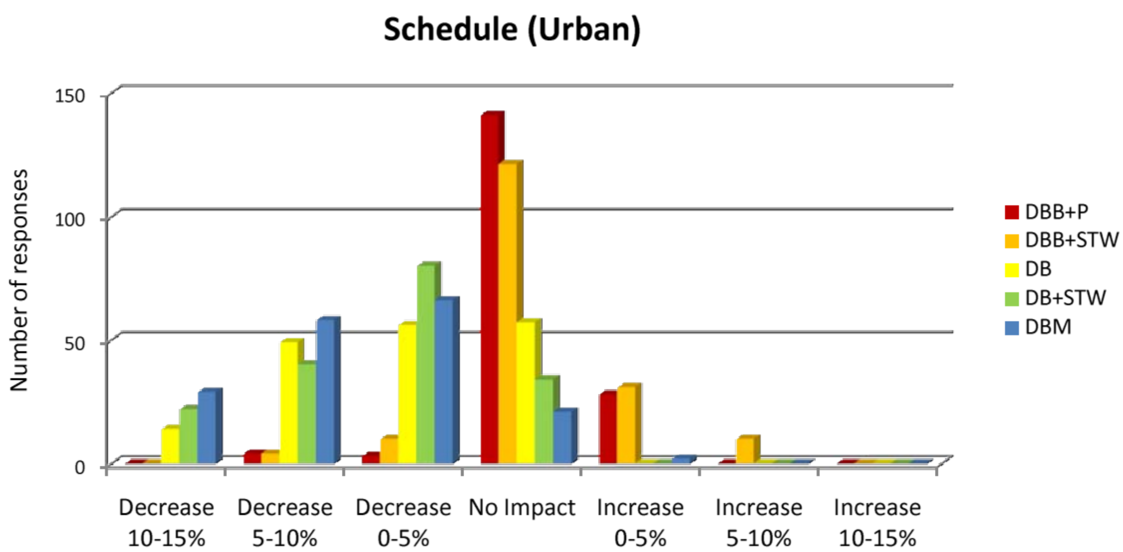
Inspection and Administration Cost

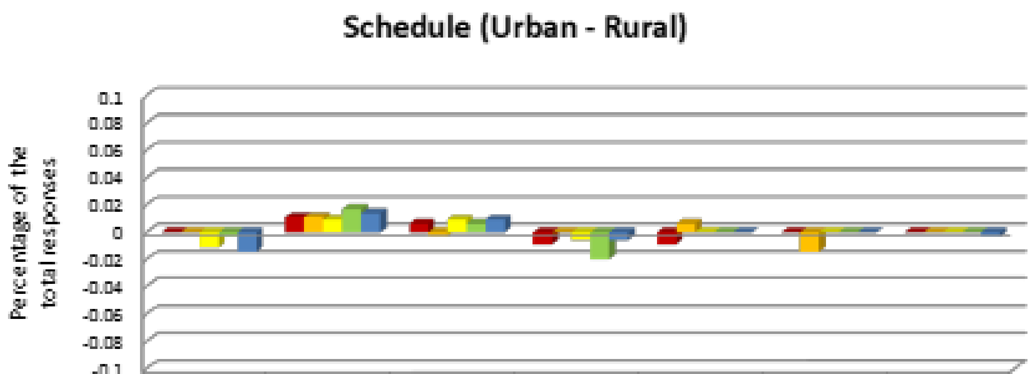




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0.009	-0.017	-0.003	0.011	0	0
DBB+STW	0	-0.011	0.014	-0.011	0.009	0	0
DB	0	0.02	-0.003	-0.006	0	0.006	-0.017
DB+STW	0	0.02	-0.011	-0.009	0	0	0
DBM	0.003	-0.003	0.003	-0.006	0	0	0.003

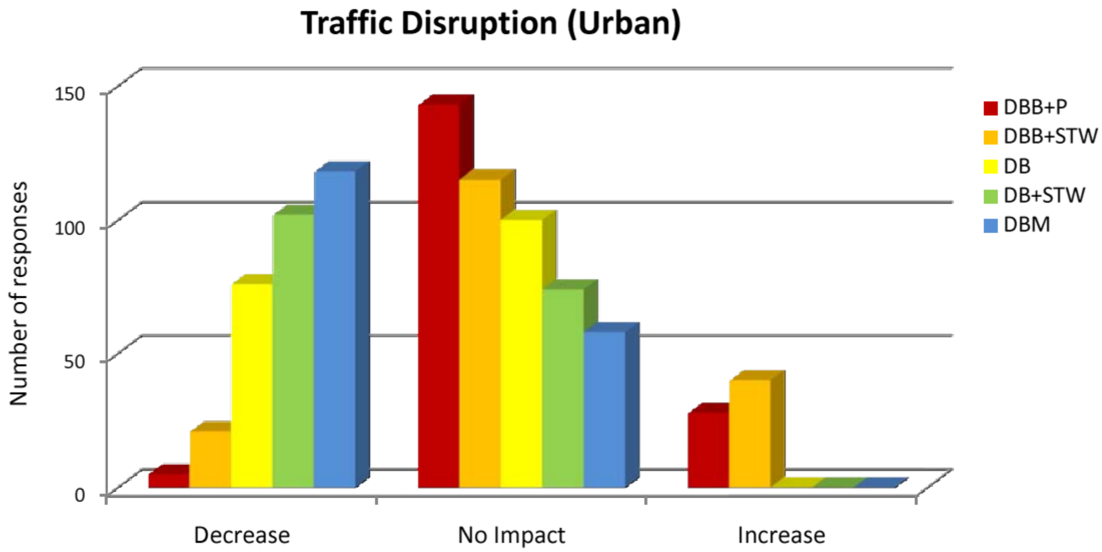
Schedule

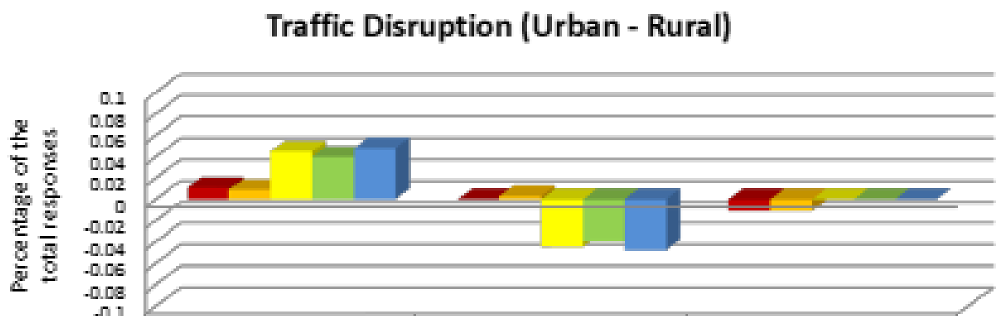




	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%	No Impact	Increase 0-5%	Increase 5-10%	Increase 10-15%
DBB+P	0	0.011	0.006	-0.009	-0.009	0	0
DBB+STW	0	0.011	-0.003	0	0.006	-0.014	0
DB	-0.011	0.009	0.009	-0.006	0	0	0
DB+STW	-0.003	0.017	0.006	-0.02	0	0	0
DBM	-0.014	0.014	0.009	-0.006	0	0	-0.003

Traffic Disruption



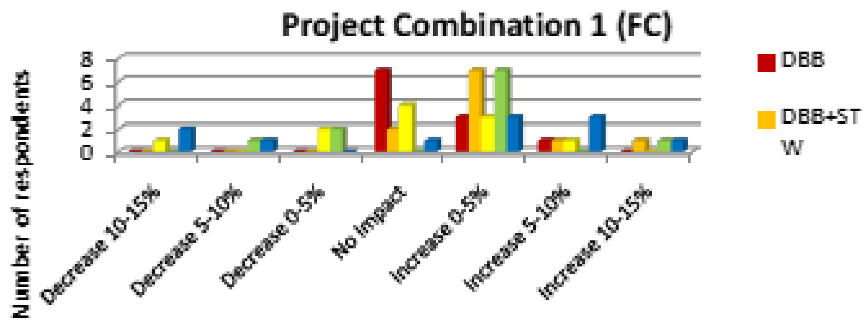


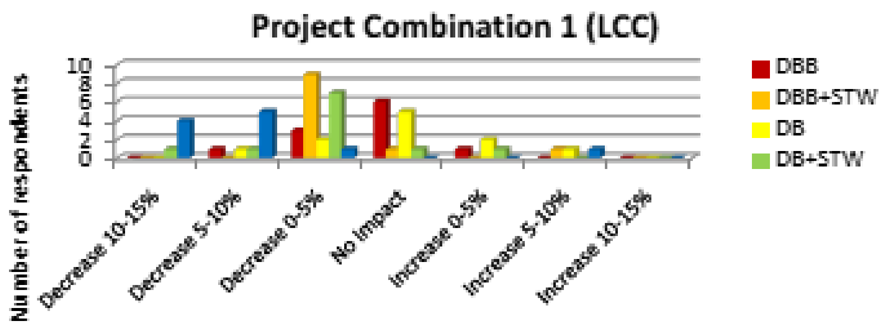
	Decrease 10-15%	Decrease 5-10%	Decrease 0-5%
DBB+P	0.011	0	-0.011
DBB+STW	0.009	0.003	-0.011
DB	0.045	-0.045	0
DB+STW	0.04	-0.04	0
DBM	0.048	-0.048	0

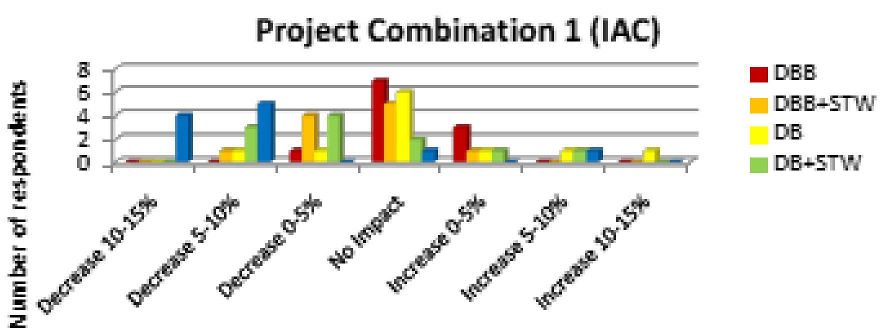
Round 2 Survey Results: Individual Project Combination Results

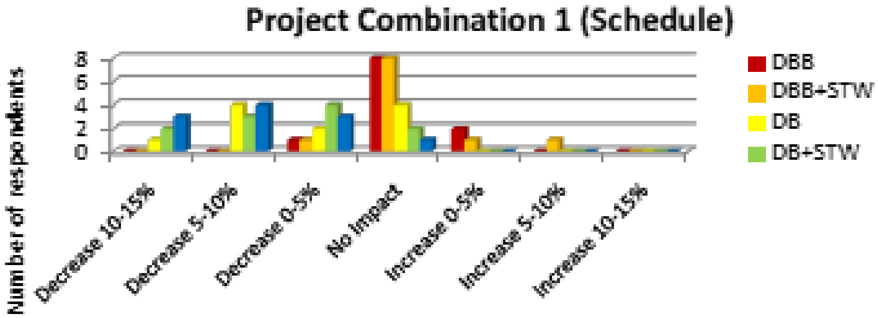
Project Combination 1

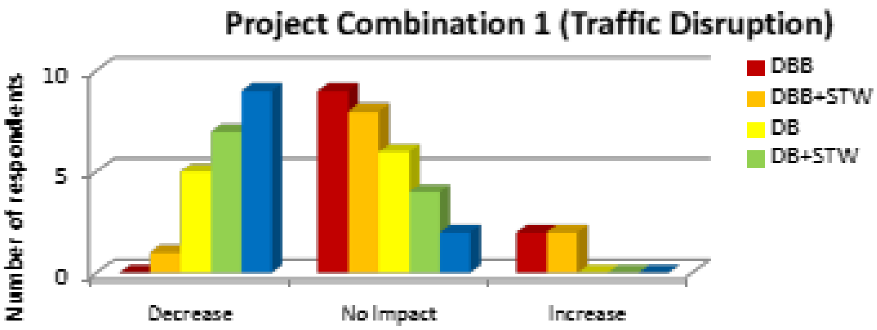
Size	Type	Traffic	Complexity	Location
Large	New construction	High AADT	High	Urban





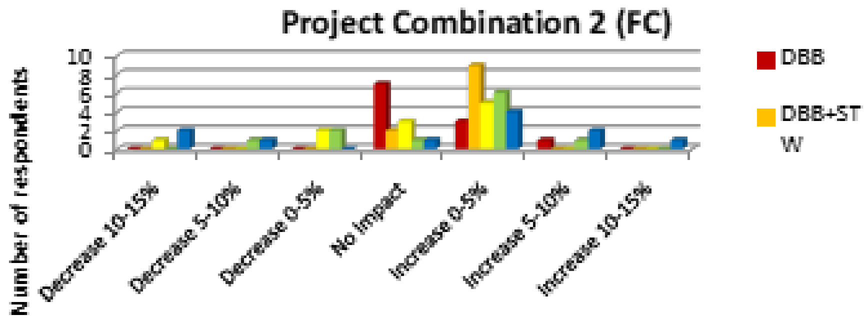


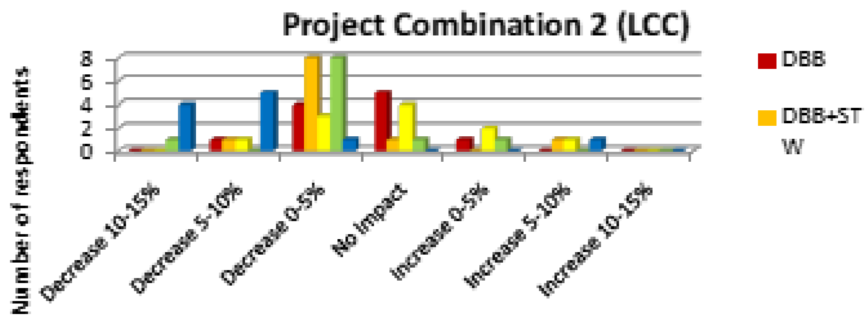

Project Combination 1 (Schedule)
Number of respondents
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW
DB
DB+STW

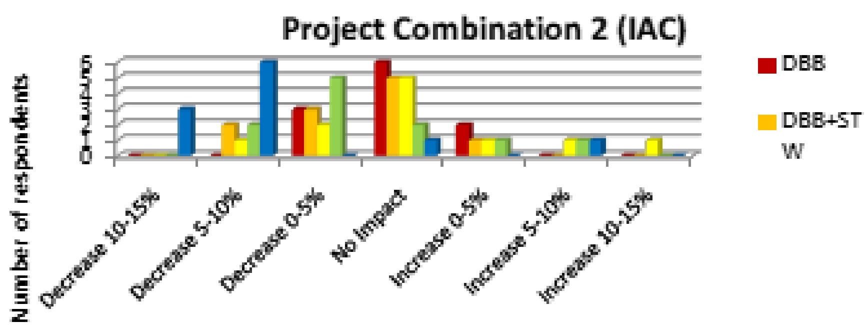

Project Combination 1 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW
DB
DB+STW

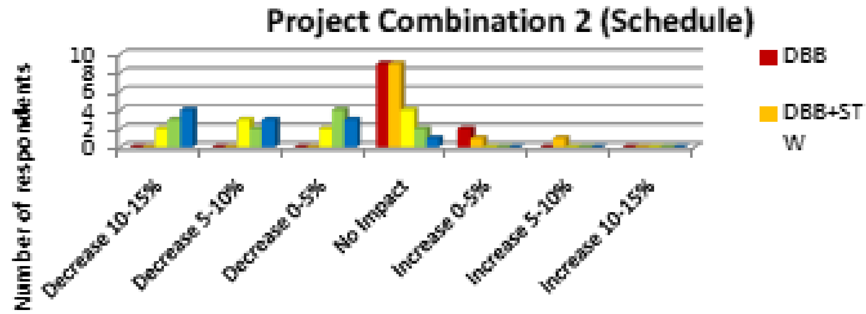
Project Combination 2

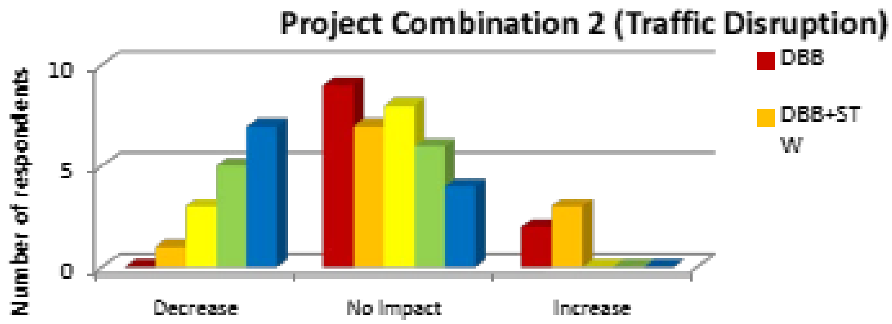
Size	Type	Traffic	Complexity	Location
Large	New construction	High AADT	High	Urban





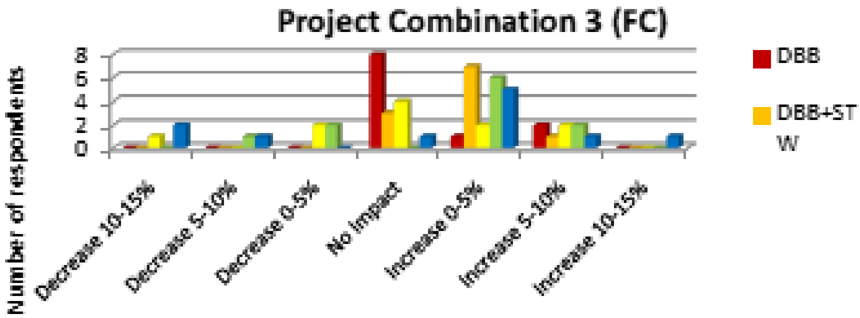


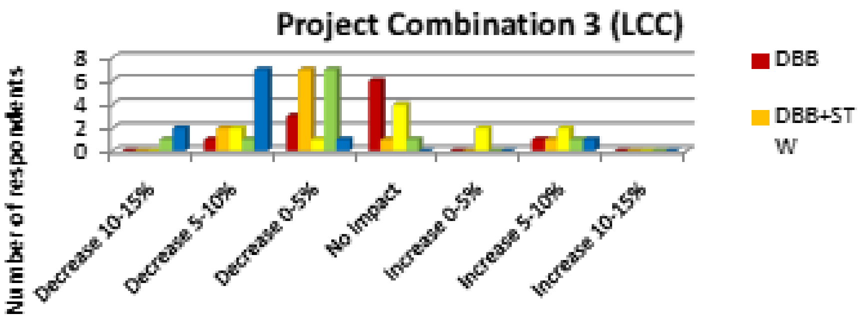

Project Combination 2 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

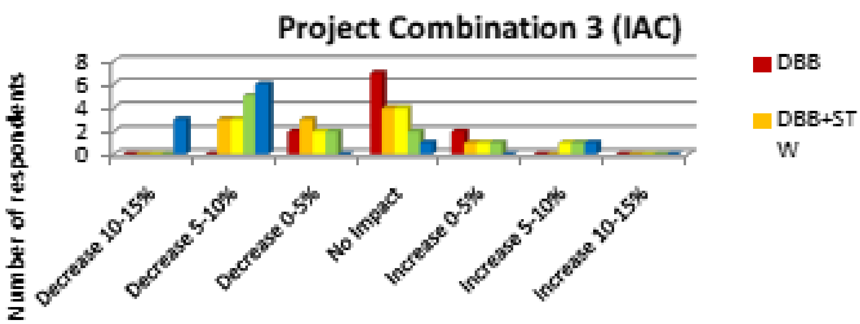

Project Combination 2 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

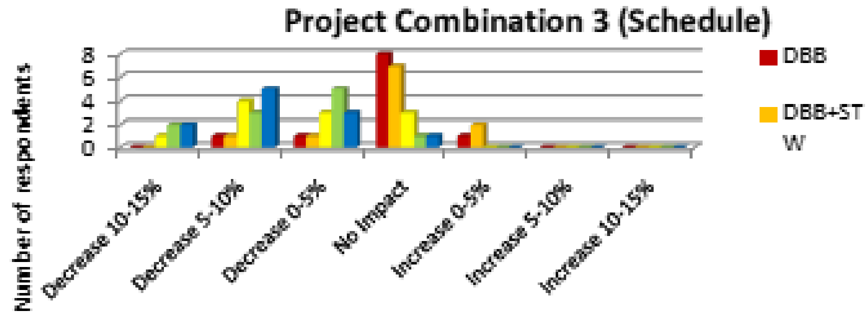
Project Combination 3

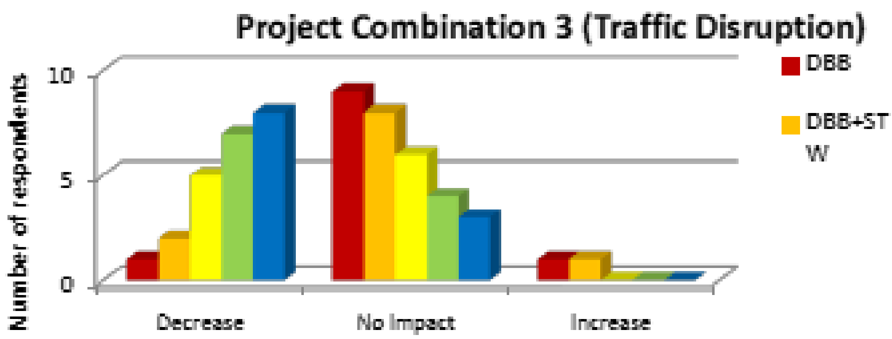
Size	Type	Traffic	Complexity	Location
Large	New construction	High AADT	High	Urban





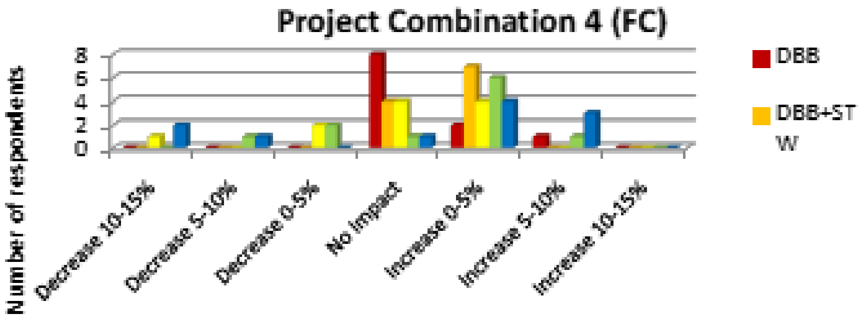


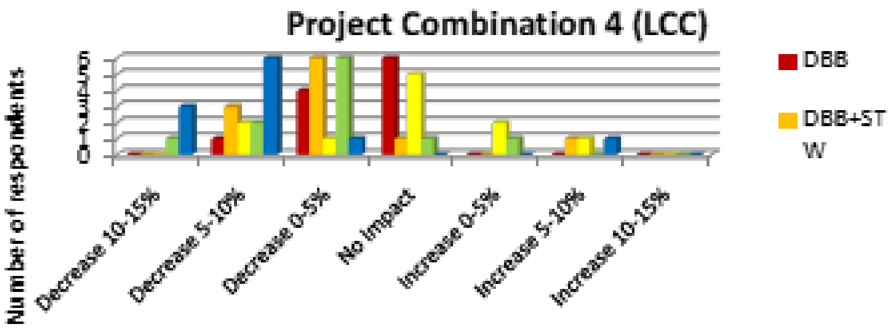

Project Combination 3 (Schedule)
Number of respondents
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

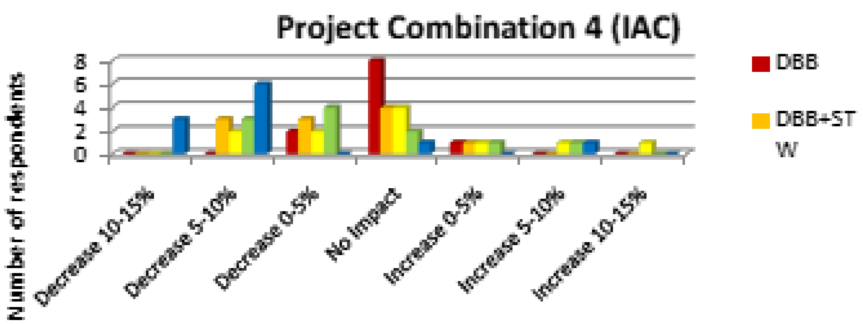

Project Combination 3 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

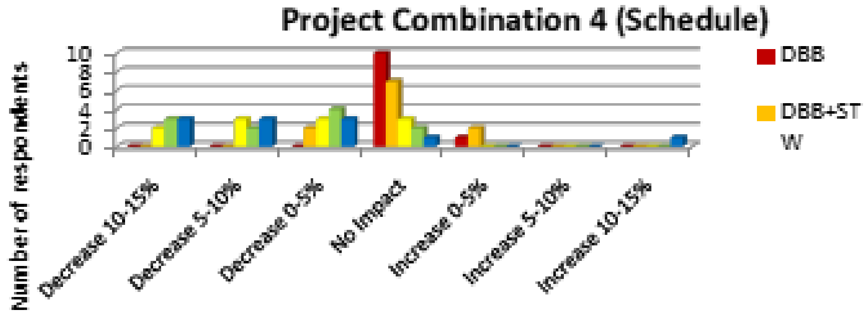
Project Combination 4

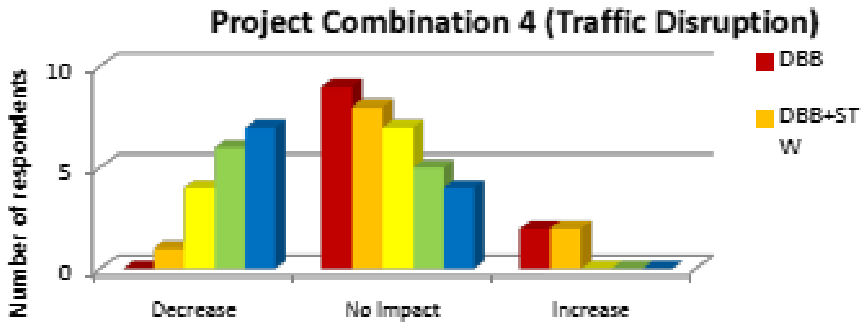
Size	Type	Traffic	Complexity	Location
Large	New construction	High AADT	Low	Rural





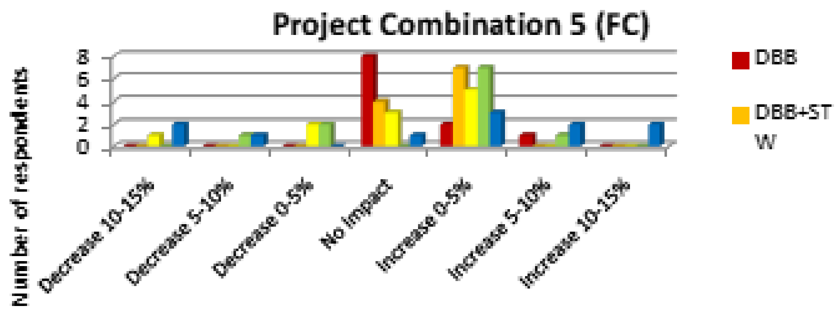


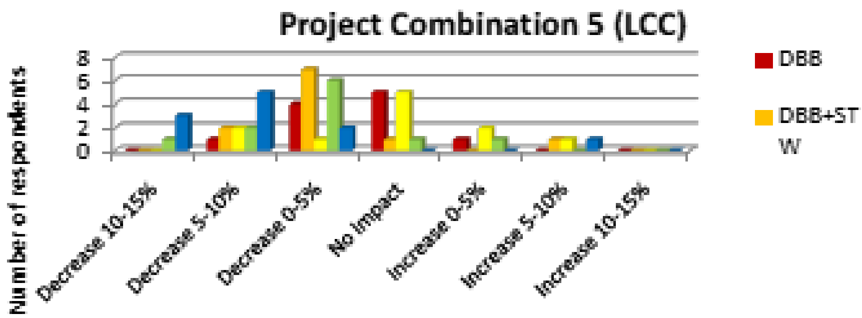

Project Combination 4 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

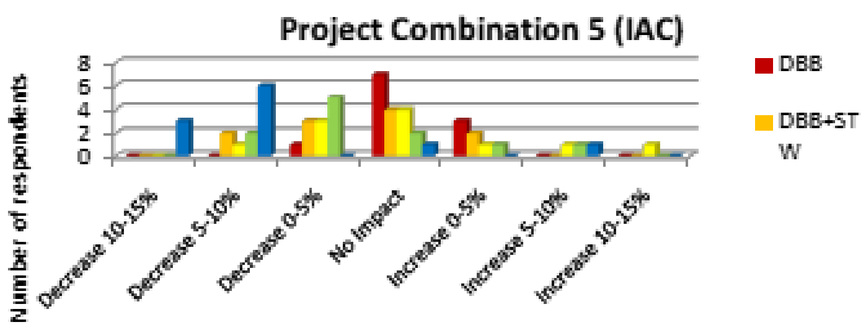

Project Combination 4 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

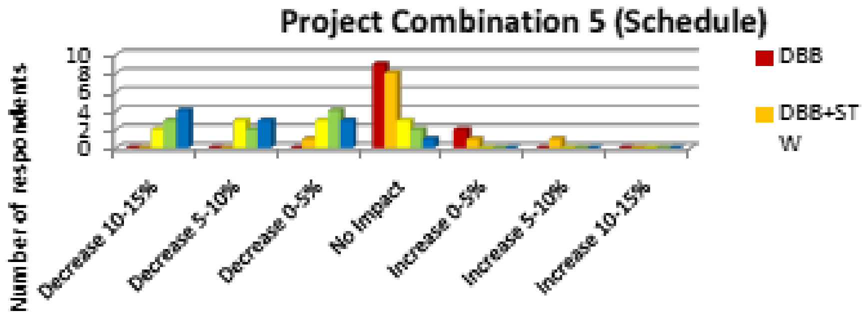
Project Combination 5

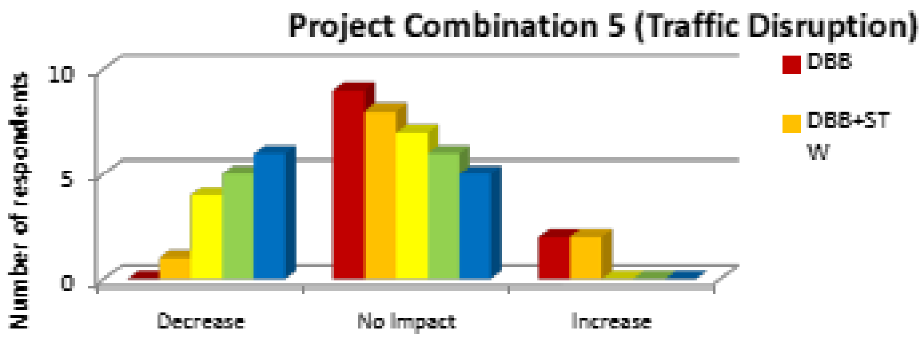
Size	Type	Traffic	Complexity	Location
Large	New construction	High AADT	High	Urban





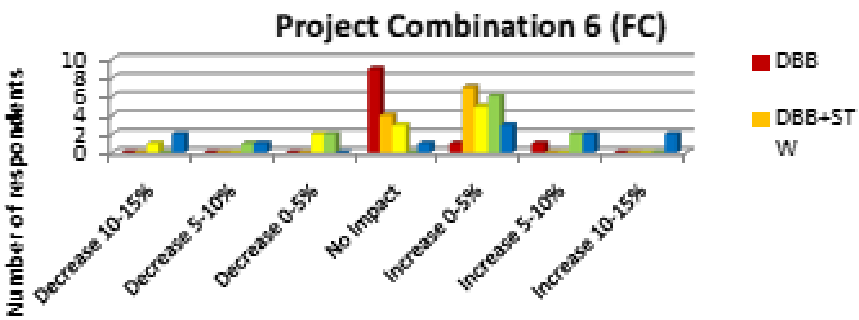


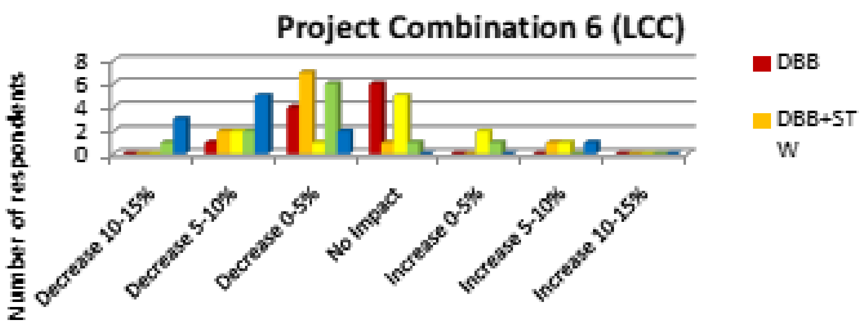

Project Combination 5 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

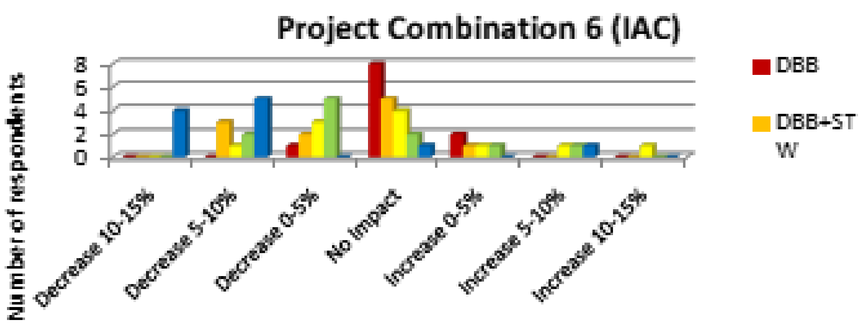

Project Combination 5 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

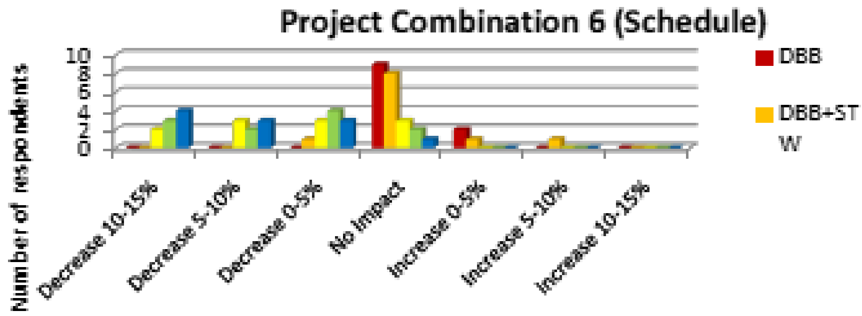
Project Combination 6

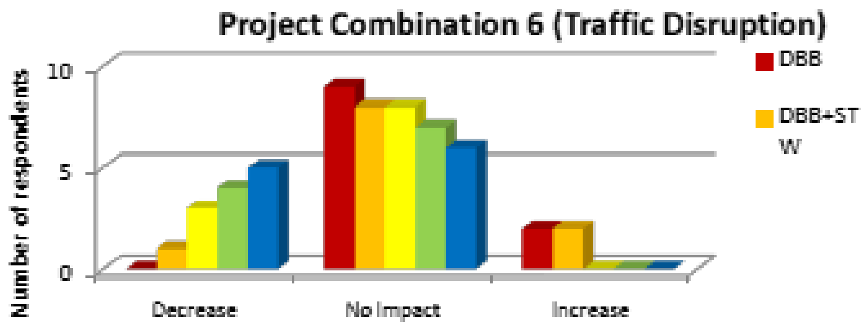
Size	Type	Traffic	Complexity	Location
Large	New construction	High AADT	High	Rural





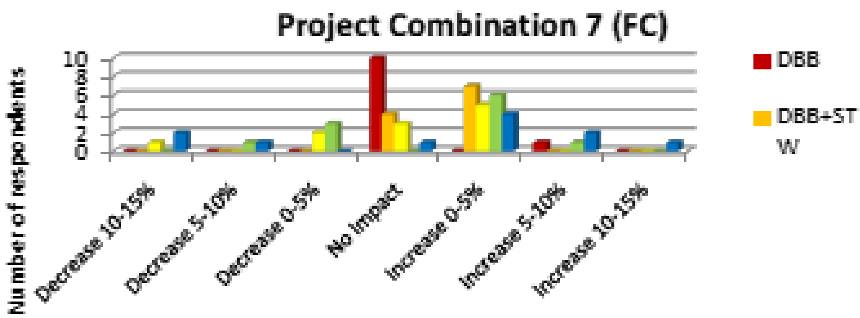


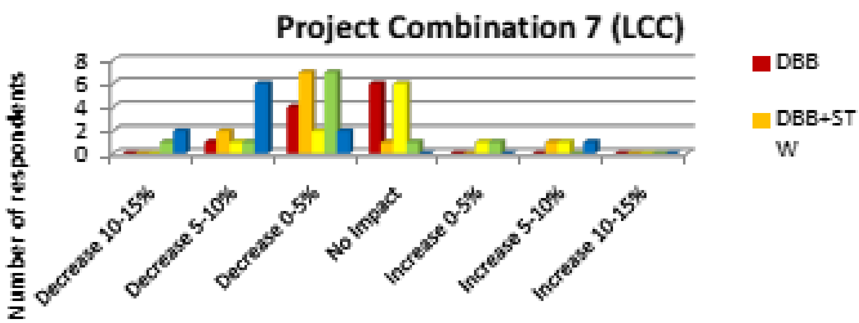

Project Combination 6 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

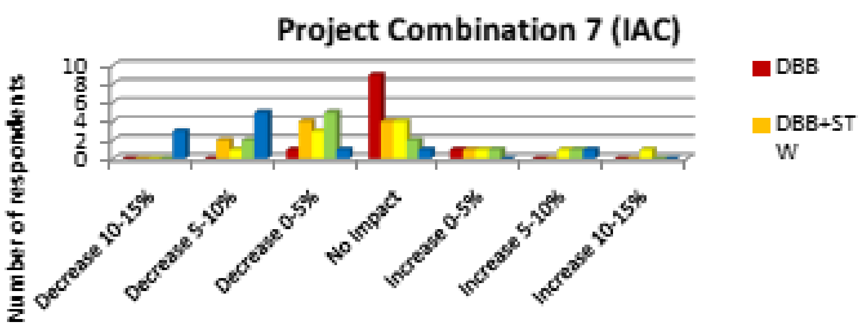

Project Combination 6 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

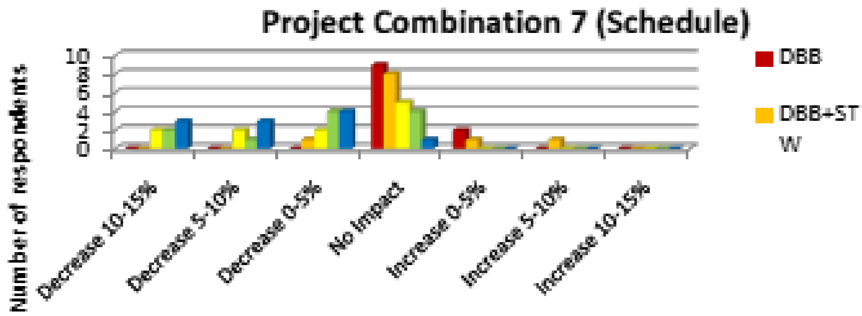
Project Combination 7

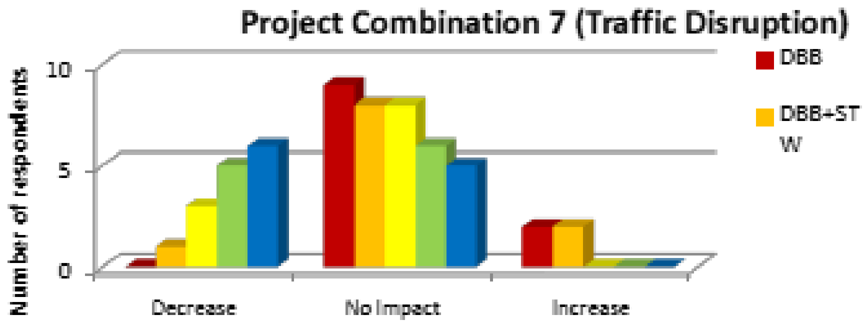
Size	Type	Traffic	Complexity	Location
Large	New construction	Low AADT	Low	Urban





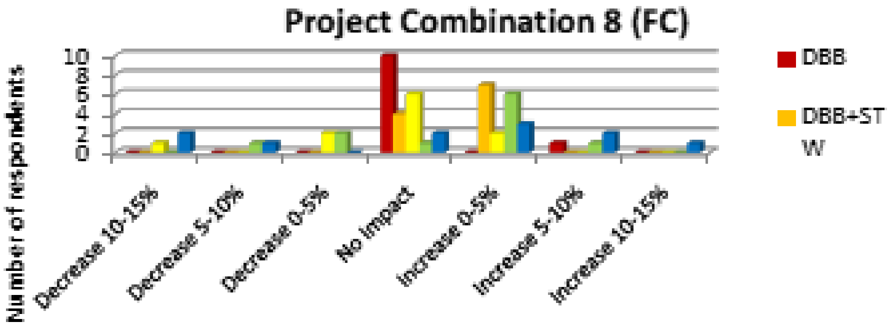


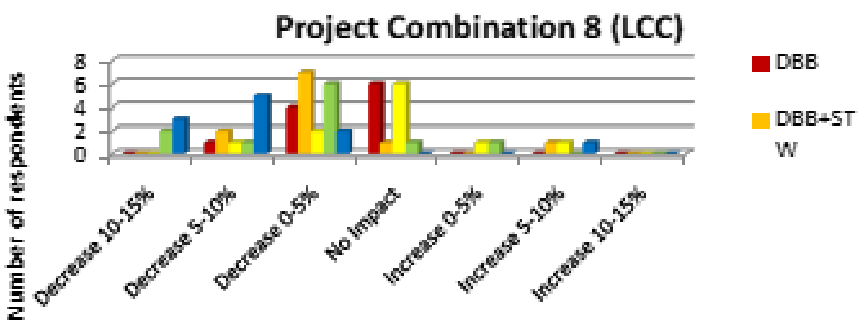

Project Combination 7 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST W

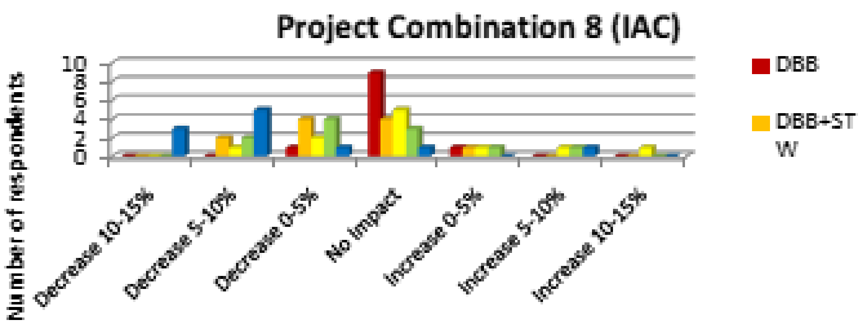

Project Combination 7 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST W

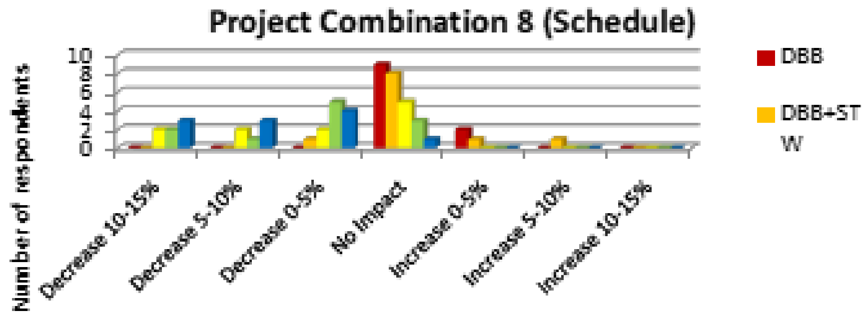
Project Combination 8

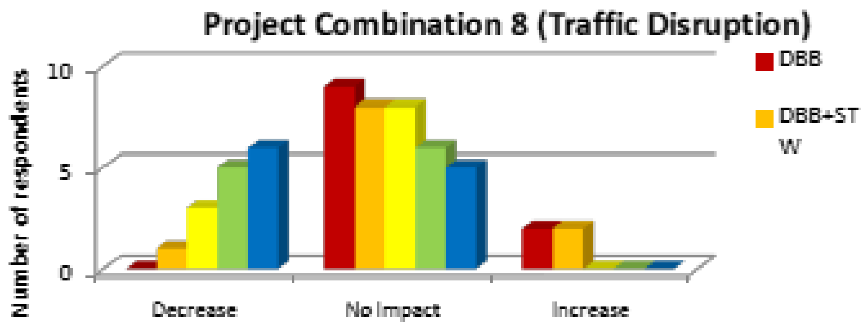
Size	Type	Traffic	Complexity	Location
Large	New construction	Low AADT	Low	Rural





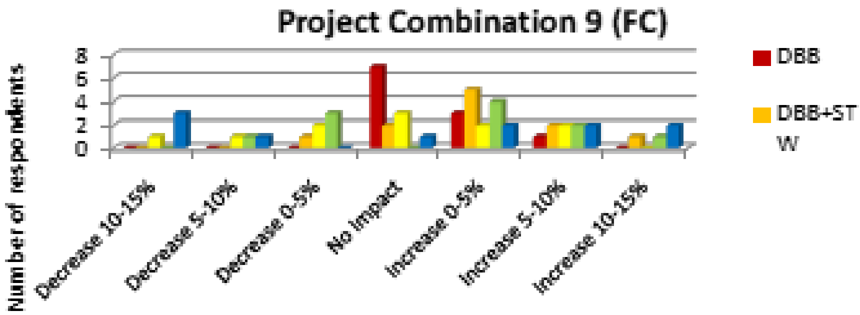


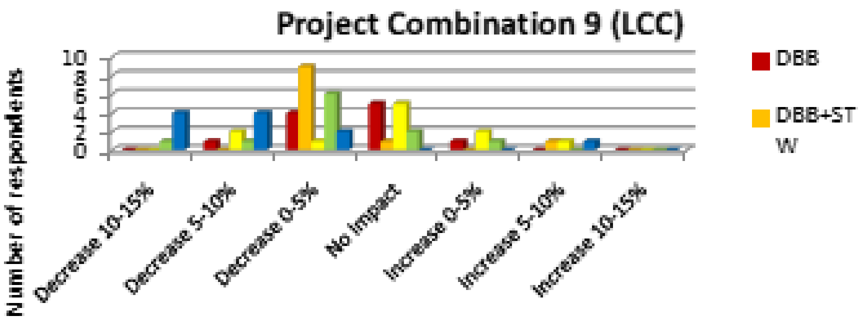

Project Combination 8 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

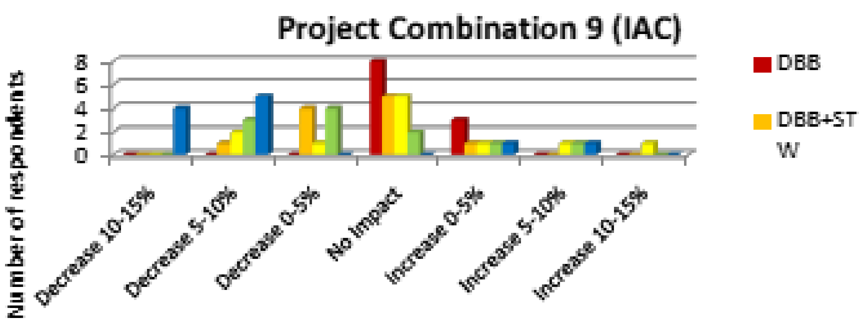

Project Combination 8 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

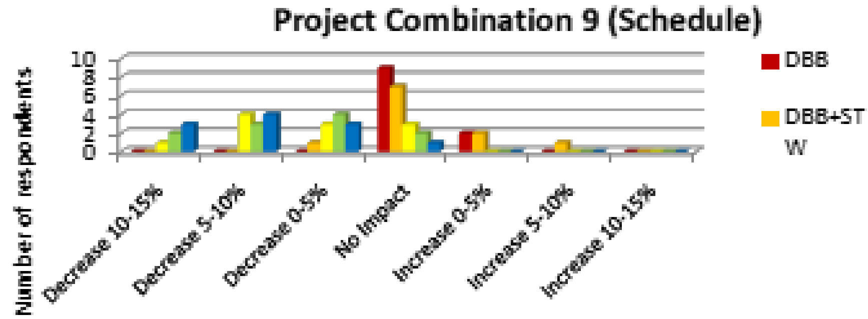
Project Combination 9

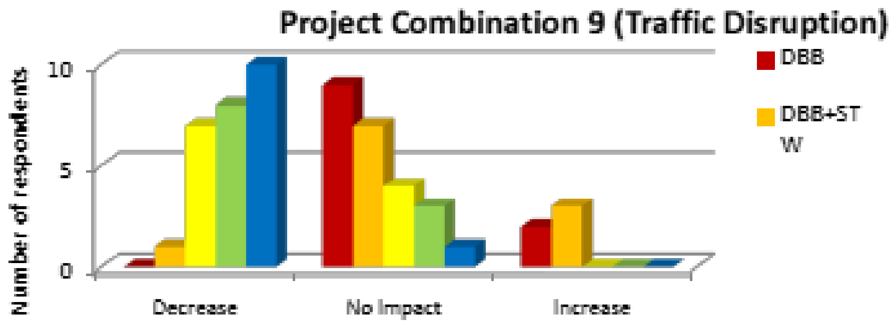
Size	Type	Traffic	Complexity	Location
Large	4R construction	High AADT	High	Urban





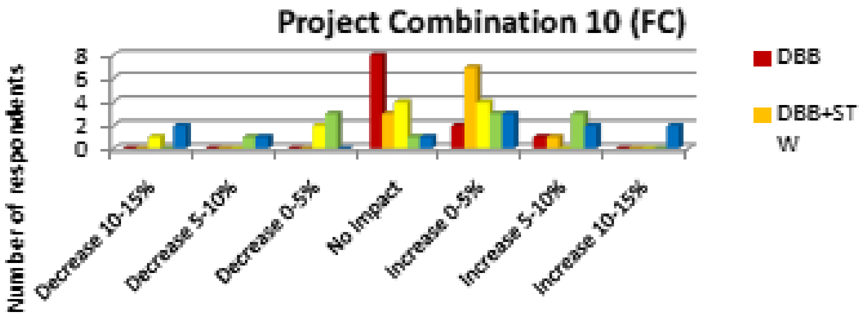


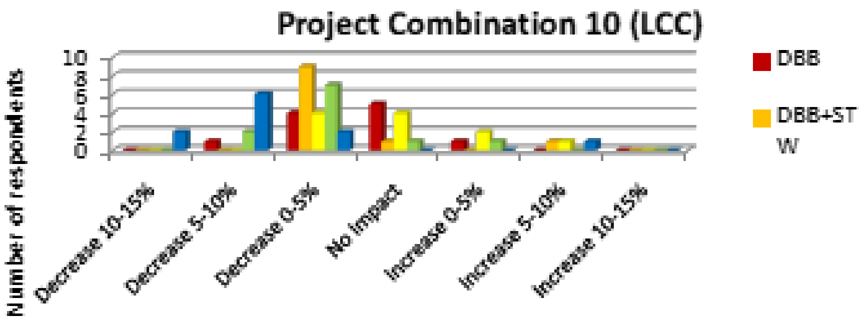

Project Combination 9 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

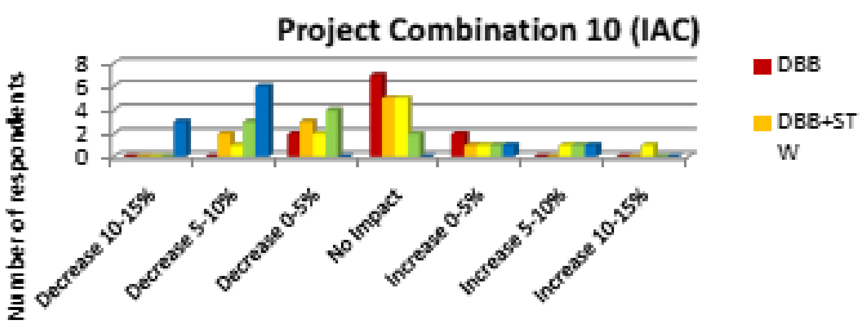

Project Combination 9 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

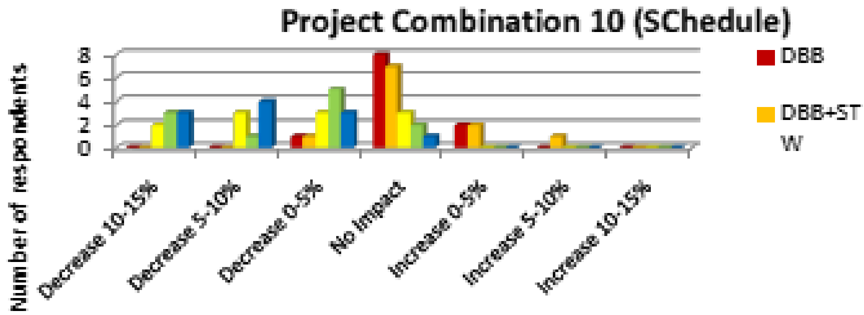
Project Combination 10

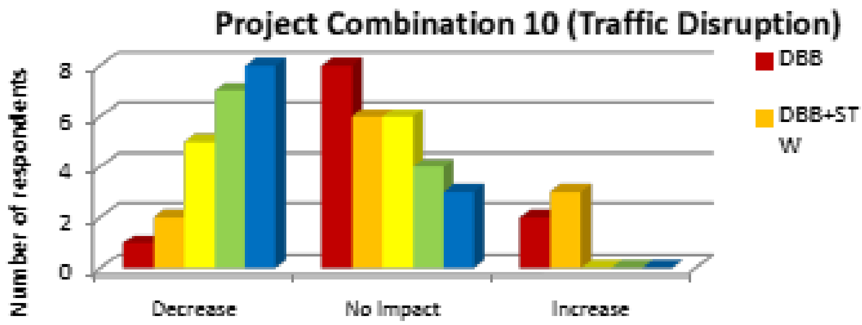
Size	Type	Traffic	Complexity	Location
Large	4R construction	High AADT	High	Rural





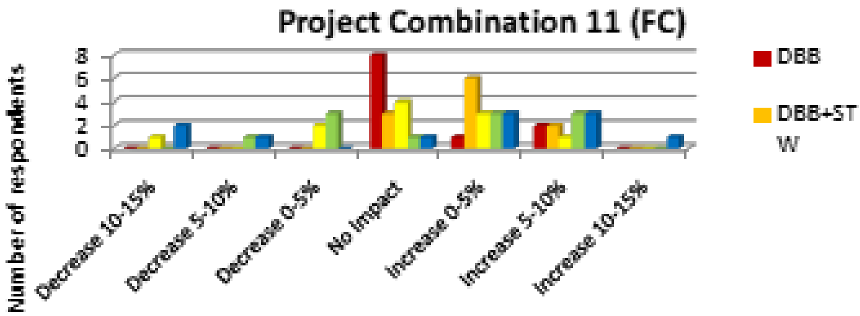


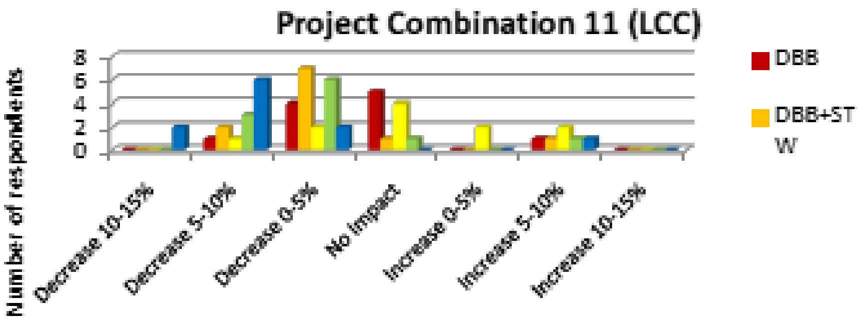

Project Combination 10 (SChedule)
Number of respondents
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

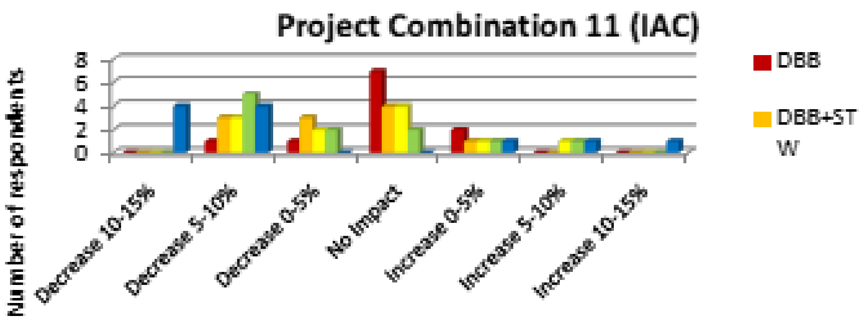

Project Combination 10 (Traffic Disruption)
Number of respondents
8
6
4
2
0
Decrease
No Impact
Increase
DBB
DBB+STW

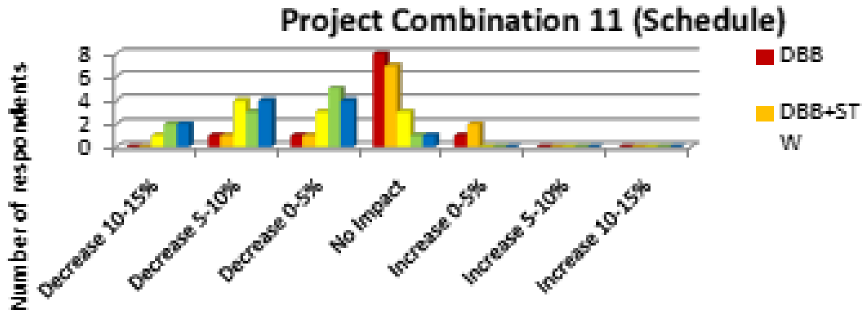
Project Combination 11

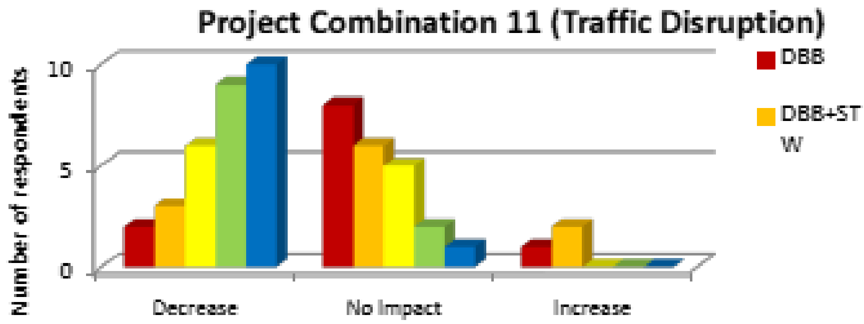
Size	Type	Traffic	Complexity	Location
Large	4R construction	High AADT	Low	Urban





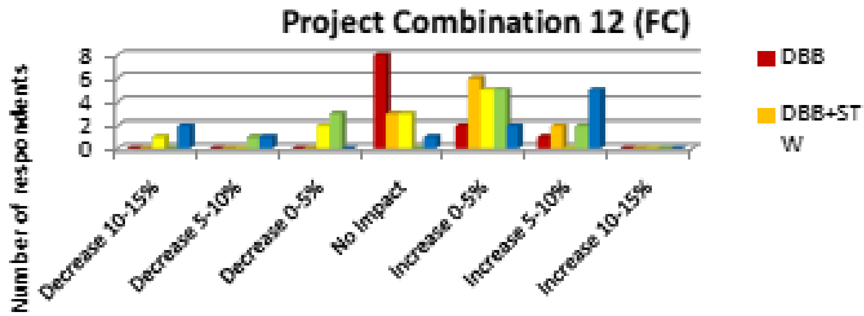


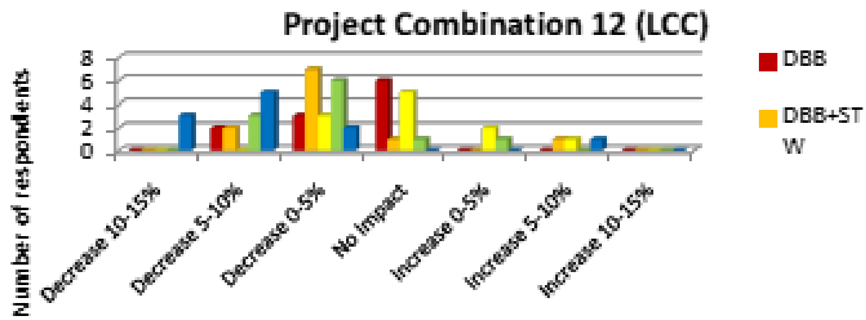

Project Combination 11 (Schedule)
Number of respondents
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

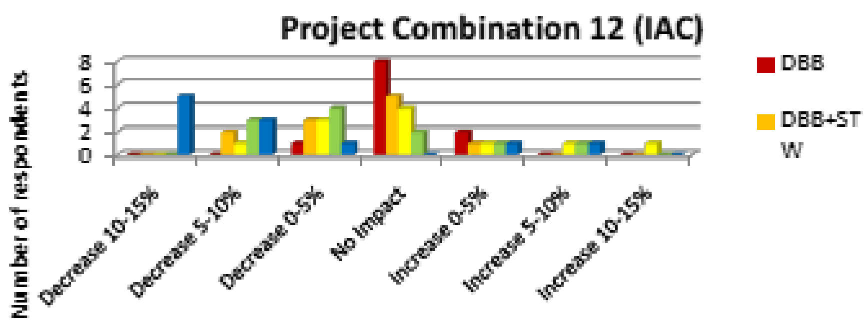

Project Combination 11 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

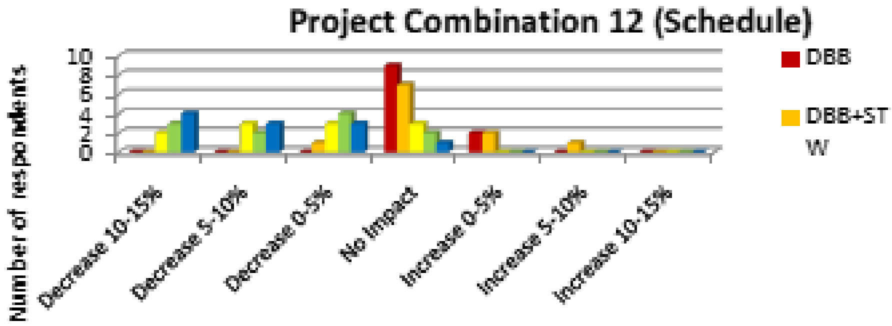
Project Combination 12

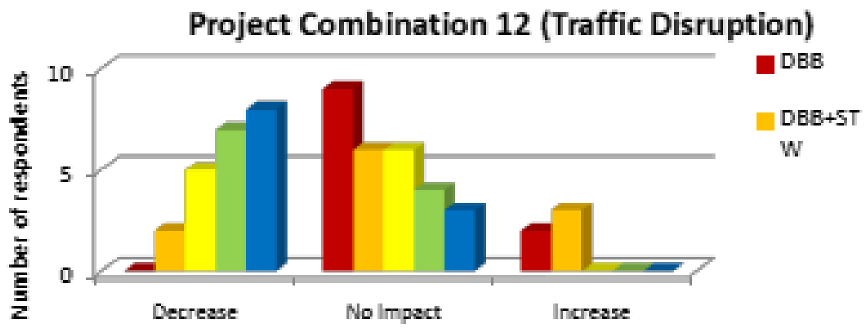
Size	Type	Traffic	Complexity	Location
Large	4R construction	High AADT	Low	Urban





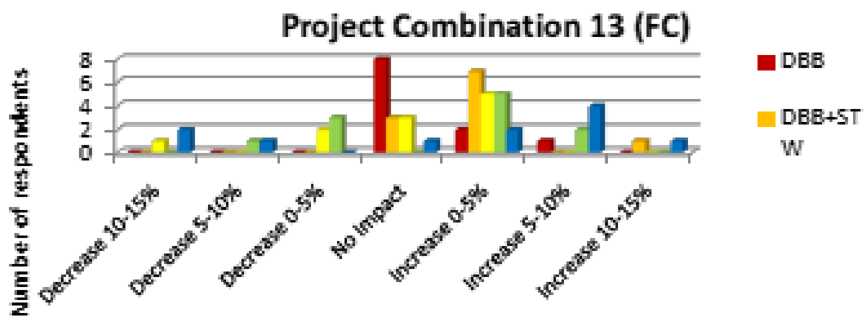


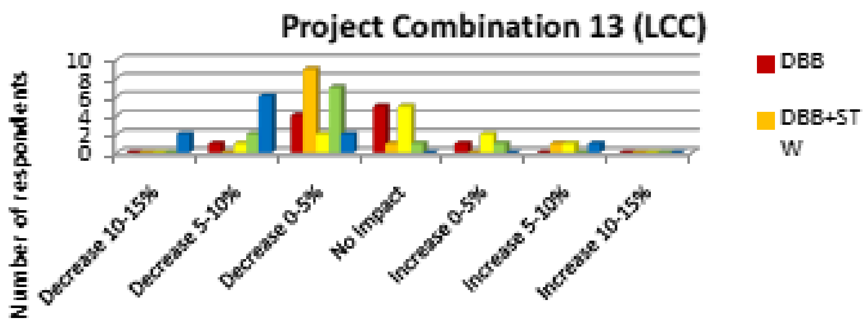

Project Combination 12 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

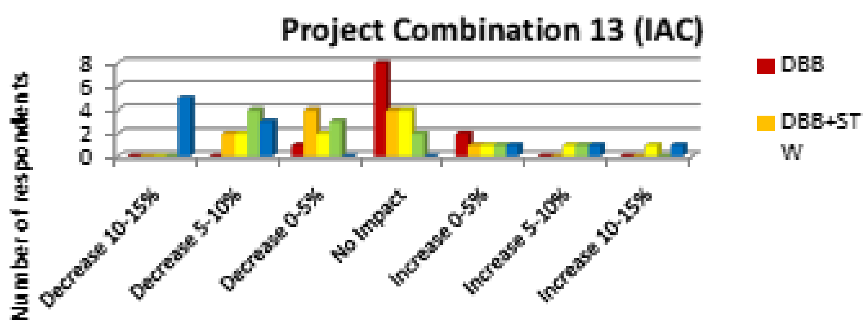

Project Combination 12 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

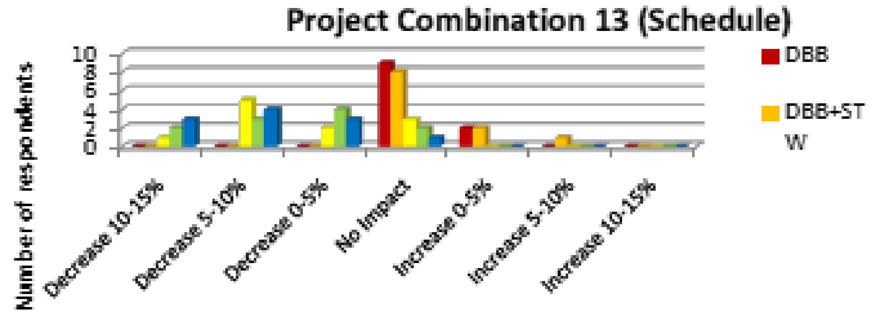
Project Combination 13

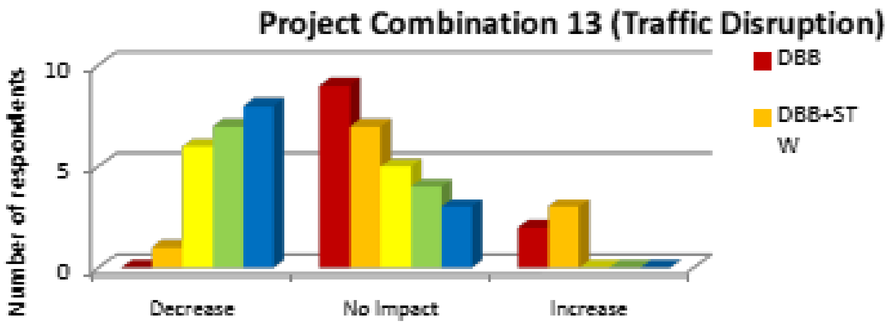
Size	Type	Traffic	Complexity	Location
Large	4R construction	Low AADT	High	Urban





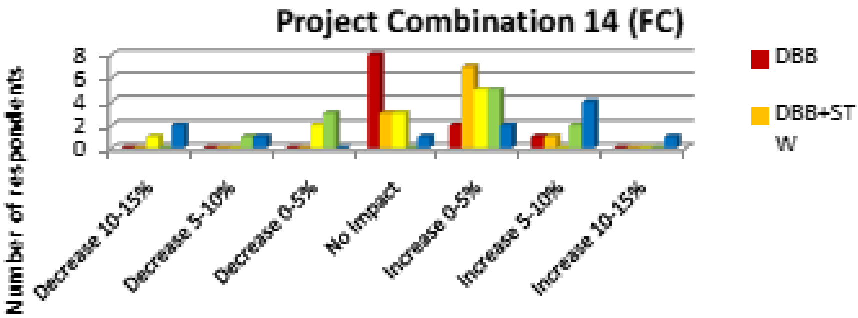


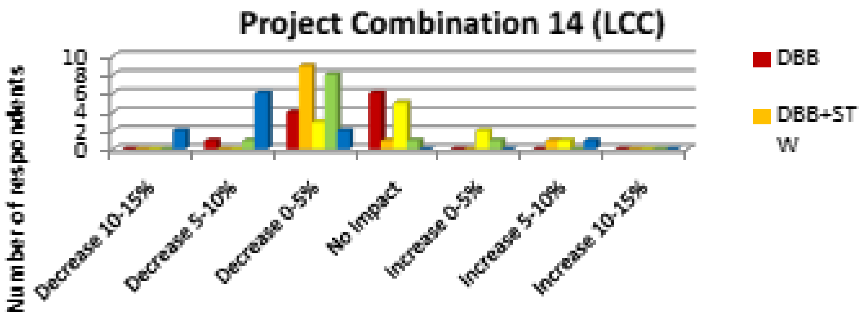

Project Combination 13 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

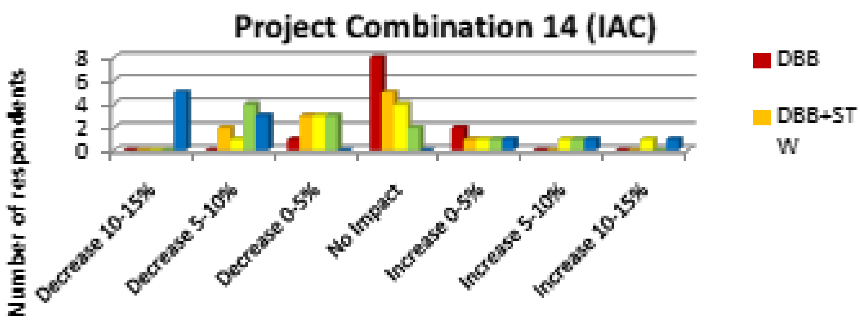

Project Combination 13 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

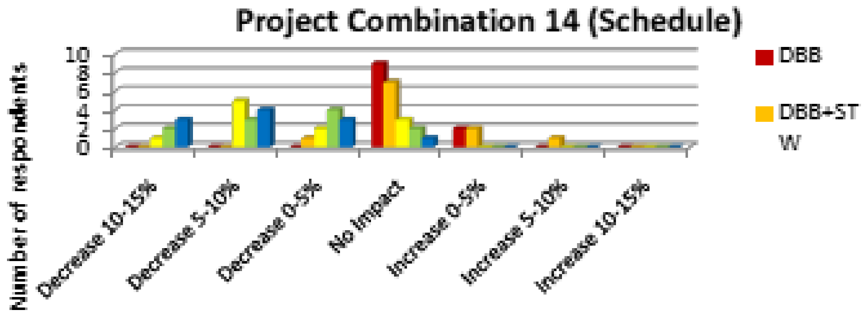
Project Combination 14

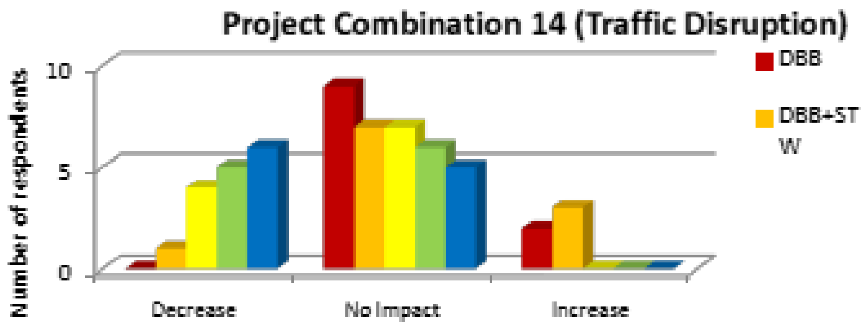
Size	Type	Traffic	Complexity	Location
Large	4R construction	Low AADT	High	Rural





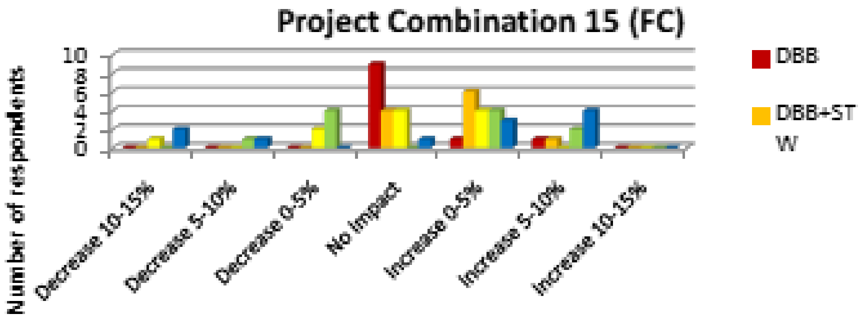


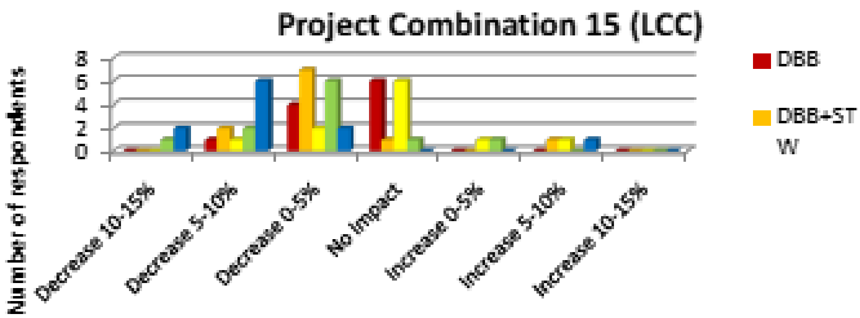

Project Combination 14 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST W

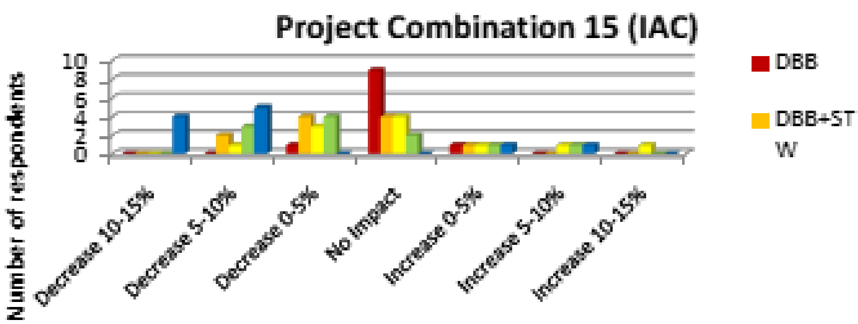

Project Combination 14 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST W

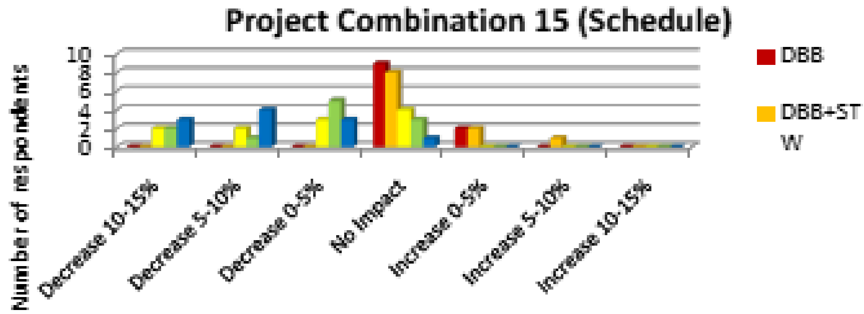
Project Combination 15

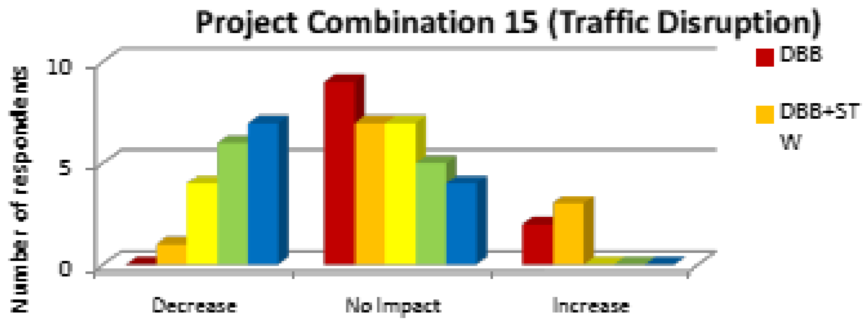
Size	Type	Traffic	Complexity	Location
Large	4R construction	Low AADT	Low	Urban





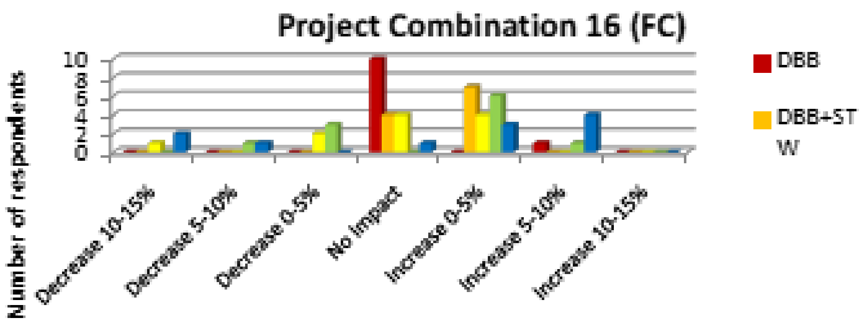


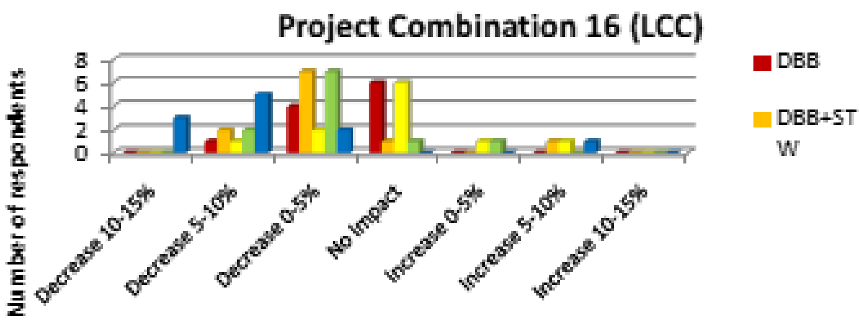

Project Combination 15 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

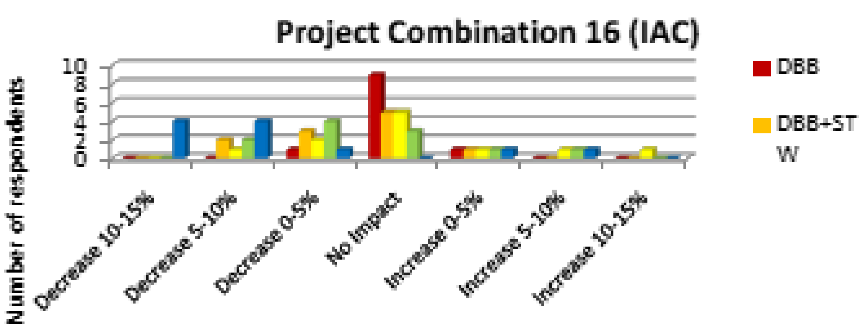

Project Combination 15 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

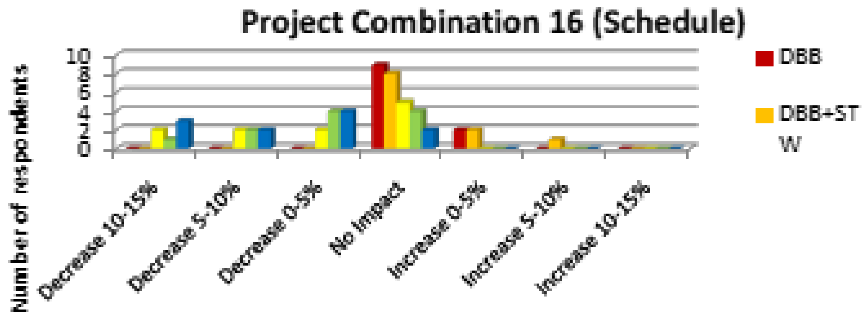
Project Combination 16

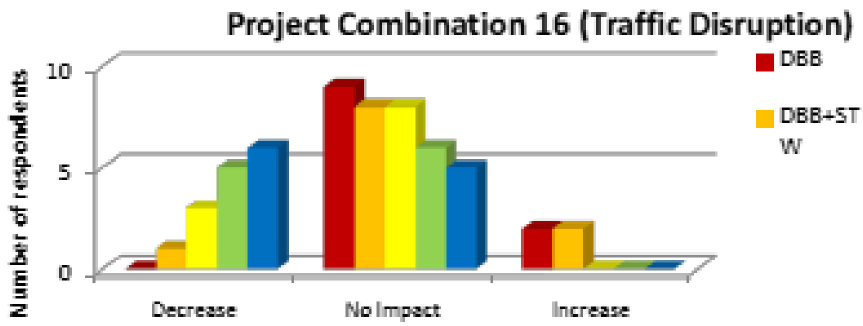
Size	Type	Traffic	Complexity	Location
Large	4R construction	Low AADT	Low	Rural





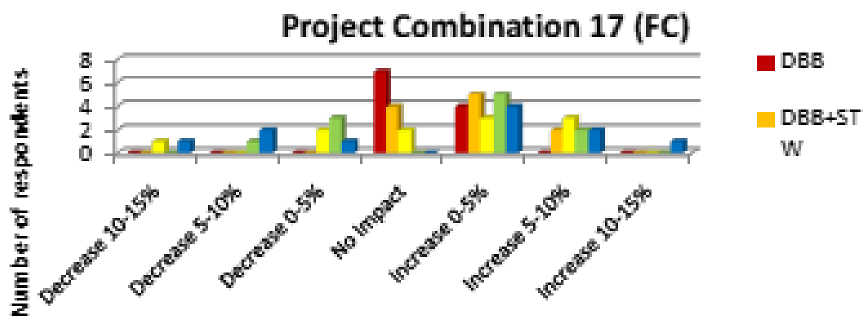


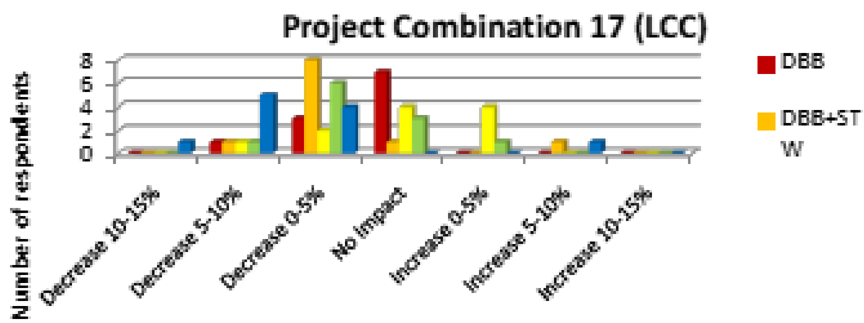

Project Combination 16 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

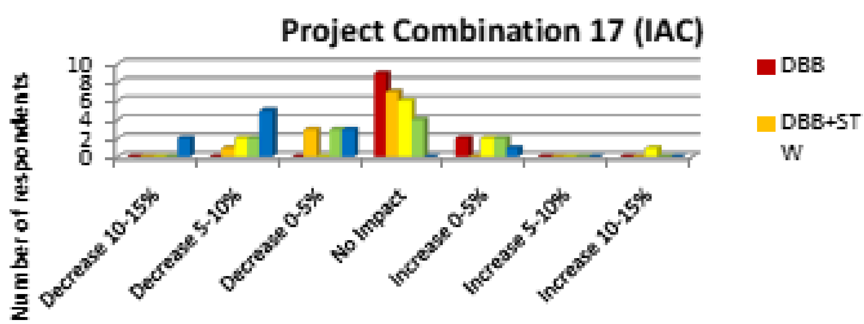

Project Combination 16 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

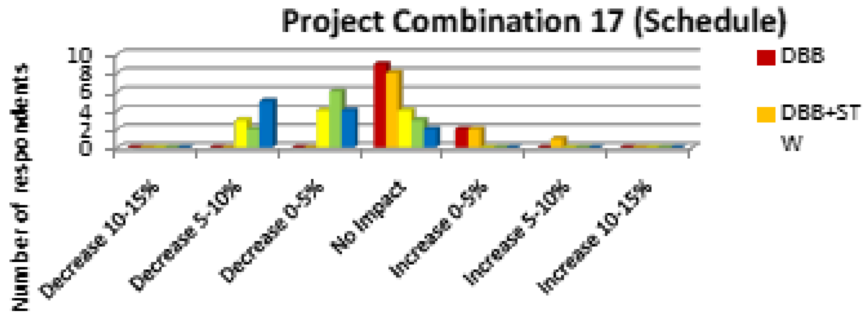
Project Combination 17

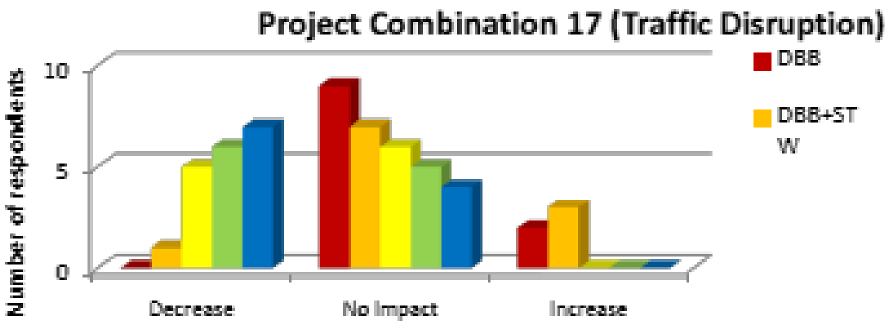
Size	Type	Traffic	Complexity	Location
Small	New construction	High AADT	High	Urban





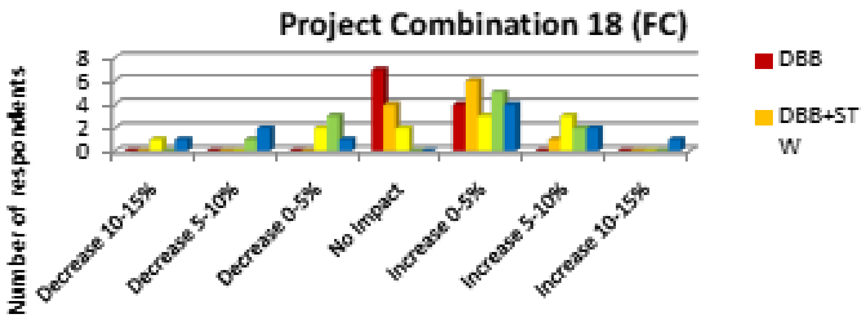


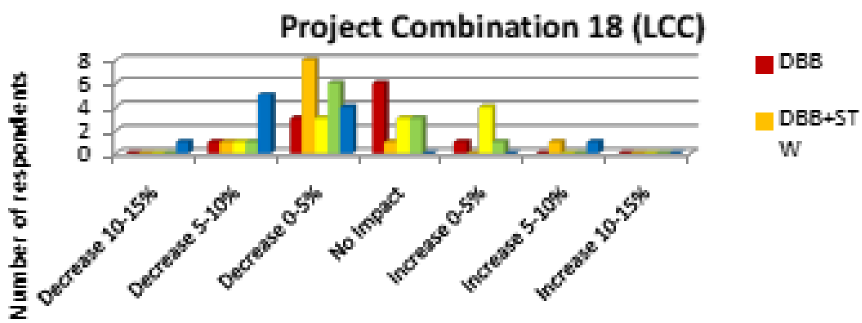

Project Combination 17 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

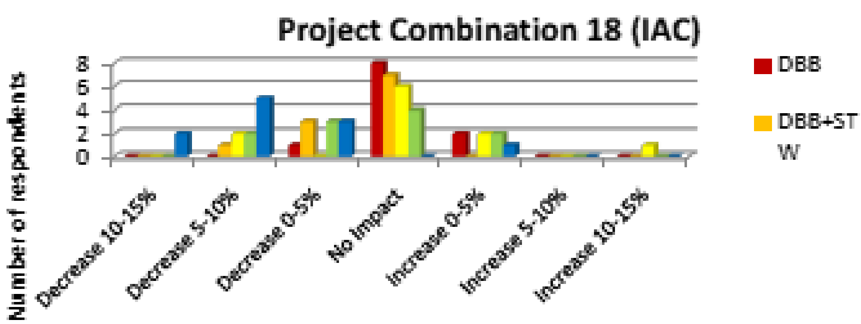

Project Combination 17 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

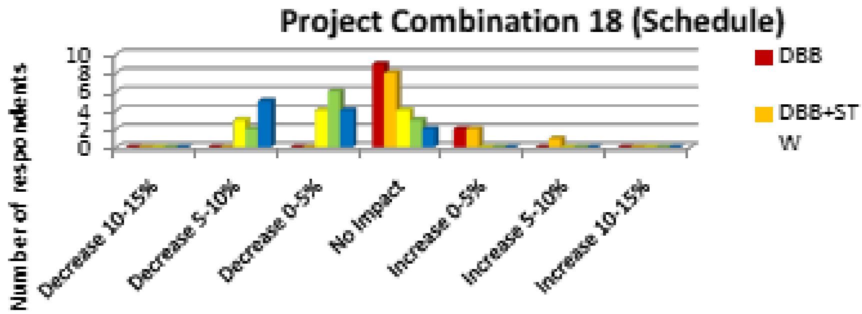
Project Combination 18

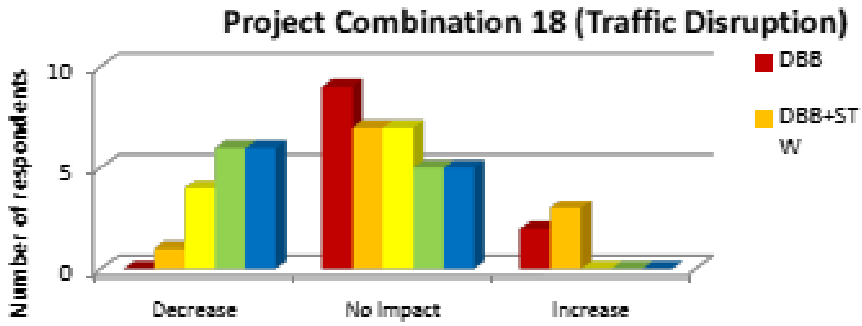
Size	Type	Traffic	Complexity	Location
Small	New construction	High AADT	High	Urban





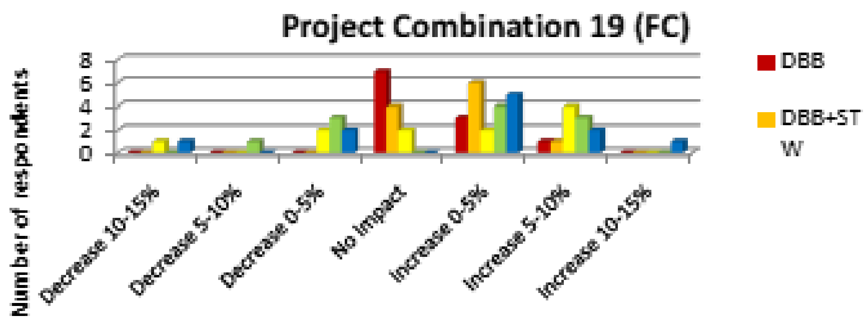


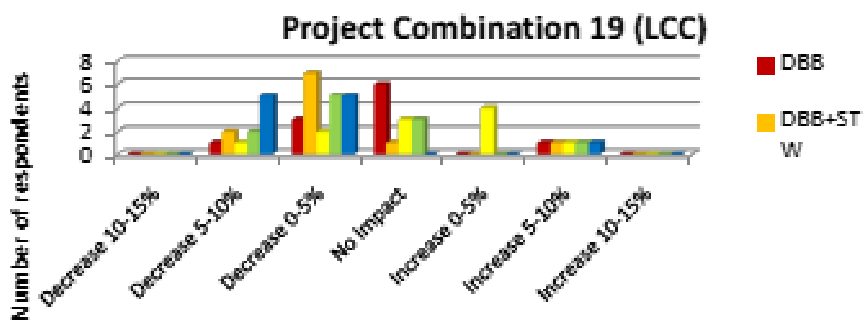

Project Combination 18 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

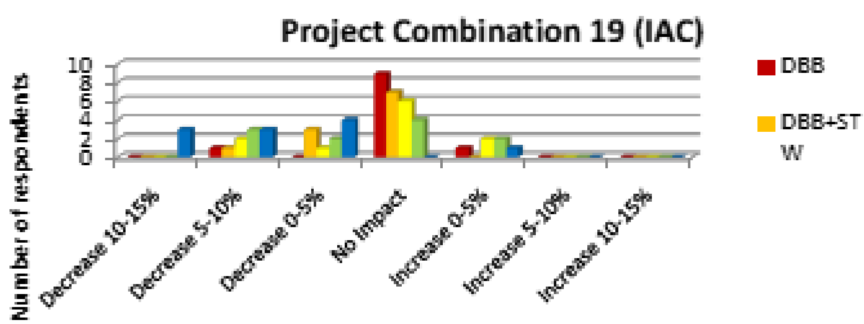

Project Combination 18 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

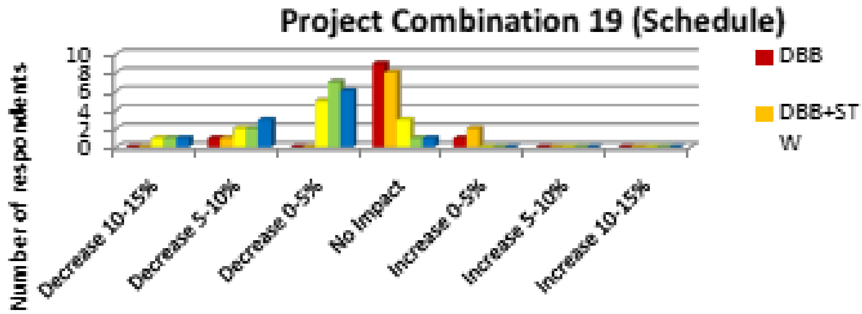
Project Combination 19

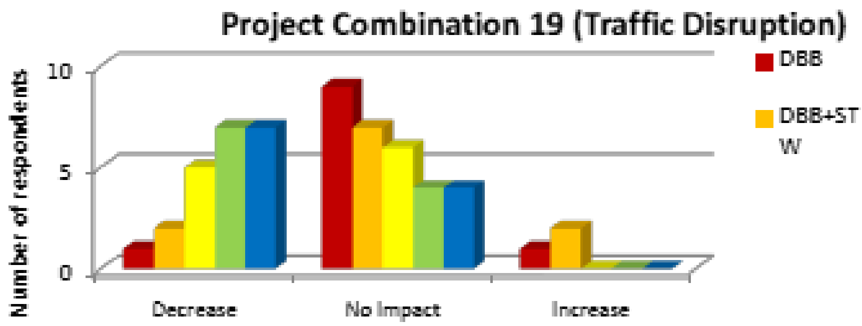
Size	Type	Traffic	Complexity	Location
Small	New construction	High AADT	Low	Urban





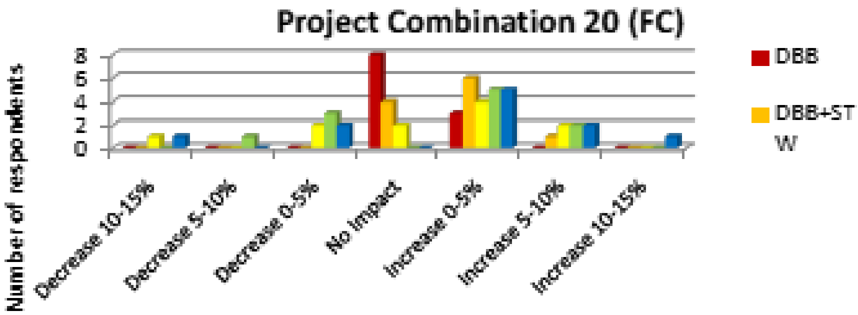


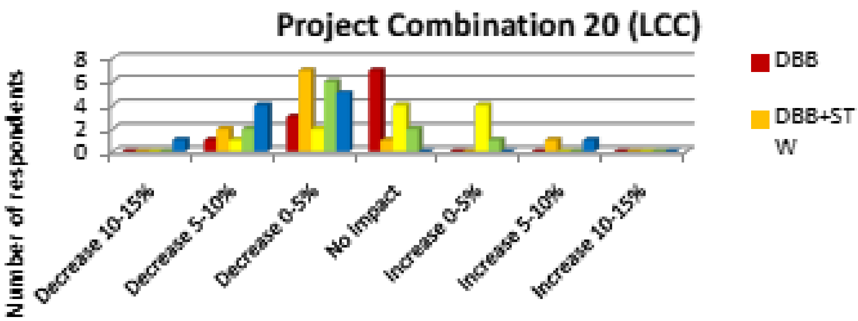

Project Combination 19 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

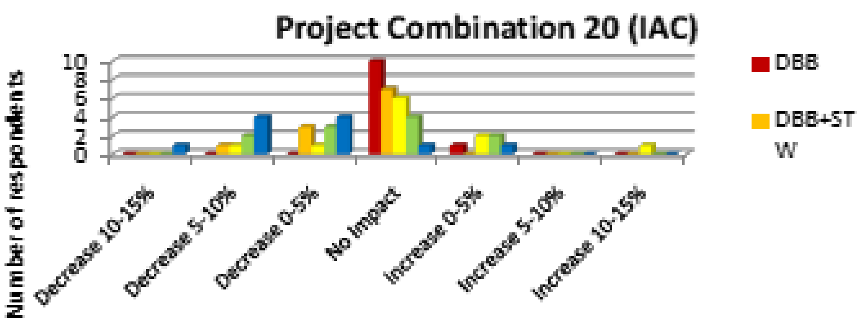

Project Combination 19 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

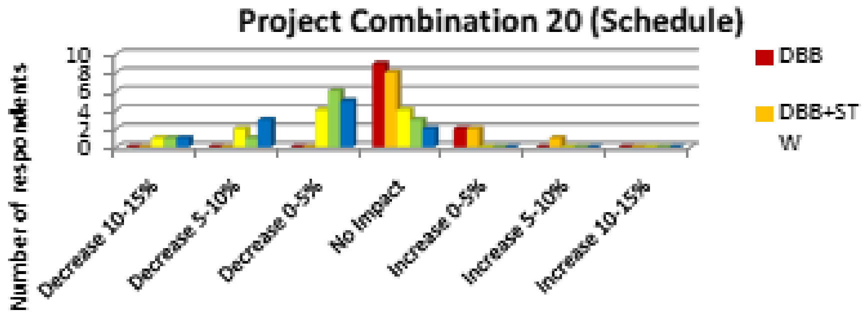
Project Combination 20

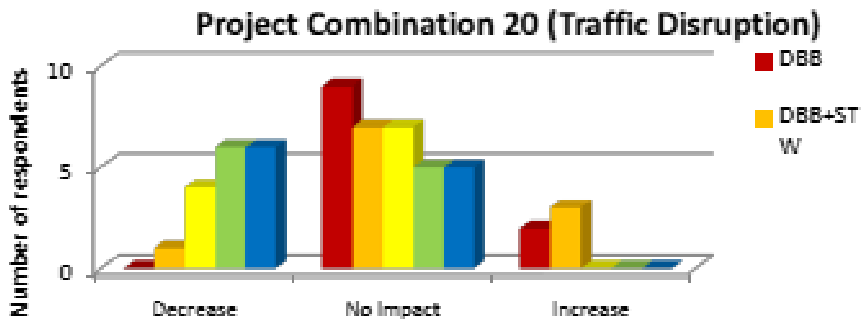
Size	Type	Traffic	Complexity	Location
Small	New construction	High AADT	Low	Rural





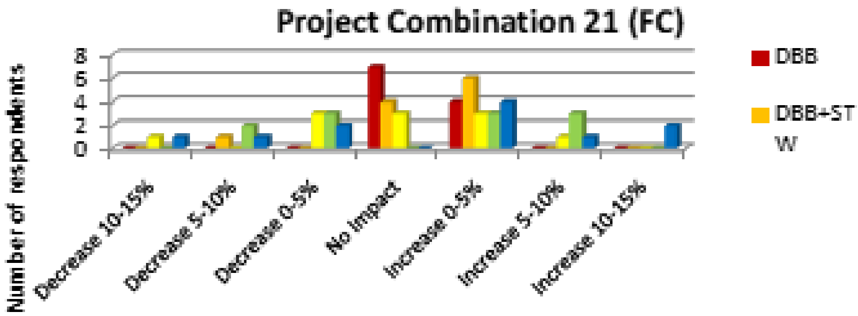


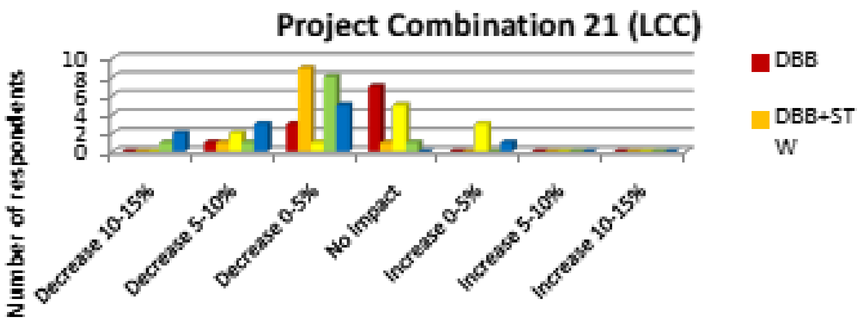

Project Combination 20 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

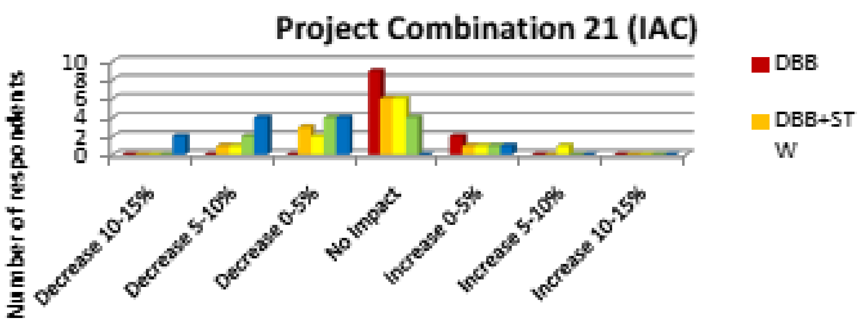

Project Combination 20 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

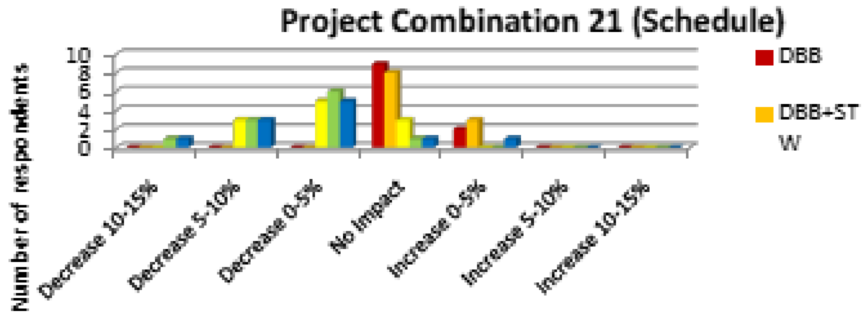
Project Combination 21

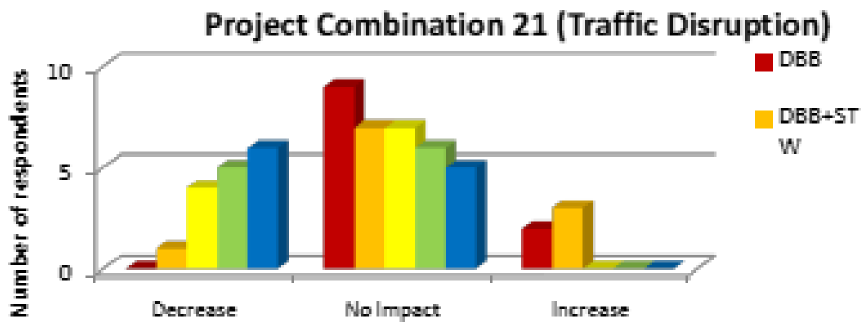
Size	Type	Traffic	Complexity	Location
Small	New construction	Low AADT	High	Urban





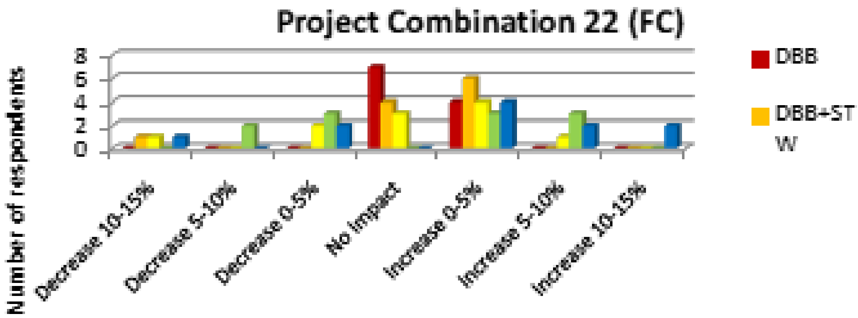


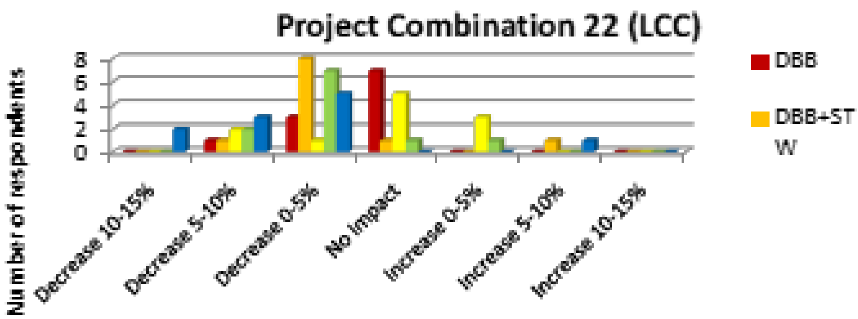

Project Combination 21 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST W

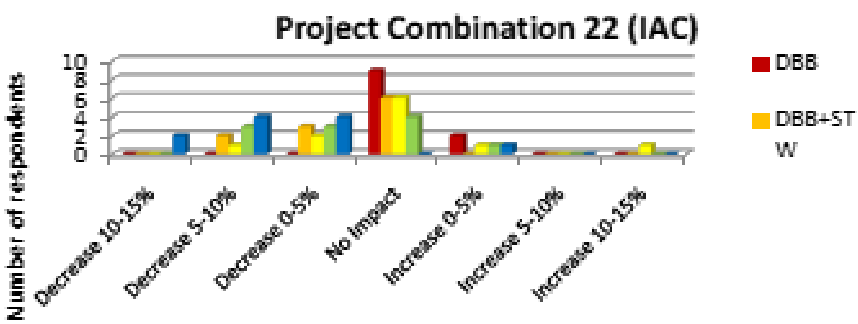

Project Combination 21 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST W

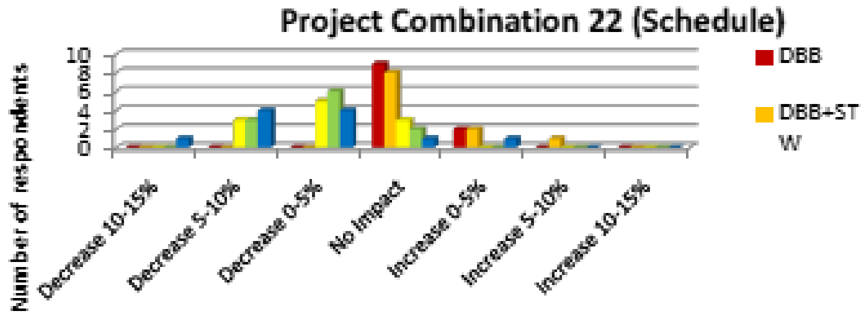
Project Combination 22

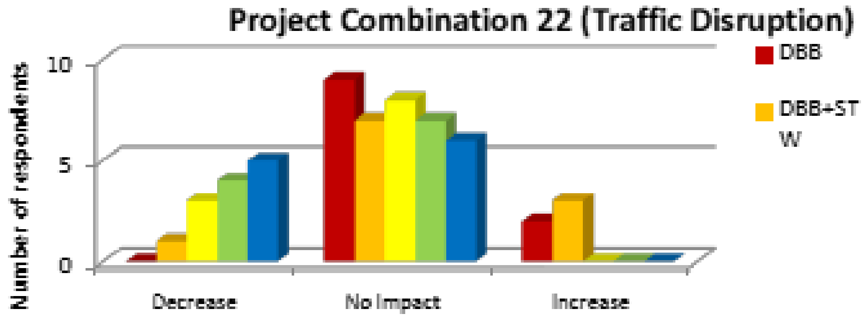
Size	Type	Traffic	Complexity	Location
Small	New construction	Low AADT	High	Rural





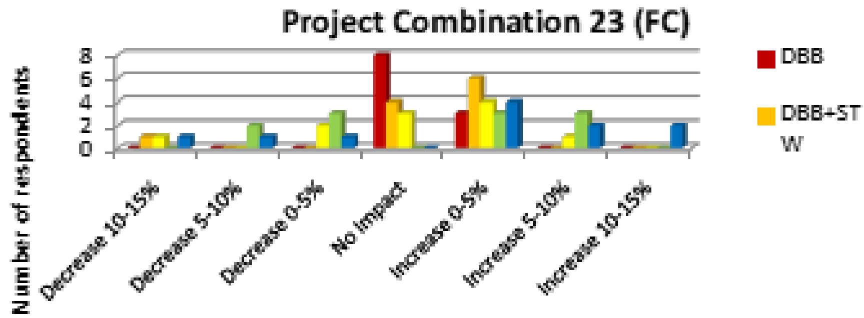


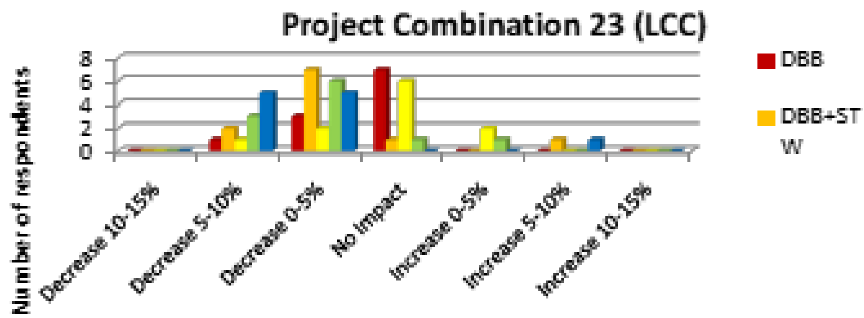

Project Combination 22 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

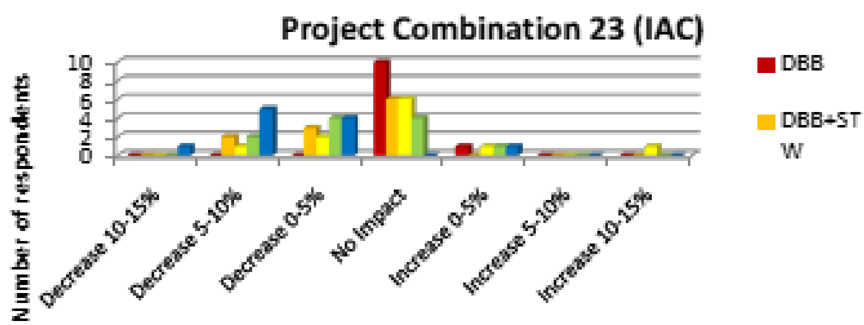

Project Combination 22 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

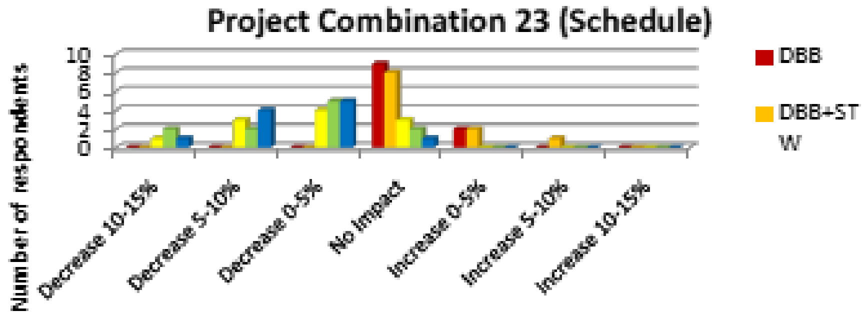
Project Combination 23

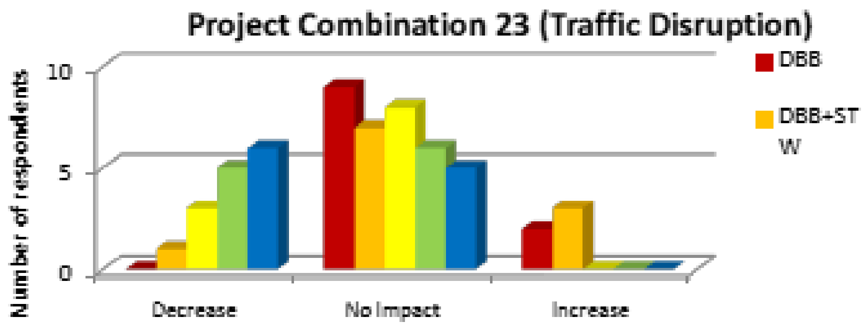
Size	Type	Traffic	Complexity	Location
Small	New construction	Low AADT	Low	Urban





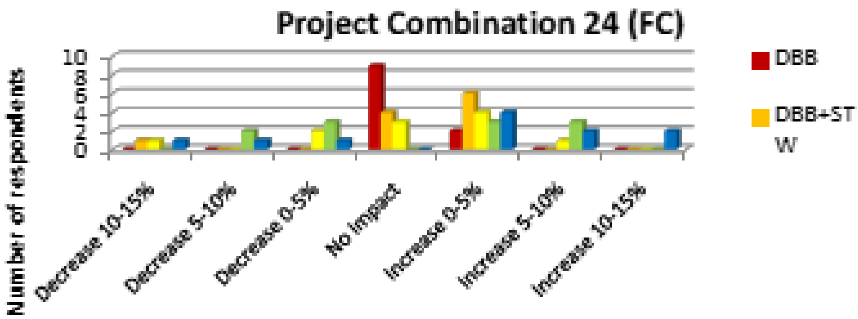


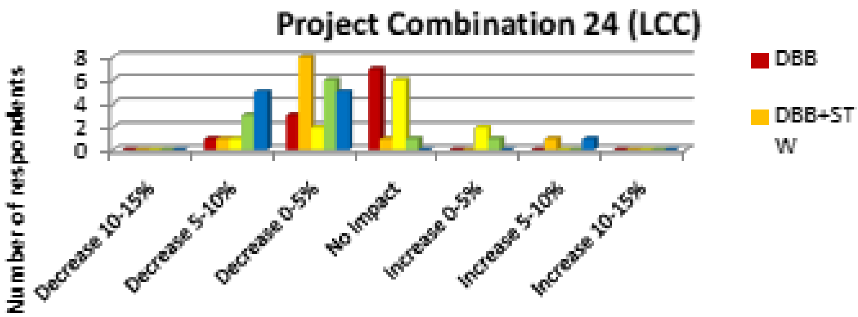

Project Combination 23 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

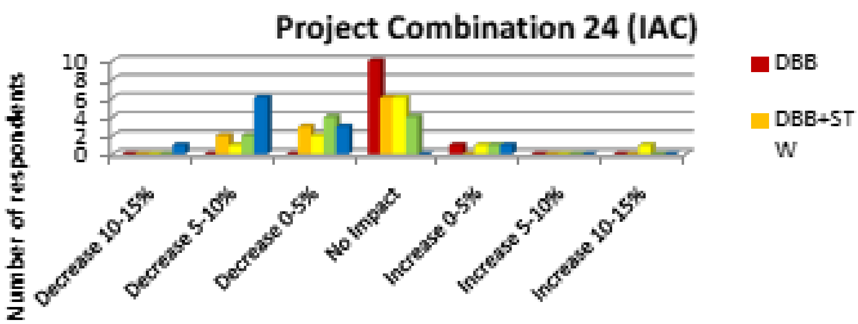

Project Combination 23 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

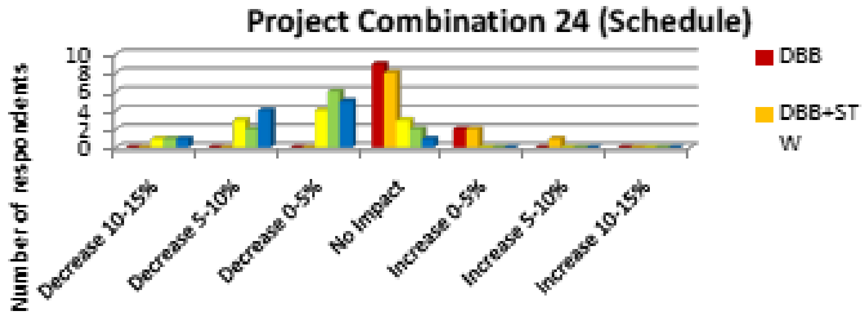
Project Combination 24

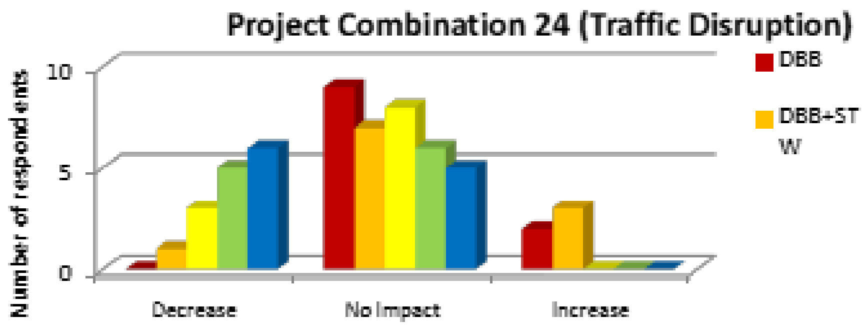
Size	Type	Traffic	Complexity	Location
Small	New construction	Low AADT	Low	Rural





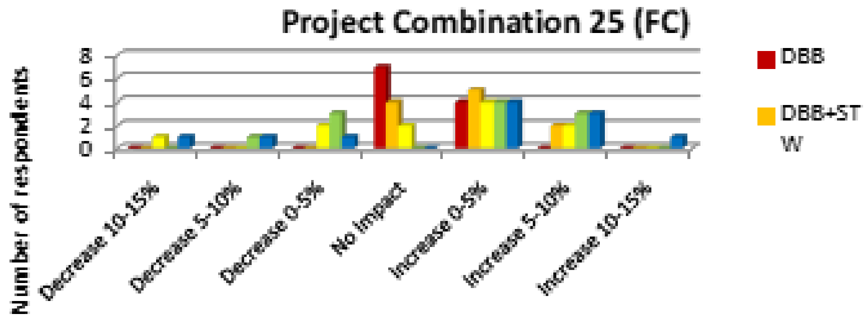


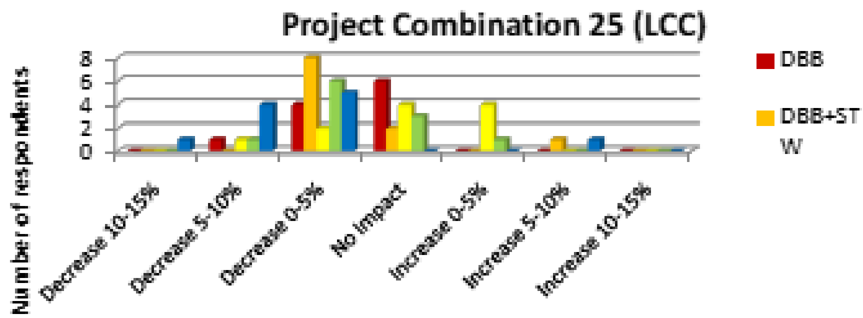

Project Combination 24 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

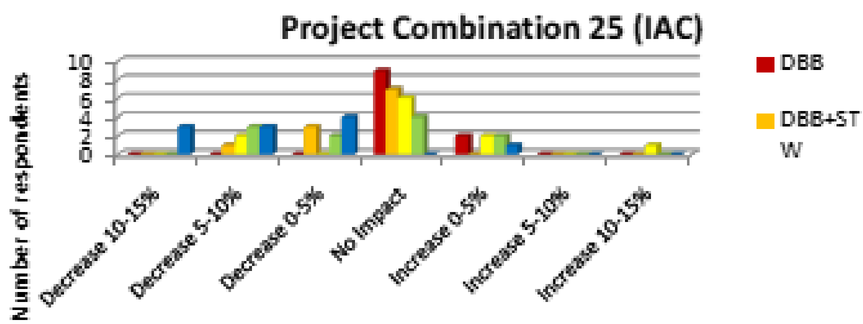

Project Combination 24 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

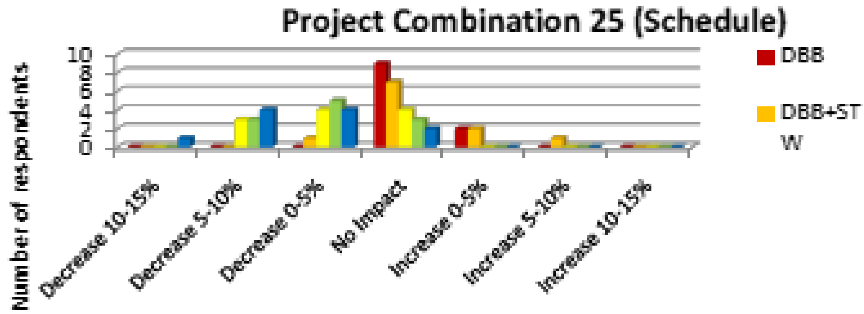
Project Combination 25

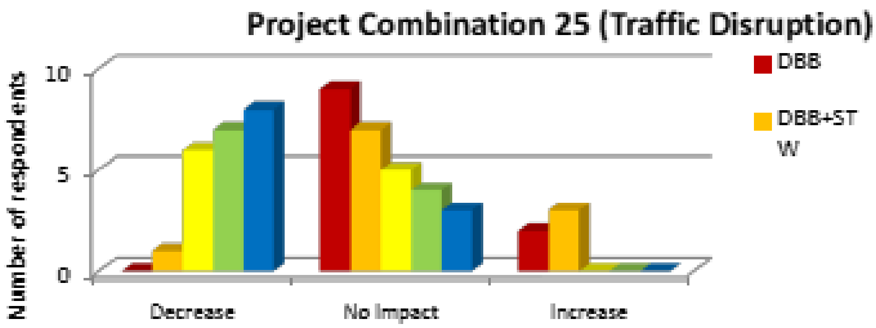
Size	Type	Traffic	Complexity	Location
Small	4R construction	High AADT	High	Urban





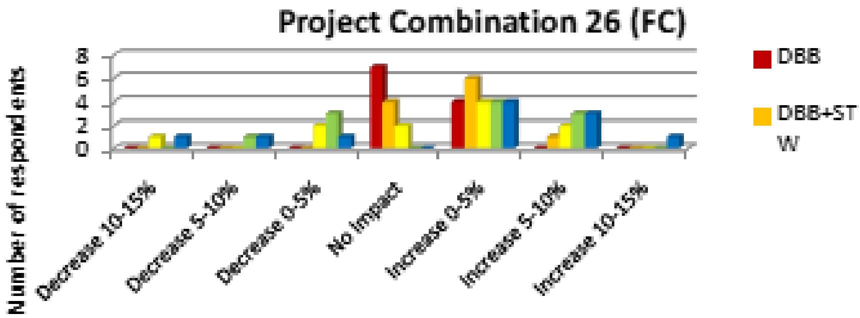


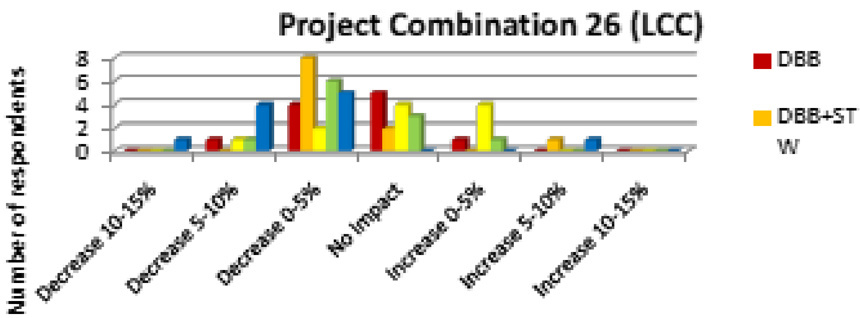

Project Combination 25 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

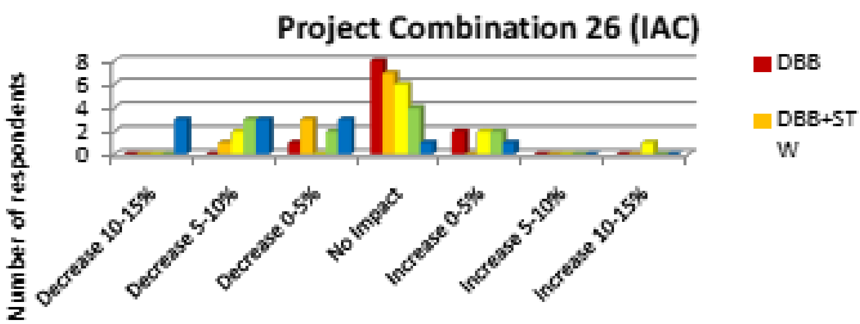

Project Combination 25 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

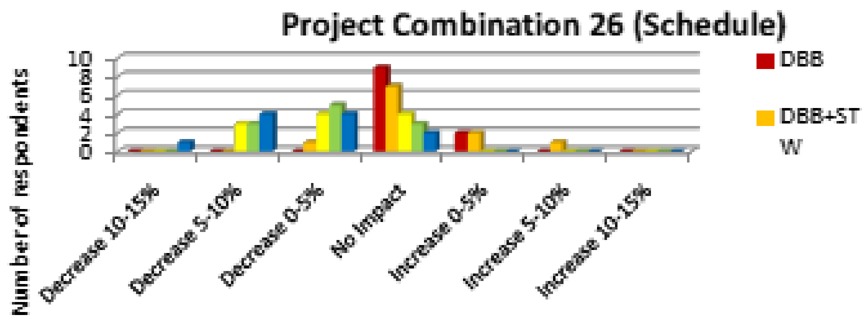
Project Combination 26

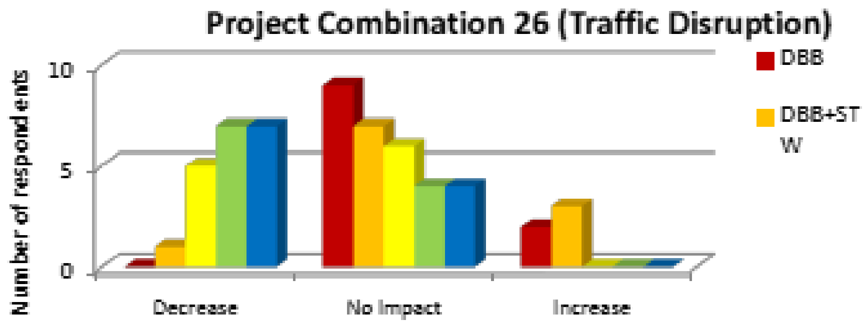
Size	Type	Traffic	Complexity	Location
Small	4R construction	High AADT	High	Rural





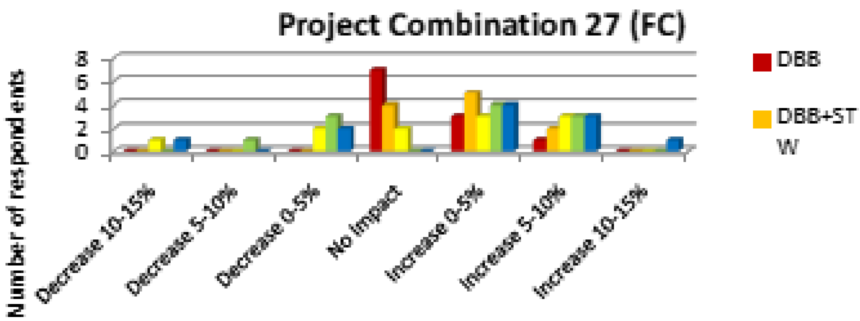


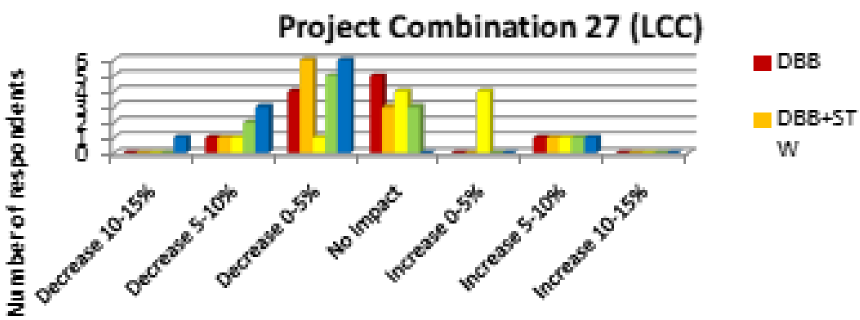

Project Combination 26 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

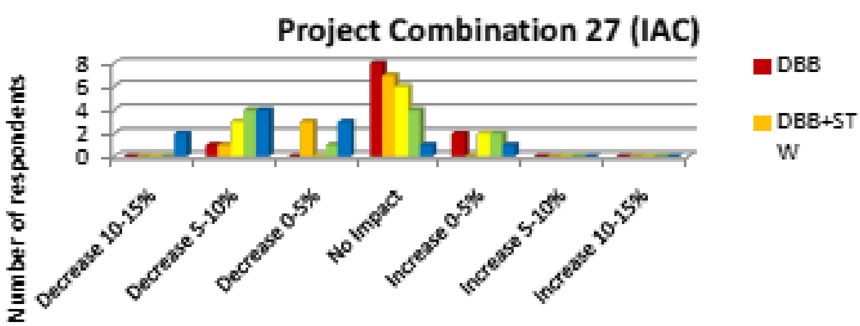

Project Combination 26 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

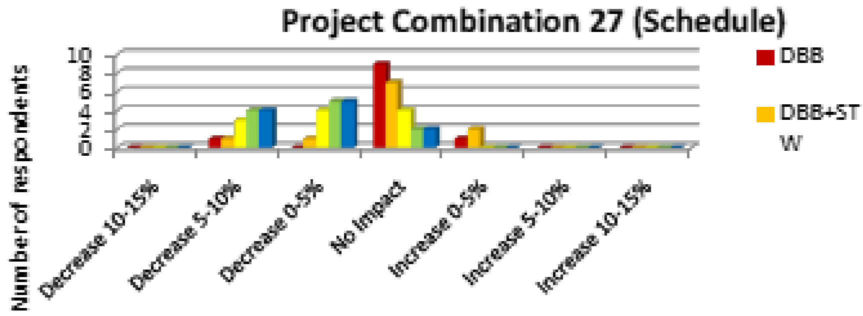
Project Combination 27

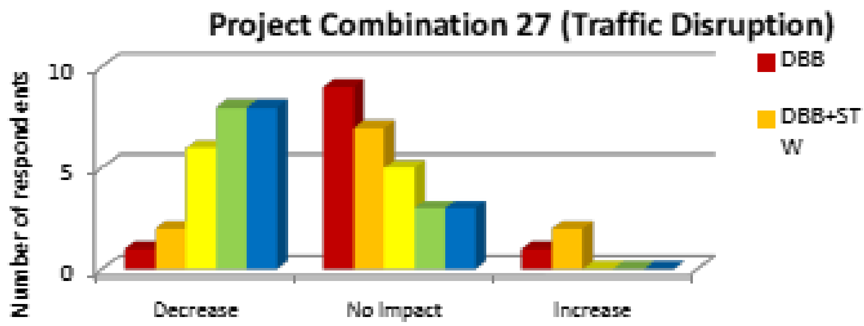
Size	Type	Traffic	Complexity	Location
Small	4R construction	High AADT	Low	Urban





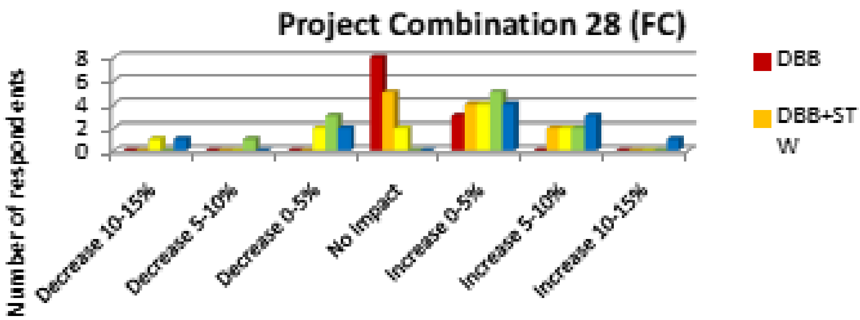


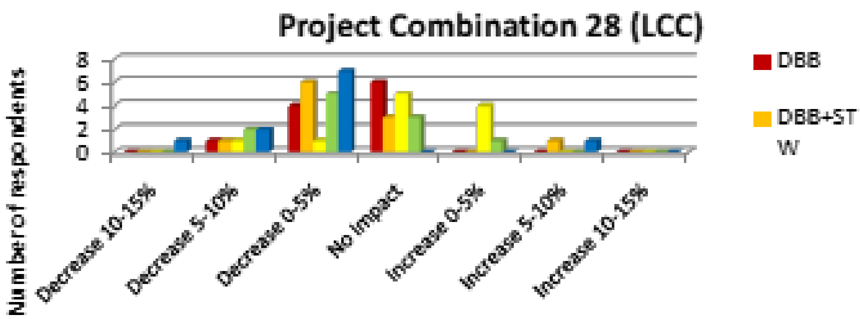

Project Combination 27 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

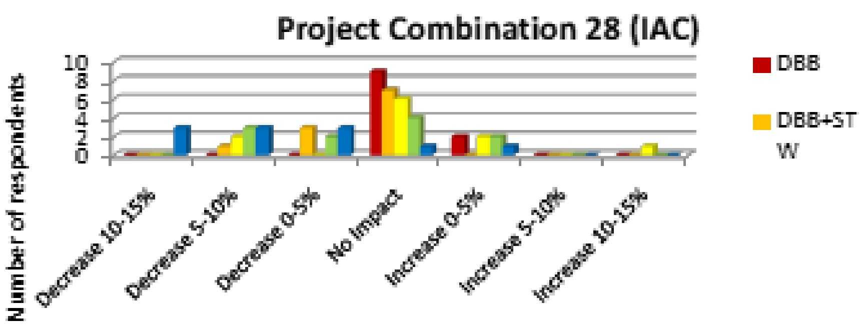

Project Combination 27 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

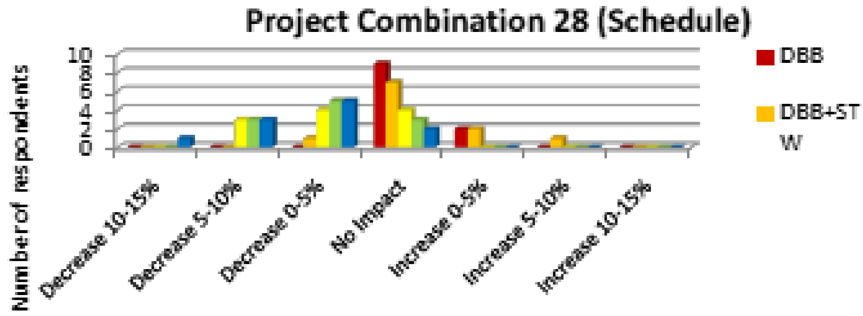
Project Combination 28

Size	Type	Traffic	Complexity	Location
Small	4R construction	High AADT	Low	Rural

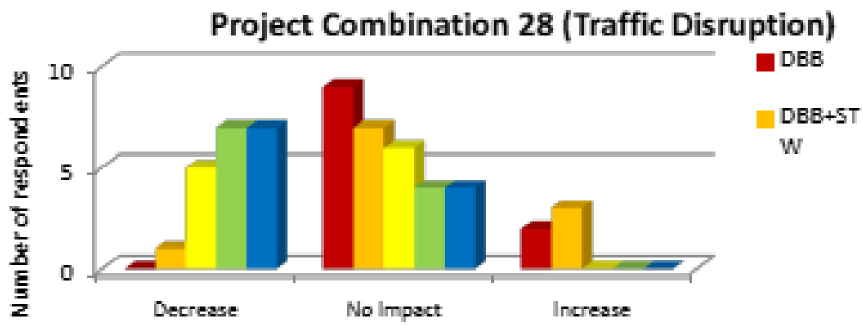








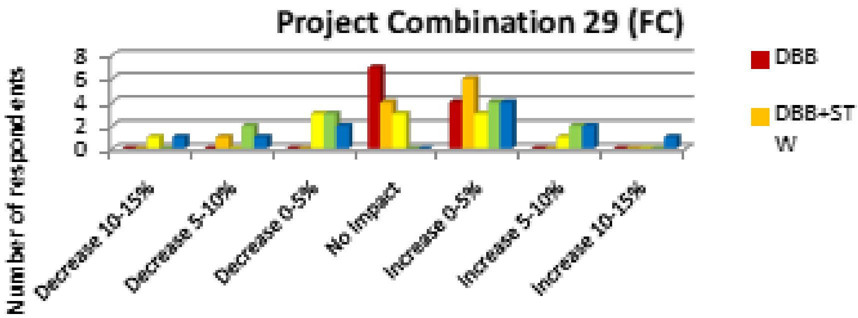
Project Combination 28 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+STW

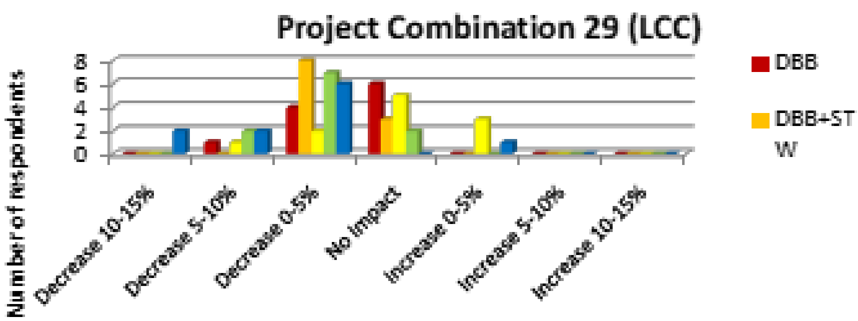


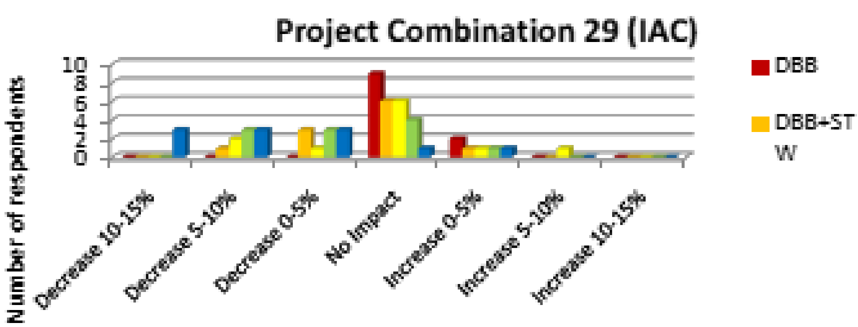
Project Combination 28 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+STW

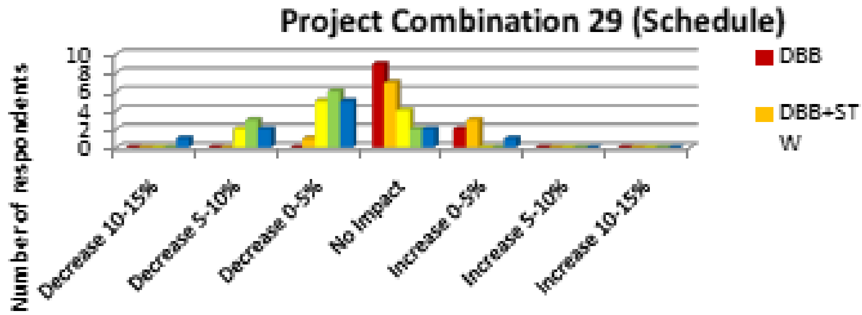
Project Combination 29

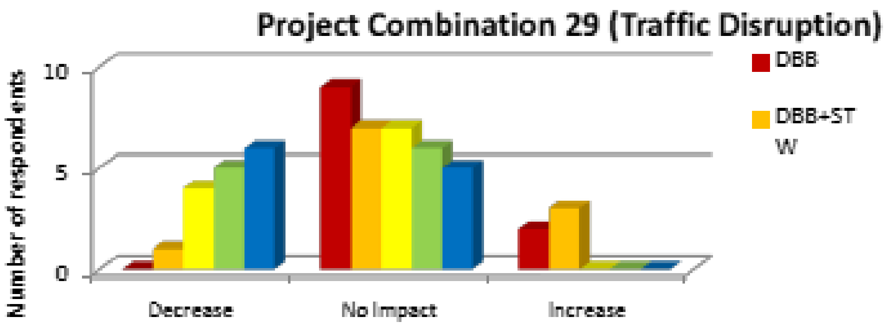
Size	Type	Traffic	Complexity	Location
Small	4R construction	Low AADT	High	Urban





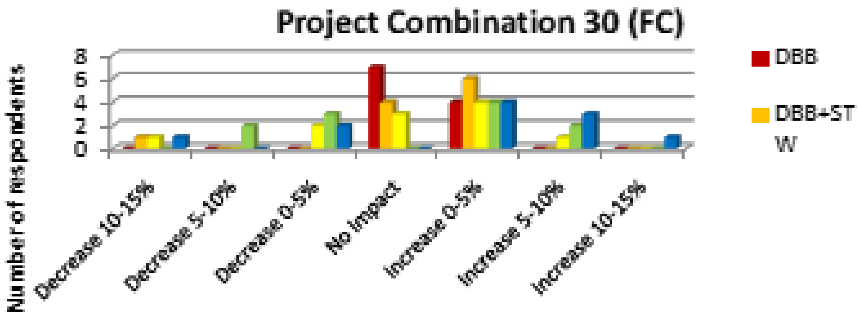


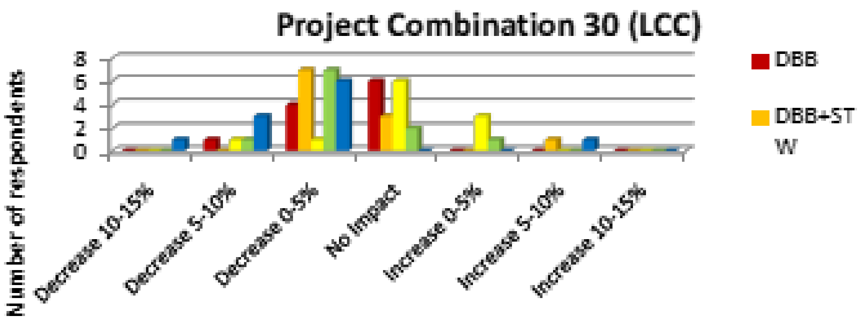

Project Combination 29 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

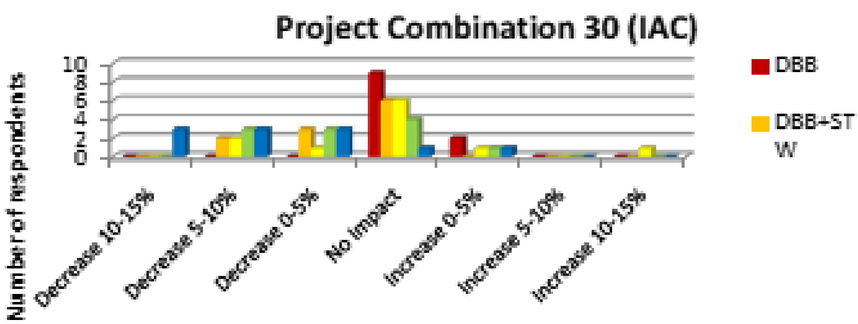

Project Combination 29 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

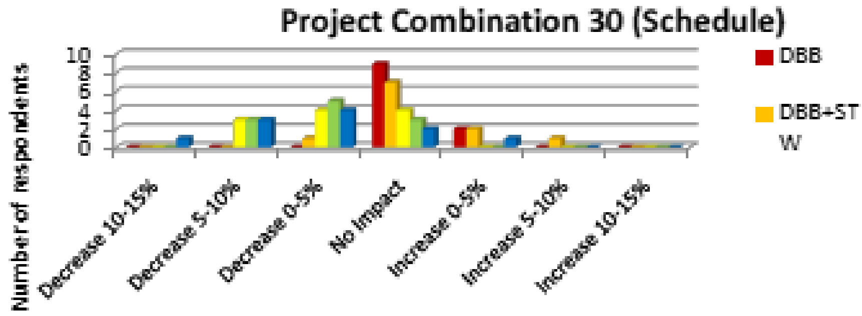
Project Combination 30

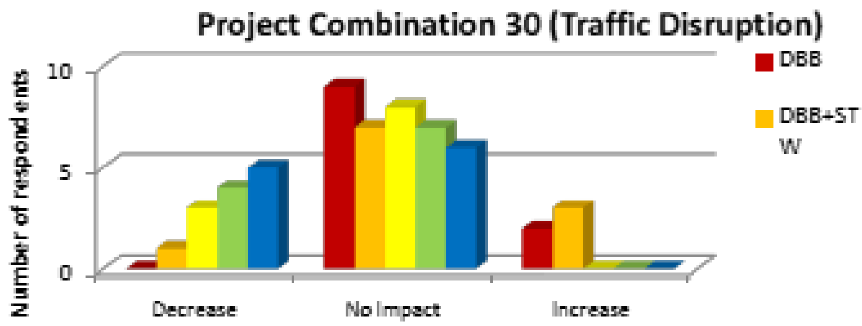
Size	Type	Traffic	Complexity	Location
Small	4R construction	Low AADT	High	Rural





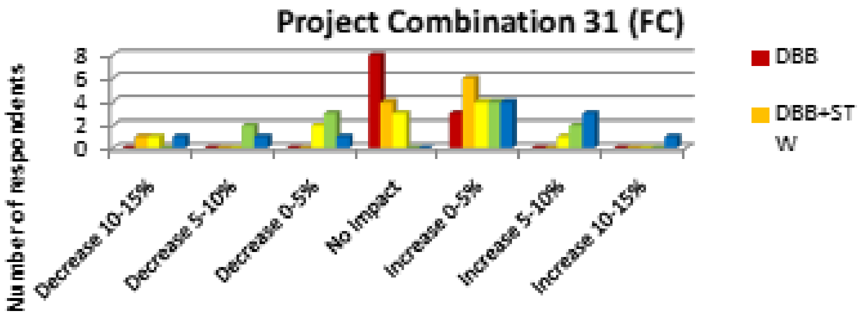


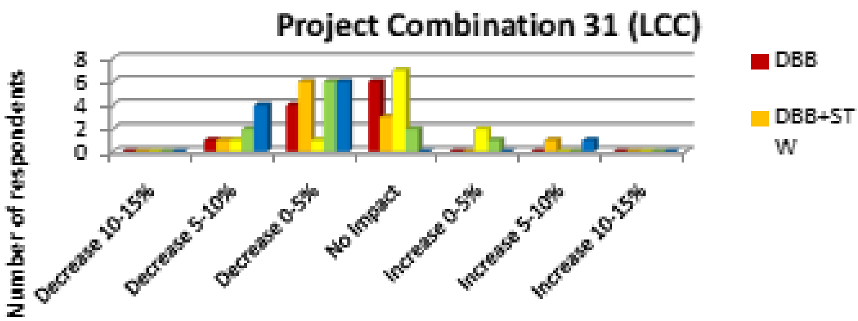

Project Combination 30 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

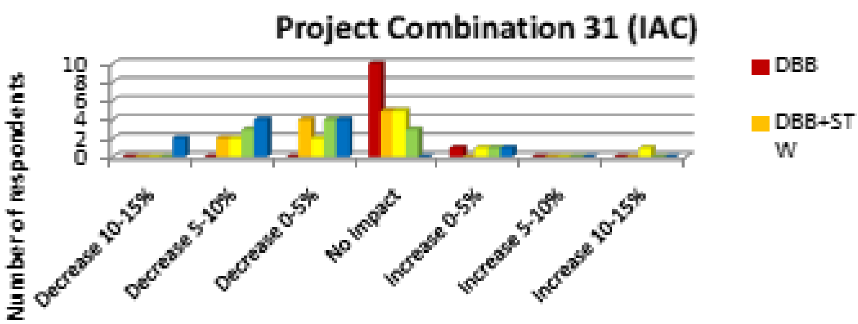

Project Combination 30 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

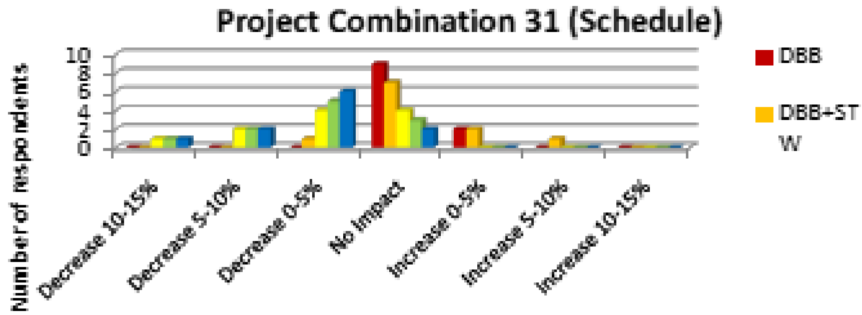
Project Combination 31

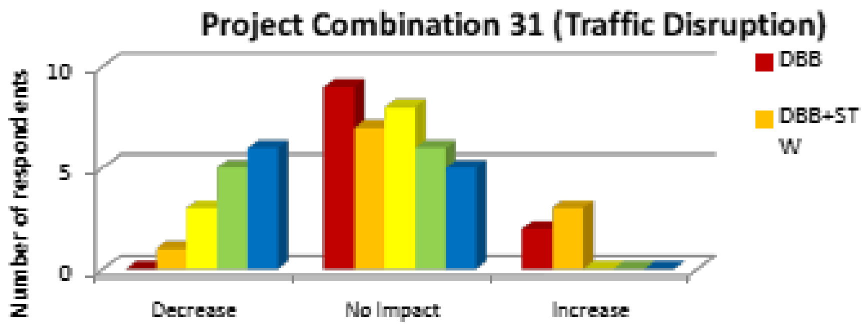
Size	Type	Traffic	Complexity	Location
Small	4R construction	Low AADT	Low	Urban





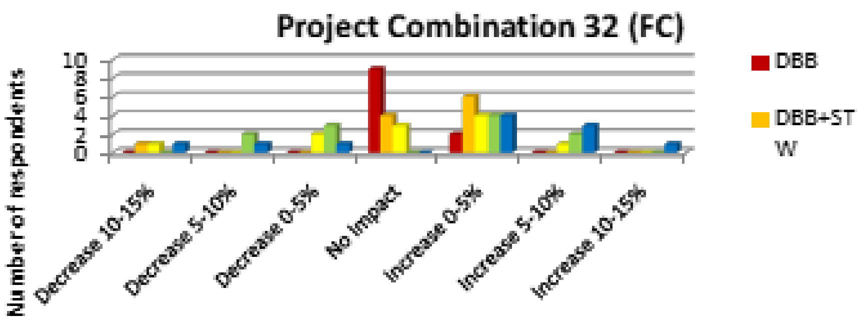


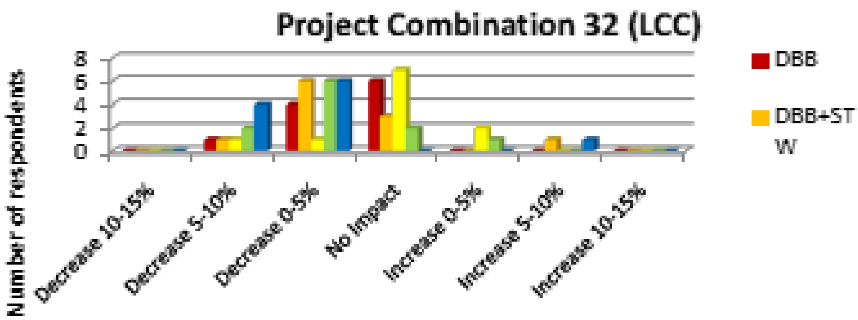

Project Combination 31 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W

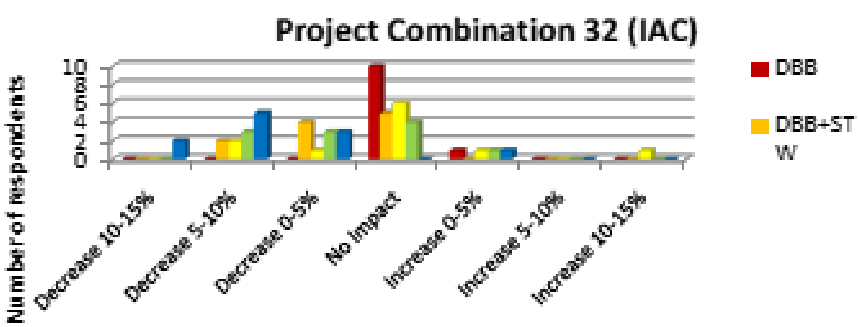

Project Combination 31 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

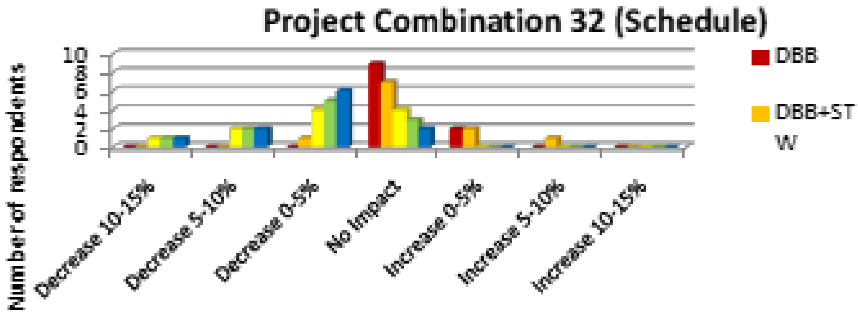
Project Combination 32

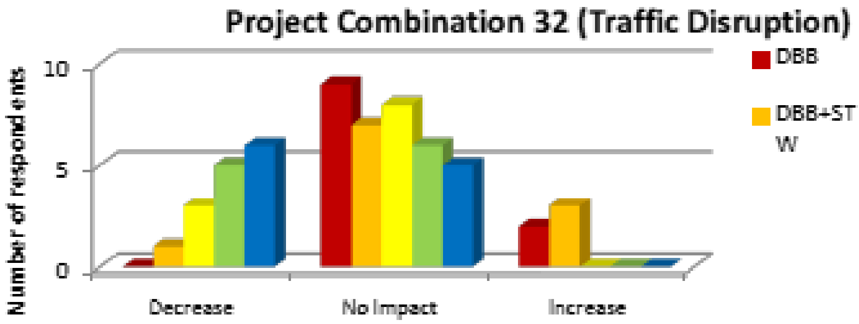
Size	Type	Traffic	Complexity	Location
Small	4R construction	Low AADT	Low	Rural








Project Combination 32 (Schedule)
Number of respondents
10
8
6
4
2
0
Decrease 10-15%
Decrease 5-10%
Decrease 0-5%
No Impact
Increase 0-5%
Increase 5-10%
Increase 10-15%
DBB
DBB+ST
W


Project Combination 32 (Traffic Disruption)
Number of respondents
10
5
0
Decrease
No Impact
Increase
DBB
DBB+ST
W

Related SHRP 2 Research

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform (R02)

Innovative Bridge Designs for Rapid Renewal (R04)

Precast Concrete Pavement Technology (R05)

Guidance for the Process of Management of Risk on Rapid Renewal Projects (R09)

Design Guide for Bridges for Service Life (R19A)

Composite Pavement Systems (R21)

Using the Existing Pavement In-Place and Achieving Long Life (R23)