Long-Term Plan for Concrete Pavement Research and Technology—The Concrete Pavement Road Map: Volume II, Tracks

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Foreword

The concrete paving industry has experienced many changes in the last 15 years. To achieve concrete pavement's full potential in the 21st century, the industry has identified trends that call for dramatic, even revolutionary, improvements. With an aim toward a holistic approach, the improvements can best be served by a carefully developed and aggressively implemented strategic plan for research and technology transfer. The Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map) is that plan.

This is volume 2 of two volumes. It contains the research problem statements to be addressed under the CP Road Map. Sufficient copies of this report are being distributed to provide eight copies to each FHWA Resource Center, five copies to each FHWA Division, and a minimum of eight copies to each State highway agency. Direct distribution is being made to the division offices for their forwarding to the State highway agencies. Additional copies for the public are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

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Acting Director, Office of Infrastructure Research and Development

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16. Abstract

The Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map) is a holistic, strategic plan for concrete pavement research and technology transfer. The CP Road Map is a 7- to 10-year plan that includes 12 distinct but integrated research tracks leading to specific products and processes. The resulting improvements will help the concrete pavement industry meet the challenges of, and achieve the industry's full potential in, the 21st century. The plan was developed in close partnership with stakeholders representing all aspects of the concrete pavement community, public and private, and the research will be conducted through partnerships of stakeholders. The CP Road Map is presented in two volumes. Volume I (FHWA HRT-05-51) describes why the research plan is needed, how it was developed, and, generally, what the plan includes. Volume I also describes the research management plan that will guide the conduct and implementation of research. Volume II describes in detail the 12 tracks of research. Each track description includes a general overview, a track goal, track action items, a list of subtracks, and detailed problem statements within each subtrack.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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THE CP ROAD MAP

The Concrete Pavement (CP) Road Map is a comprehensive and strategic plan for concrete pavement research that will guide the investment of research dollars for the next several years. It will result in technologies and systems that help the concrete pavement community meet the paving needs of today, and the as-yet unimagined paving challenges of tomorrow. In short, the CP Road Map will result in a new generation of concrete pavements for the 21st century.

WHAT IS UNIQUE ABOUT THE CP ROAD MAP?

Strategic—It combines more than 250 research problem statements into 12 fully integrated, sequential, and cohesive tracks of research leading to specific products that will dramatically affect the way concrete pavements are designed and constructed.

Innovative—From the way it was developed, to its unique track structure and cross-track integration, to the plan for conducting the research, the CP Road Map introduces a new, inclusive, and far-reaching approach to pavement research.

Stakeholder involvement—This CP Road Map plan is for the Federal, State, and private concrete pavement community. Peers helped create it, so it reflects all needs.

No cost or time limitations—In general, it is a 7- to 10-year plan with an estimated overall cost of $250 million.

Independent of any one agency or pot of money—Stakeholders with funds and expertise will pool their resources, jointly conduct and coordinate the research, and apply the results. The plan incorporates innovative, effective research implementation to move useful new products and systems to the field quickly.

A VISIONARY CHARGE

The Federal Highway Administration (FHWA) and the concrete pavement industry have commissioned a national research plan for the 21st century. Why is such a plan needed?

For most of the 20th century, the same materials—portland cement, high-quality aggregate, and water—were used in pavement concrete, with only minor refinements. It was a fairly forgiving formula that allowed some variations in subgrade quality, construction practices, and other variables without sacrificing pavement performance. For generations, the industry had the luxury of keeping traffic off of new concrete pavements for several days, even weeks, while the concrete developed its internal design strength.

In the past 15 years, the industry has experienced more changes than those that occurred in the previous 80 years, and these changes are turning the process of building concrete pavements on end:

- Today’s concrete mix designs must integrate a multitude of new, sometimes marginal materials, resulting in serious compatibility problems and reduced tolerance for variations.
- Motorists are more demanding. They will tolerate only minimal road closures and delays due to roadwork, increasing the need for new paving methods that allow road crews to get in, get out, and stay out. And motorists want smoother, quieter pavements, pushing the industry to control pavement surface characteristics.

- Highway agency focus has shifted from building new pavements to rehabilitating and maintaining existing ones, which requires different designs, systems, materials, and equipment.
- Environmental pressures, including traffic congestion and drainage and runoff issues, are affecting mix designs and pavement construction practices.
- Highway budgets are being squeezed at every level. The pavement community simply must do more with less.

In this environment, the old system for constructing concrete pavements is not meeting today's demands. Pavement failures have occurred that were unheard of 25 years ago. The concrete pavement community cannot continue business as usual if it is going to meet the growing demands on highway construction and rehabilitation. The CP Road Map gives the community an opportunity to proactively reinvent itself through research.

DRAWING A NEW MAP FOR CONCRETE PAVEMENTS

The project to develop the Long-Term Plan for Concrete Pavement Technology began in 2001 through an agreement between the Innovative Pavement Research Foundation and a team led by Iowa State University's Center for Portland Cement Concrete Pavement Technology (PCC Center).

In May 2003, FHWA initiated a new agreement with the PCC Center to complete the work. The Transportation Research Board (TRB) Committee for Research on Improved Concrete Pavements acted as the project advisory panel. Twenty percent of total funding for the project was provided by Iowa State University. The concrete pavement industry and State departments of transportation (DOT) provided valuable input to the CP Road Map and support its implementation.

An Iowa State University-led team facilitated development of the CP Road Map. They developed a database of existing research and gathered input, face-to-face, from the highway community. The team identified gaps in research that became the basis for problem statements, which are organized into a cohesive, strategic research plan.

A "Living" Research Database

The research database is a thorough catalog of recently completed and in-progress research projects and their products. If regularly updated and maintained, as recommended in the research management plan (described later in this report), the database will be a valuable resource for many years.

Stakeholder Input

To ensure the adoption and success of the CP Road Map, it was developed through a cooperative process involving high levels of stakeholder teamwork.

Five major brainstorming and feedback sessions were conducted at the following events: the October 2003 meeting of the Midwest Concrete Consortium (MC^2) in Ames, IA; a special November 2003 regional workshop for eastern and southern stakeholders in Syracuse, NY; the May 2004 meeting of the American Concrete Pavement Association (ACPA) in Kansas City, MO; a special January 2004 regional teleconference for western stakeholders; and, in October 2004, a final meeting of national stakeholders hosted by FHWA at the Turner-Fairbank Highway Research Center in McLean, VA.

Through these events, plus special presentations at more than 20 professional conferences and workshops across the country, more than 400 engineers and managers provided direct input into the CP Road Map.

Participants represented the following entities:

- State and local DOTs.
- FHWA.
- ACPA, including several State chapters.
- Portland Cement Association (PCA).
- American Association of State Highway and Transportation Officials (AASHTO).
- National Ready Mixed Concrete Association (NRMCA).
- TRB/National Cooperative Highway Research Program (NCHRP) committees.
- American Public Works Association (APWA).
- National Association of County Engineers (NACE).
- Contractors.
- Materials suppliers.
- Research universities, especially departments conducting applied research.
- Private concrete testing laboratories.

Input was provided in four broad categories:

- Mixtures and materials.
- Design.
- Construction.
- Pavement management/business systems.

Again and again, stakeholders who participated in these brainstorming events said they needed more and better analysis tools for measuring the hows and whys of pavement failures and successes—that is, to measure pavement performance. Better quality assurance and quality control methods/tools are needed for every stage of the pavement system, particularly mix design, design, and construction. Because variables in each stage affect the others, the methods/tools must be integrated across stages.

From these concepts of pavement performance and systems integration, the following overall vision for the CP Road Map was developed:

By 2015, the highway community will have a comprehensive, integrated, and fully functional system of concrete pavement technologies that provides innovative solutions for customer-driven performance requirements.

Based on this goal and other stakeholder input, dozens of specific research objectives were identified:

- Maximize public convenience.
- Improve the driving experience.
- Integrate design, mixtures and materials, and construction with pavement performance predictions.
- Improve pavement reliability.
- Identify new and innovative business relationships to focus on performance requirements.
- Constrain costs while improving pavement performance.
- Protect and improve the environment.
- Expand opportunities to use concrete pavement.

The objectives were "filtered" through the project team's database of existing research to determine gaps in research. These gaps became the basis for problem statements.

Approximately 250 problem statements were written, reviewed, and fine tuned. Final versions of the problem statements were added to the research database as work to be accomplished via the CP Road Map.

Research problem statements, projects, budgets, timelines, and research results in the database must be regularly updated. The CP Road Map will succeed only if the database is managed and maintained.

From Stakeholder Input to Plan

Most of the 250-plus problem statements did not neatly fit into just one of the brainstorming categories (mixtures and materials, design, construction, and pavement management/business systems).To capture the cross-categories and the integrated nature of the problem statements, the problem statements were organized into 12, product-focused tracks of research within the database. This structure encourages various stakeholder groups to step forward as champions for a specific track.

Problem Statements

Each problem statement is a topical summary only. Most problem statements will be further broken down into specific research project statements that provide detailed descriptions of the research to be accomplished, budgets, and timelines. The research management plan (described later in this document) makes research track team leaders responsible for data entry of detailed project statements into the database.

Track Integration

As noted in the 12 brief track descriptions on pages 8–11, research in one track often affects or is affected by research in another track. In the CP Road Map, this interdependence and other critical relationships are outlined in the track and problem statement descriptions. It will be the responsibility of research track team leaders, as described later in this document, to ensure that research is appropriately coordinated and integrated.

Moreover, the research database can be sorted to isolate problem statements on a variety of subjects. For example, several important problem statements related to foundations and drainage systems, maintenance and rehabilitation, and environment advancements are included in various tracks. In the CP Road Map, problem statements related to these particular topics have been listed in separate cross-reference tables.

CP ROAD MAP RESEARCH TRACKS

Each of the CP Road Map tracks is a full research program in itself, with its own budget, 2 to 7 subtracks, and as many as 20 problem statements. Tracks 1 through 9 consist of timed sequences of research leading to particular products that are essential to reaching overall research goals. In the CP Road Map, one subtrack in every phased track is devoted to developing innovative technology transfer, training tools, and methods to ensure that innovative research products are quickly and efficiently moved into practice. Tracks 10, 11, and 12 are not phased because timing is not as critical.

The products developed through the first four tracks may be especially critical to helping the industry achieve the full potential of concrete pavements.

Following is a brief description of each research track:

1. **Performance-Based Concrete Pavement Mix Design System.** The final product of this track will be a practical yet innovative concrete mix design procedure with new equipment, consensus target

values, common laboratory procedures, and full integration with both structural design and field quality control—a lab of the future. This track also lays the groundwork for the concrete paving industry to assume more responsibility for mix designs as State highway agencies move from method specifications to more advanced acceptance tools. For such a move to be successful, it is important that the concrete paving industry and owner-agencies refer to a single document for mix design state of the art.

2. **Performance-Based Design Guide for New and Rehabilitated Concrete Pavements.** Under this track, the concrete pavement research community will expand the mechanistic approach to pavement restoration and preservation strategies. This track builds on the comprehensive work done under NCHRP 1–37A (development of the *Mechanistic-Empirical* (M-E) *Pavement Design Guide*) and continues to develop the models from that key work.[1] The work in this track needs to be closely integrated with track 1.

3. **High-Speed Nondestructive Testing and Intelligent Construction Systems.** This track will develop high-speed, nondestructive quality control systems to monitor pavement properties continuously during construction. As a result, immediate adjustments can be made to ensure the highest quality finished product that meets given performance specifications. Many problem statements in this track relate to both tracks 1 and 2.

4. **Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements.** This track will improve understanding of concrete pavement surface characteristics. It will provide tools for engineers to help meet or exceed predetermined requirements for friction/safety, tire-pavement noise, smoothness, splash and spray, wheel path wear (hydroplaning), light reflection, rolling resistance, and durability (longevity). Each of the functional elements of a pavement listed above is critical. The challenge is to improve one characteristic without compromising another characteristic, especially when it comes to safety of the public.

5. **Equipment Automation and Advancements.** This track will result in process improvements and equipment developments for high-speed, high-quality concrete paving equipment to meet the concrete paving industry's projected needs and the traveling public's expectations for highway performance in the future. Examples include the next generation of concrete batching and placement equipment; behind-the-paver equipment to improve curing, surface treatment, and jointing; mechanized ways to place and control subdrains and other foundation elements; equipment to remove/replace the slab in one-pass construction; improved repair processes that decrease the time of operations and provide the workforce and traveling public with less exposure; and methods for evaluating new equipment on actual construction projects.

6. **Innovative Concrete Pavement Joint Design, Materials, and Construction.** Potential products for this track include a new joint design, high-speed computer analysis techniques for joint performance, a more accurate installation scheme, and faster rehabilitation strategies. The problem statements in this track address the basics—joint design, materials, construction, and maintenance activities. The track also specifies research that will help develop breakthrough technologies and extremely high-speed joint repair techniques. This is a crosscutting track to ensure that all topics related to innovative joints are addressed. Much of the proposed research will develop important incremental improvements.

7. **High-Speed Concrete Pavement Rehabilitation and Construction.** Faster techniques and higher quality can and must be accomplished in the future. This track addresses a series of activities, from the planning and simulation of high-speed construction and rehabilitation, precast and modular options for concrete pavements, and fast-track concrete pavement construction and rehabilitation, to the evaluation and technology transfer of high-speed construction and rehabilitation products and

processes developed through research. Some high-speed construction issues will likely be investigated in tracks 1 and 3, and those efforts will be closely coordinated with this track.

8. **Long Life Concrete Pavements.** The need for pavements that last longer between maintenance, restoration, or rehabilitation is integrated throughout the CP Road Map. However, this track draws attention to some specific research that may address pavement life approaching 60 years or more.

9. **Concrete Pavement Accelerated and Long-Term Data Collection.** This track provides the infrastructure—such as testing methods and data collection and reporting tools—for a future national program that will plan accelerated loading and long-term data needs, construct test sections, and collect and share data. The problem statements in this track will explore which data are most useful and determine the amount of time needed to collect the data.

10. **Concrete Pavement Performance.** This track addresses key elements of pavement management and asset management systems. Such systems determine if and how pavements meet performance characteristics for highway agencies and users. Research in this track will determine and address the functional aspects of concrete pavement performance, particularly factors such as tire-pavement noise, friction, smoothness, and others. Research also will provide rapid concrete pavement performance feedback and examine ways to schedule surface characteristics and condition improvements. Developing feedback loops in highway agencies' pavement management systems will be crucial to monitor performance effectively and rapidly.

11. **Concrete Pavement Business Systems and Economics.** Roles and responsibilities are changing in the highway industry, affecting the way paving projects are designed, bid, built, and maintained. Contractors are being asked to assume more control of the operation and quality control inspections. By including warranty provisions in project contracts, owner-agencies are asking for additional assurance that pavements will be built and will perform as expected. Internationally, many countries have made dramatic changes in project funding methods and in the roles of contractors and suppliers. This track captures some important research that should be considered as this process of transformation continues in the United States. Problem statements cover topics such as contracting options, new technology transfer systems, public-private partnerships, and economic models.

12. **Advanced Concrete Pavement Materials.** The problem statements in this track address the development of new materials and refine or reintroduce existing advanced materials to enhance performance, improve construction, and reduce waste. Many of the existing materials studied in this track have been used thus far on a small scale or in laboratory evaluations only. Many of them have not been used in the United States but show promise based on work done in other countries. This track will experiment with such materials on a larger scale and will develop standards and recommendations for their use. The research will foster innovation in the development of additional, new, and innovative concrete pavement materials.

REACHING THE DESTINATION

The CP Road Map is accompanied by a research management plan that outlines a progressive, cooperative approach to managing and conducting the research. Under this plan, organizations identify common interests, partner with each other in executing specific contracts, and, in the end, produce and share a product that is greater than the sum of the parts.

The research management plan emphasizes scope control, phasing of research, reporting, systems integration, voluntary peer review, maintenance of the research database, program-wide technology transfer, and assistance to organizations that want to leverage their funds and human resources.

Philosophy for Managing Research

The research management plan is based on these assumptions:

- The CP Road Map is a national research plan, not a plan solely for FHWA, but for State agencies and the industry as well.
- The CP Road Map is not restricted to any single funding source. Publicly financed highway research is decentralized and will probably remain so through the next highway bill.
- Even in a decentralized arena like research, it is possible—indeed, critical—for stakeholder groups to come together voluntarily. Federal, State, and industry research staff and engineers around the country are looking for more opportunities to pool their funds and other resources in win-win situations. The MC^2 is an example of a successful cooperative approach to research.
- The all-too-common disconnection between research results and implementation of those results must be fixed. Communication, technology transfer, and outreach activities must be elevated to the same level of importance as research itself.
- The CP Road Map is too comprehensive and too important for a part-time implementation effort. Managing the overall research program effectively and judiciously will require full-time, dedicated personnel with adequate resources.

Governing Structure

In line with this general philosophy, the research management plan outlines a four-tier system of participation and responsibility: an executive advisory committee, an administrative support group, research track team leaders, and sustaining organizations.

A triparty executive advisory committee, representing FHWA, State DOTs, and industry, will provide broad oversight of the CP Road Map. It will be a decisionmaking and policymaking facilitation group with many responsibilities, including:

- Assembling research track team leaders.
- Promoting partnering arrangements.
- Ensuring adequate integration of research across tracks.
- Developing and implementing a strategy to ensure that software products developed through various research tracks will be compatible with each other.
- Identifying new research program areas.
- Overseeing updates to and maintenance of the research database.
- Developing a comprehensive technology transfer and training program for products of the CP Road Map.
- Developing a communications effort to keep the CP Road Map and its products in front of stakeholders and the public.
- Conducting self-evaluation studies.
- Keeping the momentum focused on outcomes, not just output.

An administrative support group will provide professional management services for the executive advisory committee and, to a lesser degree, the research track team leaders. It will be the “doing” body for coordination and support activities, like maintaining the research database.

Research track team leaders will coordinate and oversee all activities within a specific research track:

- Validating and updating the track.
- Developing broad problem statements into specific, separate research projects, with scopes of work, timelines, and budgets.
- Identifying organizations to conduct or partner in the research.
- Establishing and overseeing subordinate technical expert working groups to guide complex work.
- Ensuring proper integration of work within the track and across track lines.
- Developing status reports.

Sustaining organizations—agencies, consultants, universities, professional associations, and other organizations with specialized interests and skills that are interested in pooling dedicated funds—will assume responsibility for conducting research through cooperation, partnerships, and funding agreements. Some people and organizations will assume multiple roles.

In addition, sustaining organizations conducting research under the CP Road Map may retain full fiscal and technical control of the work under their jurisdictions. The key to successful conduct of the research, however, is cooperation, and the research management plan facilitates and supports cooperative efforts.

THE CP ROAD MAP TRACKS AND SUBTRACKS

The CP Road Map is a 7- to 10-year plan for concrete pavement research consisting of the following tracks and subtracks.

The general range of costs associated with each track represents the time dedicated to the CP Road Map by multiple stakeholders who contributed to its development. The support needed for this effort comes from in-kind services and funding provided by a number of participants including industry organizations, State DOTs, and Federal agencies. These estimates are subject to change as the CP Road Map evolves.

1. Performance-Based Concrete Pavement Mix Design System ($30–68 M*)

- Portland Cement Concrete (PCC) Mix Design System Development and Integration.
- PCC Mix Design Laboratory Testing and Equipment.
- PCC Mix Design Modeling.
- PCC Mix Design Evaluation and Implementation.

2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements ($41–60 M)

- Design Guide Structural Models.
- Design Guide Inputs, Performance Models, and Reliability.
- Special Design and Rehabilitation Issues.
- Improved Mechanistic Design Procedures.
- Design Guide Implementation.

3. High-Speed Nondestructive Testing and Intelligent Construction Systems ($20–41 M)

- Field Control.
- Nondestructive Testing Methods.
- Nondestructive Testing and Intelligent Control System Evaluation, and Implementation.

4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements ($25–54 M)

- Concrete Pavement Texture and Friction.
- Concrete Pavement Smoothness.
- Tire-Pavement Noise.
- Integration of Concrete Pavement Surface Characteristics.
- Evaluation of Products for Concrete Pavement Surface Characteristics.
- Concrete Pavement Surface Characteristics Implementation.
- Other Concrete Pavement Surface Characteristics.

5. Concrete Pavement Equipment Automation and Advancements ($26–56 M)

- Concrete Batching and Mixing Equipment.
- Concrete Placement Equipment.
- Concrete Pavement Curing, Texturing, and Jointing Equipment.
- Concrete Pavement Foundation Equipment.
- Concrete Pavement Reconstruction Equipment.
- Concrete Pavement Restoration Equipment.
- Advanced Equipment Evaluation and Implementation.

6. Innovative Concrete Pavement Joint Design, Materials, and Construction ($10–15 M)

- Joint Design Innovations.
- Joint Materials, Construction, Evaluation, and Rehabilitation Innovations.
- Innovative Joints Implementation.

7. High-Speed Concrete Pavement Rehabilitation and Construction ($10–20 M)

- Rehabilitation and Construction Planning and Simulation.
- Precast and Modular Concrete Pavements.
- Fast-Track Concrete Pavements.
- Rehabilitation and Construction Evaluation and Implementation.

8. Long Life Concrete Pavements ($11–17 M)

- Pavement Strategy for Long Life Concrete Pavements.
- Construction and Materials for Long Life Concrete Pavements and Overlays.
- Long Life Concrete Pavement Implementation.

9. Concrete Pavement Accelerated and Long-Term Data Collection ($10–16 M)

- Planning and Designing Accelerated Loading and Long-Term Data Collection.
- Preparation of Data Collection/Testing Procedures and Construction of Test Road.
- Accelerated Loading and Long-Term Data Collection Implementation.

10. Concrete Pavement Performance ($3–4 M)

- Technologies for Determining Concrete Pavement Performance.
- Guidelines and Protocols for Concrete Pavement Performance.

11. Concrete Pavement Business Systems and Economics ($21–31 M)

- Concrete Pavement Research and Technology Management and Implementation.
- Concrete Pavement Economics and Life Cycle Costs.
- Contracting and Incentives for Concrete Pavement Work.
- Technology Transfer and Publications for Concrete Pavement Best Practices.
- Concrete Pavement Decisions with Environmental Impact.

12. Advanced Concrete Pavement Materials ($11–23 M)

- Performance-Enhancing Concrete Pavement Materials.
- Construction-Enhancing Concrete Pavement Materials.
- Environment-Enhancing Concrete Pavement Materials.

$218–405 M Total

*All numbers are rounded.

ORGANIZATION OF VOLUMES I AND II

The CP Road Map is published in two volumes. Volume I contains the executive summary, plus eight chapters:

- Chapter 1 describes the background and need for the CP Road Map.
- Chapter 2 tells how the CP Road Map was developed.
- Chapter 3 provides an overview of the 12 tracks of planned research.
- Chapters 4 through 7 describe the critical issues and objectives that the CP Road Map addresses in the areas of design, mixtures and materials, construction, and pavement management/business systems.
- Chapter 8 describes the innovative research management plan that will guide the conduct of research.

Volume II contains the executive summary and describes in detail the 12 tracks of planned research:

- Each track begins with introductory material that summarizes the goal and objectives for the track and the gaps and challenges for its research program.
- A phasing chart is included to show the approximate sequencing of the problem statements in the track.
- A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation.
- The problem statements within each track are grouped into subtracks. Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack.
- Each subtrack begins with a framework problem statement in which the subtrack work is planned in more detail.
- The problem statements then follow.

Each problem statement clearly defines tasks that need to be performed to produce a desired product or achieve a desired objective. Each problem statement will need to be developed into appropriate research project statements with detailed descriptions of the research to be accomplished, specific budgets, and definite timelines.

Many conventional concrete pavement topics are integrated across the research tracks in the CP Road Map. Using the CP Road Map database, distinct topic areas can be easily identified and pulled out of the tracks into their own tables. For example, the following three important research topics are addressed in a number of tracks. Near the end of volume II, cross-reference tables list the relevant problem statements for each of these topics:

- Concrete pavement foundation and drainage.
- Concrete pavement maintenance and rehabilitation.
- Environmental concrete pavement advancements.

HOW CAN YOU PARTICIPATE?

Beginning a long-term research program is a long, slow process. In this case, the CP Road Map provides a framework for moving forward.

Stakeholders in the concrete pavement community are invited to participate:

- To receive a printed copy of the full two-volume CP Road Map, with complete problem statements (available 2005), contact Peter Kopac, FHWA, 202–493–3151, peter.kopac@fhwa.dot.gov.
- An electronic version of the CP Road Map and the two-volume report will be available on the FHWA Web site in 2005. See www.tfhrc.gov/.
- For additional information, go to www.tfhrc.gov and search for CP Road Map.

Track 1. Performance-Based Concrete Pavement Mix Design System (MD)

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TRACK 1 (MD) OVERVIEW

This track will develop a practical yet innovative concrete mix design procedure with new equipment, consensus target values, common laboratory procedures, and full integration into both structural design and field quality control (QC). As opposed to mix proportioning, mix design engineers a concrete mixture to meet a variety of property or performance targets. The process begins by defining the end product, and then the various materials are selected, proportioned, simulated, and optimized to meet the end product goals. This track will develop mix design rather than mix proportioning.

This ambitious track also lays the groundwork for the concrete paving industry to assume more mix design responsibility as State highway agencies move from method specification to a more advanced acceptance tool. To do this, however, the concrete paving industry and the owner-agencies must be able to refer to a single document for state-of-the-art mix design.

The track provides a plan for research in the following areas:

- Integration of volumetrics-based, property-based, performance-based, and functionally based mix designs and recycled materials into the mix design system.
- Identification of new and upgraded equipment and test procedures.
- Development of an expert system that connects test results to each other.
- Improved models to predict slab performance.
- Field evaluation and implementation procedures that provide a mechanism for user feedback.
- Technology transfer activities.

The goal and objectives for this track and the gaps and challenges for its research program are summarized below. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, then follow.

Track Goal

Innovative concrete mix material selections and mix design procedures will produce economical, compatible, and optimized concrete mixes integrated into both structural concrete pavement design and construction control.

Track Objectives

1. Develop a concrete lab of the future that will give the user a sequence of mix design tests and procedures that integrate structural design and QC with material selection and proportioning.

2. Develop the tools necessary to predict the compatibility and effectiveness of concrete mixes under specific field conditions before paving begins.

3. Detect potential construction problems early and correct them automatically using innovative QC tools.

4. Detect potential long-term durability problems more effectively during both the mix design process and the construction QC program.

5. Improve the ability to predict concrete mix properties and their relationship to slab behavior and performance (e.g., shrinkage, joint opening, and curing) using the next generation of advanced modeling techniques.

6. Identify and use innovative, nontraditional materials that accelerate concrete pavement construction, maintenance, and rehabilitation and/or extend product life at a fair cost.

Research Gaps

- Insufficient understanding of the material factors that influence pavement performance.
- Insufficient understanding of the effects that material has on durability prediction.
- Lack of equipment and test procedures to accelerate durability testing.
- Lack of cost effective programs to accelerate training on new tests.
- Insufficient understanding of the impacts that materials have on pavement constructability.
- Insufficient understanding of the relationship between materials and surface characteristics.
- Insufficient understanding of the ways to use locally available materials more effectively.
- Insufficient understanding of the ways to advance higher order use of recycled concrete materials.
- Insufficient understanding of the future roles and responsibilities of the public and private sectors.

Research Challenges

- Tie the materials used to pavement performance indicators.
- Learn more about concrete pavement deterioration and reliably identify the materials or material combinations that cause deterioration.
- Identify equipment that can measure the most relevant identified properties.
- Quantify the cost of test equipment, training, and the materials themselves.
- Recognize a connection between the materials selected and the ease of constructing with them.
- Identify the user demands for smooth, quiet, safe, and long-lasting pavements and translate those demands into material selection and optimization.
- Identify a place for all grades of materials and identify ways of using locally available materials in less critical applications (e.g., county roads or stopgap pavements).
- Prepare the concrete pavement industry in the United States to meet sustainability goals that other countries have moved toward, specifically a 100 percent reuse policy.
- Identify who will establish performance standards for future concrete pavement mixes and material selection, proportioning, and compatibility factors.

Research Track 1 (MD) Phasing

The horizontal bar chart in figure 1 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

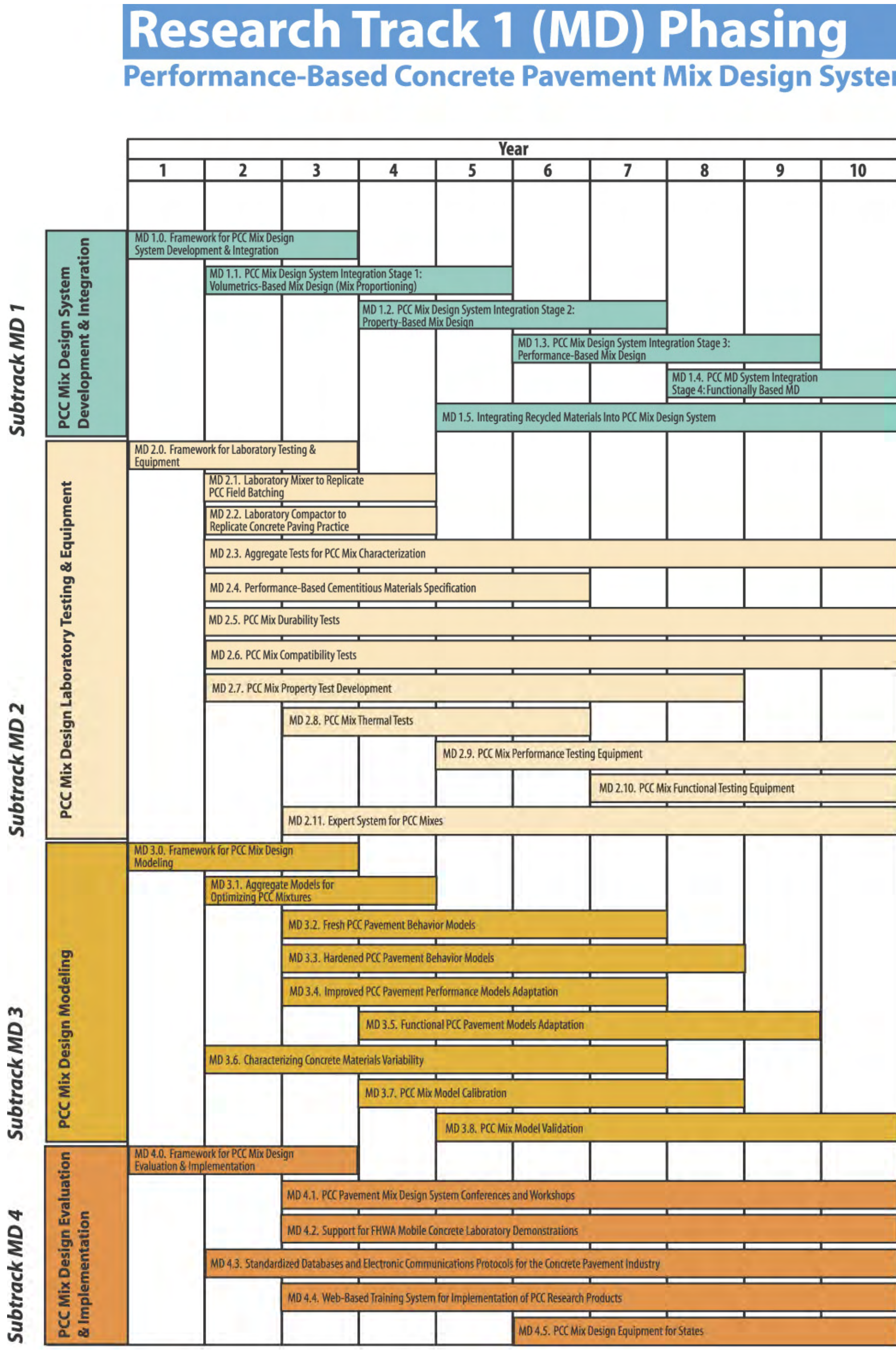

Figure 1. Track 1 (MD) subtrack and problem statement phasing chart.

Research Track 1 (MD) Estimated Costs

Table 1 shows the estimated costs for this research track.

Table 1. Research track 1 (MD) estimated costs.

Problem Statement	Estimated Cost
Subtrack MD 1. Portland Cement Concrete (PCC) Mix Design System Development and Integration	
MD 1.0. Framework for PCC Mix Design System Development and Integration (Subtrack MD 1)	$300 k
MD 1.1. PCC Pavement Mix Design System Integration Stage 1: Volumetrics-Based Mix Design (Mix Proportioning)	$500 k–$1 M
MD 1.2. PCC Pavement Mix Design System Integration Stage 2: Property-Based Mix Design	$1 M–$2 M
MD 1.3. PCC Pavement Mix Design System Integration Stage 3: Performance-Based Mix Design	$1 M–$2 M
MD 1.4. PCC Pavement Mix Design System Integration Stage 4: Functionally Based Mix Design	$1 M–$2 M
MD 1.5. Integrating Recycled Materials into PCC Mix Design System	$500 k–$1 M
Subtrack MD 2. PCC Mix Design Laboratory Testing and Equipment	
MD 2.0. Framework for PCC Mix Design Laboratory Testing and Equipment (Subtrack MD 2)	$200 k
MD 2.1. Laboratory Mixer to Replicate PCC Field Batching	$1 M–$2 M
MD 2.2. Laboratory Compactor to Replicate Concrete Paving Practice	$1 M–$2 M
MD 2.3. Aggregate Tests for PCC Mix Characterization	$2 M–$5 M
MD 2.4. Performance-Based Cementitious Materials Specifications	$1 M–$2 M
MD 2.5. PCC Mix Durability Tests	$2 M–$5 M
MD 2.6. PCC Mix Compatibility Tests	$2 M–$5 M
MD 2.7. PCC Mix Property Test Development	$2 M–$5 M
MD 2.8. PCC Mix Thermal Tests	$500 k–$1 M
MD 2.9. PCC Mix Performance Testing Equipment	$2 M–$5 M
MD 2.10. PCC Mix Functional Testing Equipment	$2 M–$5 M
MD 2.11. Expert System for PCC Mixes	$1 M–$2 M
Subtrack MD 3. PCC Mix Design Modeling	
MD 3.0. Framework for PCC Mix Design Modeling (Subtrack MD 3)	$150k
MD 3.1. Aggregate Models for Optimizing PCC Mixtures	$250 k–$500 k
MD 3.2. Fresh PCC Pavement Behavior Models	$1 M–$2 M
MD 3.3. Hardened PCC Pavement Behavior Models	$250 k–$500 k
MD 3.4. Improved PCC Pavement Performance Models Adaptation	$250 k–$500 k
MD 3.5. Functional PCC Pavement Models Adaptation	$250 k–$500 k
MD 3.6. Characterizing Concrete Materials Variability	$250 k–$500 k
MD 3.7. PCC Mix Model Calibration	$1 M–$2 M
MD 3.8. PCC Mix Model Validation	$500 k–$1 M
Subtrack MD 4. PCC Mix Design Evaluation and Implementation	
MD 4.0. Framework for PCC Mix Design Evaluation and Implementation (Subtrack MD 4)	$150 k
MD 4.1. PCC Pavement Mix Design System Conferences and Workshops	$2 M–$5 M
MD 4.2. Support for FHWA Mobile Concrete Laboratory Demonstrations	$1 M–$2 M
MD 4.3. Standardized Databases and Electronic Communications Protocols for the Concrete Pavement Industry	$250 k–$500 k
MD 4.4. Web-Based Training System for Implementation of PCC Research Products	$500 k–$1 M
MD 4.5. PCC Mix Design Equipment for States	$1 M–$2 M
Track 1 (MD)	
Total	$29.8 M–$67.8 M

Track Organization: Subtracks and Problem Statements

Track 1 (MD) problem statements are grouped into four subtracks:

- Subtrack MD 1. PCC Mix Design Development and Integration.
- Subtrack MD 2. PCC Mix Design Laboratory Testing and Equipment.
- Subtrack MD 3. PCC Mix Design Modeling.
- Subtrack MD 4. PCC Mix Design Evaluation and Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements then follow.

SUBTRACK MD 1. PCC MIX DESIGN SYSTEM DEVELOPMENT AND INTEGRATION

This subtrack develops the overall track structure and integrates all the output from the other four subtracks into a comprehensive, cohesive product. The problem statements in this track will integrate volumetrics-based, property-based, performance-based, and functionally based mix designs and recycled materials into the mix design system. Table 2 provides an overview of this subtrack.

Table 2. Subtrack MD 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
MD 1.0. Framework for PCC Mix Design System Development and Integration (Subtrack MD 1)	$300 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
MD 1.1. PCC Pavement Mix Design System Integration Stage 1: Volumetrics-Based Mix Design (Mix Proportioning)	$500 k–$1 M	Software, guidelines, and supporting products for a new generation of concrete mix design that will optimize concrete mixtures for paving.	A procedure to allow job-specific optimization of concrete paving mixtures based largely on currently available technology, rather than current mix proportioning methods based on either previous experience or procedural guidance developed for a broad range of concretes.
MD 1.2. PCC Pavement Mix Design System Integration Stage 2: Property-Based Mix Design	$1 M–$2 M	Updates to the software, guidelines, and supporting products for concrete mix design and optimization.	Building on the foundational work conducted under MD 1.1 (PCC Pavement Mix Design System Integration Stage 1: Volumetrics-Based Mix Design), a procedure capable of designing and optimizing a mix for more specific and pertinent concrete properties, possibly including strength, workability, permeability, stiffness, shrinkage, and coefficient of thermal expansion.
MD 1.3. PCC Pavement Mix Design System Integration Stage 3: Performance-Based Mix Design	$1 M–$2 M	Updates to the software, guidelines, and supporting products for concrete mix design and optimization.	A quantum improvement to the mix design process; newly developed tests and models for predicting pavement performance that allow the mix to be optimized to meet the service requirements of structural and material performance.
MD 1.4. PCC Pavement Mix Design System Integration Stage 4: Functionally-Based Mix Design	$1 M–$2 M	Updates to the software, guidelines, and supporting products for concrete mix design and optimization.	A sophisticated optimization system capable of selecting the most appropriate mixture to meet both performance requirements as well as functional requirements; a procedure based on new test procedures that identify the potential for concrete to provide a smooth, safe, and quiet pavement.
MD 1.5. Integrating Recycled Materials into PCC Mix Design System	$500 k–$1 M	Guidance and possible modifications to the mix design products that allow a user to design a concrete mixture using recycled materials.	Mix design procedures capable of economically and accurately characterizing recycled materials as concrete constituents; facing the challenge of moving to a 100 percent reuse policy, as many countries outside of the United States are doing, particularly in Europe.

Problem Statement MD 1.0. Framework for PCC Mix Design System Development and Integration (Subtrack MD 1)

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 1. PCC Mix Design System Development and Integration
Approximate Phasing:	Years 1–3
Estimated Cost:	$300 k

Subtrack MD 1 (PCC Mix Design System Development and Integration) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack MD 1 (PCC Mix Design System Development and Integration), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack MD 1 (PCC Mix Design System Development and Integration).

Problem Statement MD 1.1. PCC Pavement Mix Design System Integration Stage 1: Volumetrics-Based Mix Design (Mix Proportioning)

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 1. PCC Mix Design System Development and Integration
Approximate Phasing:	Years 2–5
Estimated Cost:	$500 k–$1 M

Today's mix design for concrete paving mixtures relies on experience, often in the form of recipe mixes. While this experience should not be ignored, the specific mixture used in a particular job should not be considered ideal for every job of that type. There can be a wide range of demands on paving jobs (e.g., required time of opening and use of admixtures and supplementary cementitious materials). Optimization techniques are necessary to select the most appropriate mixture that balances these job-specific conditions with long-term durability, while remaining cost effective.

The first step for successfully implementing a mix design system is to develop one that includes methods and parameters with which the industry is familiar. Volumetric-based design (proportioning) includes procedures that specify contents (e.g., minimum cement) and ratios (e.g., water-cement mix) for concrete-making constituents. The guidance given in American Concrete Institute (ACI) 211 committee documents might serve as a starting point for newer methods, supplemented with state-of-the-art proportioning guidance advanced by individuals such as J.M. Shilstone and K.C. Hover, and by agencies including the National Institute of Standards and Technology (NIST) and the U.S. Army Corps of Engineers (USACE), among others. This first stage of the mix design system will employ commonly used lab tests and will limit mix parameter modeling, relying instead on the empirical relationships between mix volumetrics and concrete properties of interest (e.g., strength, workability, and permeability).

Tasks:

1. Identify and assemble available mix design and proportioning systems.
2. Assess user needs for the mix design system and determine ways to incorporate the state of the practice to implement this first stage of the overall system quickly.
3. Assemble the requisite models for the system.
4. Identify the requisite laboratory test procedures and ensure standardized reporting for input to the mix design system.
5. Develop a beta version of the system and solicit peer review.
6. Develop a final version of the system and prepare it for training and implementation.

Benefits:	A procedure to allow for job-specific optimization of concrete paving mixtures based largely on currently available technology, rather than current mix proportioning methods based on either previous experience or procedural guidance developed for a broad range of concretes.
Products:	Software, guidelines, and supporting products for a new generation of concrete mix design that will optimize concrete mixtures for paving.
Implementation:	This first stage of the mix design system will be implementable immediately, and will advance the industry. Further refinements will be made to this system in subsequent stages to capture mix properties and pavement performance more directly.

Problem Statement MD 1.2. PCC Pavement Mix Design System Integration Stage 2: Property-Based Mix Design

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 1. PCC Mix Design System Development and Integration
Approximate Phasing:	Years 4–7
Estimated Cost:	$1 M–$2 M

While the first stage of the mix design system is based on volumetric ratios and limits, the second stage will offer a more fundamental approach to mix design by measuring and predicting mix properties relevant to pavement performance. The specific properties will be identified when the system itself is developed, and fresh properties such as rheology and hardened properties such as strength and permeability will be included as targets. The result of the second stage will be a mix design system built on the framework established in the first stage. By thus using a common interface and process, implementation of this and subsequent stages will be seamless.

Tasks:

1. Assemble the requisite models for the system.
2. Identify the requisite laboratory test procedures and ensure standardized reporting for input to the mix design system.
3. Develop a beta version of the system and solicit peer review.
4. Develop a final version of the system and prepare it for training and implementation.

Benefits:	Building on the foundational work conducted under MD 1.1 (PCC Pavement Mix Design System Integration Stage 1: Volumetrics-Based Mix Design), a procedure capable of designing and optimizing a mix for more specific and pertinent concrete properties, possibly including strength, workability, permeability, stiffness, shrinkage, and coefficient of thermal expansion.
Products:	Updates to the software, guidelines, and supporting products for concrete mix design and optimization.
Implementation:	This second stage of the mix design system will be implementable immediately and will advance the industry. Further refinements will be made to this system in subsequent stages to capture pavement performance more directly.

Problem Statement MD 1.3. PCC Pavement Mix Design System Integration Stage 3: Performance-Based Mix Design

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 1. PCC Mix Design System Development and Integration
Approximate Phasing:	Years 6–9
Estimated Cost:	\$1 M–\$2 M

Volumetric- and property-based mix design procedures cannot describe PCC paving mixtures accurately in terms of the mixtures' impact on pavement performance. The result of these approaches, largely based on an empirical understanding of the effects of properties on performance, is poor design reliability. To offset this shortcoming, this third stage in developing a mix design system will integrate sophisticated pavement performance models. The result will be a seamless tool that can predict various performance measures of a concrete pavement as a function of the concrete mix. Optimization techniques then can be used to select the ideal materials and proportions for achieving the desired level of pavement performance, while maintaining desired levels of other concrete properties (e.g., strength and workability).

Tasks:

1. Assemble the requisite models for the system.
2. Identify the requisite laboratory test procedures and ensure standardized reporting for input to the mix design system.
3. Develop a beta version of the system and solicit peer review.
4. Develop a final version of the system and prepare it for training and implementation.

Benefits:	A quantum improvement to the mix design process; newly developed tests and models for predicting pavement performance that allow the mix to be optimized to meet the service requirements of structural and material performance.
Products:	Updates to the software, guidelines, and supporting products for concrete mix design and optimization.
Implementation:	This third stage of the mix design system will be implementable immediately and will advance the industry. Further refinements will be made to this system in subsequent stages to capture the functional performance of the concrete pavement more directly.

Problem Statement MD 1.4. PCC Pavement Mix Design System Integration Stage 4: Functionally Based Mix Design

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 1. PCC Mix Design System Development and Integration
Approximate Phasing:	Years 8–10
Estimated Cost:	$1 M–$2 M

Pavement and materials engineering decisions often are driven by functional requirements responding to a public need—for example, demands for quieter, smoother, and safer pavements. While concrete pavements can meet all of these functional demands, pavements must be designed appropriately to do so. As part of this fourth stage, a system will be developed to evaluate the effects of concrete materials and mixture on pavement function (e.g., noise, ride quality, texture). By better understanding these relationships, a more rational approach to meeting these functional requirements can be met with improved mix design techniques. Using these procedures, innovative solutions such as two-lift pavements can be designed optimally, with the top layer designed to meet a set of functional demands.

Tasks:

1. Assemble the requisite models for the system.
2. Identify the requisite laboratory test procedures and ensure standardized reporting for input to the mix design system.
3. Develop a beta version of the system and solicit peer review.
4. Develop a final version of the system and prepare it for training and implementation.

Benefits:	A sophisticated optimization system capable of selecting the most appropriate mixture to meet both performance and functional requirements; a process based on new test procedures that identify the potential for concrete to provide a smooth, safe, and quiet pavement.
Products:	Updates to the software, guidelines, and supporting products for concrete mix design and optimization.
Implementation:	This final stage of the mix design system will be implementable immediately. It is the final product from this research track.

Problem Statement MD 1.5. Integrating Recycled Materials into PCC Mix Design System

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 1. PCC Mix Design System Development and Integration
Approximate Phasing:	Years 5–10
Estimated Cost:	$500 k–$1 M

Previous studies have demonstrated that recycled concrete and other recycled materials can be used in new concrete mixtures successfully, as long as the effects of using recycled materials in the mixture are compared to the effects of using virgin materials. This study will build on that work, determining innovative ways to use recycled materials in PCC pavements. Because sustainability is being emphasized increasingly in the United States and abroad, identifying creative uses for recycled materials will sustain and likely extend their desirability.

Tasks:

1. Investigate using recycled materials in mix designs for shorter performance life pavements, such as an 8-year pavement.
2. Investigate using recycled materials for various portions of the product, for example, the fine or course fractions of the aggregate.
3. Investigate the boundaries for using recycled materials in bases and two-lift construction.
4. Combine the recommended guidance into supplements or adjustments to the new performance-based mix design system.

Benefits:	Mix design procedures capable of economically and accurately characterizing recycled materials as concrete constituents; facing the challenge of moving to a 100 percent reuse policy, as many countries outside of the United States are doing, particularly in Europe.
Products:	Guidance and possible modifications to the mix design products that allow users to design a concrete mixture using recycled materials.
Implementation:	With pressure to use recycled materials expected to increase, having proper guidance available to users will ensure that the PCC pavement industry is prepared to meet these demands.

SUBTRACK MD 2. PCC MIX DESIGN LABORATORY TESTING AND EQUIPMENT

This subtrack identifies all the new and upgraded equipment and test procedures needed for the concrete laboratory of the future. This subtrack also addresses a range of opportunities, from improved laboratory mixing to more accelerated durability testing. It concludes with an expert system that connects the test results. Table 3 provides an overview of this subtrack.

Table 3. Subtrack MD 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
MD 2.0. Framework for PCC Mix Design Laboratory Testing and Equipment (Subtrack MD 2)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
MD 2.1. Laboratory Mixer to Replicate PCC Field Batching	$1 M–$2 M	AASHTO-formatted specifications for constructing and operating a laboratory mixer capable of replicating the full-scale batching and mixing process.	Lab equipment capable of simulating the full-scale batching process, resulting in more representative concrete test specimens and thus a more reliable mix design.
MD 2.2. Laboratory Compactor to Replicate Concrete Paving Practice	$1 M–$2 M	AASHTO-formatted specifications for constructing and operating a laboratory compactor capable of replicating the full-scale compacting (consolidating) effort induced by the vibration and extrusion process of a slipform paver.	Lab equipment capable of simulating the compacting effort of a slipform paver, resulting in more representative concrete test specimens and thus providing a more reliable mix design.
MD 2.3. Aggregate Tests for PCC Mix Characterization	$2 M–$5 M	Various AASHTO-formatted materials specifications and test procedures capable of evaluating aggregate properties most sensitive to the behavior, durability, performance, and function of both paving concrete and the concrete pavement.	New and improved aggregate test procedures, providing the mix designer with a more reliable system for selecting and proportioning the optimum aggregate for paving mixtures; ways to avoid potential early durability problems.
MD 2.4. Performance-Based Cementitious Materials Specifications	$1 M–$2 M	New AASHTO-formatted specifications for specifying cementitious materials used in concrete paving mixtures.	Specifications that will allow the mix designer to make informed choices about the proper materials based on desired level of performance and with a clear understanding of compatibility or performance issues; materials specifications that keep pace with the dramatic changes in the materials themselves.
MD 2.5. PCC Mix Durability Tests	$2 M–$5 M	Various AASHTO-formatted materials specifications and test procedures capable of evaluating the durability of concrete mixtures.	Test procedures that will identify the potential of durability-related problems in the laboratory during mix design and in the field during placement; alleviation of durability-related issues, ranging from alkali-silica reaction (ASR) to freeze-thaw durability, and including numerous chemical and mechanical distress mechanisms.

Table 3. Subtrack MD 2 overview, continued.

Problem Statement	Estimated Cost	Products	Benefits
MD 2.6. PCC Mix Compatibility Tests	$2 M–$5 M	Various AASHTO-formatted test procedures capable of identifying compatibility problems within a mixture or between the mixture and the paving environment.	Practical and accurate test procedures for identifying incompatibilities that will reduce cost and improve concrete paving performance; avoiding the increasing possibility of incompatibility from newer constituents added to concrete mixtures as well as conditions during placement, such as climate.
MD 2.7. PCC Mix Property Test Development	$2 M–$5 M	Various AASHTO-formatted test procedures capable of quickly measuring concrete mix properties in a repeatable and reproducible fashion.	New test procedures for measuring concrete mix properties that constitute a critical component of the mix design system, providing the data necessary by the models for optimization.
MD 2.8. PCC Mix Thermal Tests	$500 k–$1 M	AASHTO-formatted test procedures for measuring critical thermodynamic properties of a concrete mix including calorimetry and thermal transport properties.	Test procedures for thermal properties of concrete mixes that allow the industry to quantify the impact that the hydration process has on both the early-age behavior and long-term performance of the concrete pavement.
MD 2.9. PCC Mix Performance Testing Equipment	$2 M–$5 M	AASHTO-formatted test procedures for new equipment (or a combination of existing equipment) capable of assessing the performance potential of a concrete mix (e.g., susceptibility to fatigue cracking or spalling).	Increased concrete pavement quality through tracking the properties that are the most relevant to concrete pavement performance.
MD 2.10. PCC Mix Functional Testing Equipment	$2 M–$5 M	AASHTO-formatted test procedures for new equipment (or a combination of existing equipment) capable of assessing the performance potential of a concrete mix (e.g., ability to construct a smooth, safe, and quiet surface).	Increased concrete pavement quality through tracking the properties that are the most relevant to concrete pavement performance.
MD 2.11. Expert System for PCC Mixes	$1 M–$2 M	A robust computerized expert system with an intuitive interface that allows users to access best practices and to troubleshoot.	Preservation of institutional memory, which is fading as many industry experts retire; an expert system that captures their experience in a form that is easily accessible to anyone.

Problem Statement MD 2.0. Framework for PCC Mix Design Laboratory Testing and Equipment (Subtrack MD 2)

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 1–3
Estimated Cost:	$200 k

Subtrack MD 2 (PCC Mix Design Laboratory Testing and Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack MD 2 (PCC Mix Design Laboratory Testing and Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	The research will provide the organization and validation essential for the success of this subtrack. Implementing this problem statement will set the stage for the rest of the problem statements in subtrack MD 2 (PCC Mix Design Laboratory Testing and Equipment).

Problem Statement MD 2.1. Laboratory Mixer to Replicate PCC Field Batching

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–4
Estimated Cost:	$1 M–$2 M

The techniques used to mix concrete in the laboratory differ from field techniques. For example, differences are evident in charging sequences and mixing energy. This research will develop performance specifications for a new generation of laboratory mixers that can better replicate the full-sized mixers commonly used in concrete paving. The cost and efficiency of a laboratory mixer will be considered. If successful, the new laboratory mixer will evaluate new and innovative PCC mix designs more quickly for research, mix development, and QC.

Tasks:

1. Identify available technologies and previous trials of similar laboratory mixers.
2. Develop additional technology and equipment as needed.
3. Compare various concrete mixtures as mixed in full-scale batching operations with those mixed in the new laboratory mixer. Comparisons should be made based on pertinent properties, such as air void structure, strength, and permeability.
4. If a new mixer is successfully identified, develop an AASHTO-formatted standard.

Benefits:	Lab equipment capable of simulating the full-scale batching process, resulting in more representative concrete test specimens and thus a more reliable mix design.
Products:	AASHTO-formatted specifications for constructing and operating a laboratory mixer capable of replicating the full-scale batching and mixing process.
Implementation:	This technology, if identified, can be a key component of the laboratory of the future that will feed key mix test results into the mix design system.

Problem Statement MD 2.2. Laboratory Compactor to Replicate Concrete Paving Practice

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–4
Estimated Cost:	$1 M–$2 M

The techniques employed to consolidate laboratory specimens (either in the field or in the lab) do not represent the nature of the concrete in place after paving. Differences in the source and energy of consolidation result in differences in the quantity, position, and orientation of the various concrete constituents within the mixture (particularly the air void structure). This research will develop a consolidation device that can better simulate the consolidation process that results from slipform paving (and other placement techniques as needed).

Tasks:

1. Identify available technologies and previous trials of similar laboratory compactors.
2. Develop additional technology and equipment as needed.
3. Compare various concrete mixtures compacted in place (behind a slipform paver) with mixtures compacted using the new laboratory compactor. Comparisons should be made based on pertinent properties, such as air void structure, strength, and permeability.
4. If a new compactor is identified, develop an AASHTO-formatted standard.

Benefits:	Lab equipment capable of simulating the compacting effort of a slipform paver, resulting in more representative concrete test specimens and thus providing a more reliable mix design.
Products:	AASHTO-formatted specifications for constructing and operating a laboratory compactor capable of replicating the full-scale compacting (consolidating) effort induced by the vibration and extrusion process of a slipform paver.
Implementation:	This technology, if identified, can be a key component in future laboratories that will feed key mix test results into the mix design system.

Problem Statement MD 2.3. Aggregate Tests for PCC Mix Characterization

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–10
Estimated Cost:	$2 M–$5 M

Aggregates constitute the largest component of nearly all concrete mixes, by both weight and volume. As a result, the properties of the concrete mix are driven largely by the properties of the aggregates. Because of the high costs of mining and hauling aggregates, research is needed to develop procedures for identifying the most cost effective aggregate sources for a construction project that will meet the user's durability, performance, and functional requirements. The use of an aggregate will take into account the total cost of the material, including consideration of haul distances, material quality, necessary mix design adjustments, and projected long-term PCC performance. An important aspect of this research will be to develop tests that can identify durable aggregates before the quarry wall is mined. Procedures also will be developed (or current procedures revised) for rapidly determining the ASR potential of concrete mixes made with this aggregate. Additionally, this research will identify ways to protect existing aggregate sources from urban development and to access sources that are difficult to retrieve due to environmental concerns and/or existing urban development. Above all, the test procedures developed here should clearly link to the proposed mix design system.

While this broad research will require further definition during the framework stage, specific aggregate properties expected to be researched under this task include cleanliness, thermal properties (especially coefficient of thermal expansion), and abrasion resistance, among others. To lower transport costs, lightweight aggregates should also be considered and evaluated.

Tasks:

1. Identify the needs for aggregate laboratory testing, prioritized based on the impact that the properties have on concrete pavement durability and performance.
2. Develop AASHTO-formatted aggregate test procedures as needed, establishing clear links to the mix design procedures.
3. Connect the aggregate test procedures to other tracks, including those for QC and nondestructive testing (NDT).

Benefits:	New and improved aggregate test procedures, providing the mix designer with a more reliable system for selecting and proportioning the optimum aggregate for paving mixtures; ways to avoid potential early durability problems.
Products:	Various AASHTO-formatted materials specifications and test procedures capable of evaluating aggregate properties most sensitive to the behavior, durability, performance, and function of both paving concrete and the concrete pavement.
Implementation:	Many new laboratory tests for concrete aggregates are expected. These tests will feed directly into the mix design system and be the foundation for more advanced tests as the state of the art evolves.

Problem Statement MD 2.4. Performance-Based Cementitious Materials Specifications

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–6
Estimated Cost:	$1 M–$2 M

Cementitious materials as they are currently specified (i.e., by percent replacement) and classified (i.e., by fineness and chemical composition) do not reflect their long-term performance as used in PCC pavements. Current methods of specification and classification also fail to reflect the compatibility of the cementitious materials with aggregates and chemical admixtures. This research will develop a cementitious materials specification that reflects the link between the various properties of the cementitious materials and performance and compatibility issues. The specification should be developed to differentiate the various uses of cementitious materials and their influence on concrete's fresh properties, such as slump, air void characteristics, and set time; and on concrete's hardened properties, such as strength and abrasion resistance. Ongoing efforts and specifications being developed through the American Society for Testing and Materials (ASTM) and other organizations should be considered.

Tasks:

1. Identify existing and ongoing work in developing performance-based specifications for cement, supplementary cementing materials, and cementitious materials, both individually and as a combined material.
2. Identify a structure for a performance-based specification that includes a suite of tests rationally connected to pavement performance.
3. Develop an AASHTO-formatted draft specification and evaluate it based on the performance of existing pavement sections as well as the known cementitious materials properties.
4. Refine the specification based on the evaluation and integrate it into the mix design system.

Benefits:	Specifications that will allow the mix designer to make informed choices about the proper materials, based on desired level of performance and with a clear understanding of compatibility or performance issues; materials specifications that keep pace with the dramatic changes in the materials themselves.
Products:	New AASHTO-formatted specifications for specifying cementitious materials used in concrete paving mixtures.
Implementation:	A suite of tests will result that can be used to specify cementitious materials through performance predictions. These tests will provide inputs to the mix design system as well as other research tracks, including process (quality) control.

Problem Statement MD 2.5. PCC Mix Durability Tests

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–10
Estimated Cost:	$2 M–$5 M

Contractors and owner-agencies want to know whether a mix designed to last 30 or more years will last that long when placed in the field, particularly if the pavement is constructed under a warranty or performance-based specification. Likely, no single test will be able to guarantee that a pavement will last 30 or more years, largely because of variable environmental conditions and traffic/wheel loading over the life of the pavement. However, it should be possible to develop test methods to predict the probability that a given concrete mix will last for the intended design life. While this broad research will require further definition during the framework stage, many key mix durability characteristics should be investigated as needed, including freeze-thaw durability, ASR resistance, sulfate attack resistance, and steel corrosion potential. Research is needed to develop accelerated testing methods that more accurately predict the long-term strength, durability, and performance potential of concrete. These tests will allow the owner-agency or contractor to evaluate the mix design before construction as well as after placement, based on core samples removed from the newly placed pavement. An initial step may require additional research to define the minimum water-cement ratio in the field. Meanwhile, premature materials-related distress in concrete pavements appears to be growing more widespread. As a result, additional investigation is needed to identify the various potential causes of the observed problems. Research also is needed to develop improved sulfate-resistant concretes, especially for paving applications, and a broad program of research is needed to mitigate existing ASR conditions. Finally, this task should address air void and steel corrosion issues.

Tasks:

1. Identify the various durability issues facing concrete pavements, discerning and linking research that addresses both the visible distresses and the fundamental mechanisms.
2. Study available equipment and test procedures to identify the potential for and severity of the various deterioration mechanisms as a function of the concrete mix.
3. Develop and integrate AASHTO-formatted lab test procedures that feed into the mix design system, allowing users to optimize a mix based on material durability and other criteria.

Benefits:	Test procedures that will identify possible durability-related problems in the laboratory during mix design and in the field during placement; alleviation of durability-related issues ranging from ASR to freeze-thaw durability and including numerous chemical and mechanical distress mechanisms.
Products:	Various AASHTO-formatted materials specifications and test procedures capable of evaluating the durability of concrete mixtures.
Implementation:	A suite of tests will result that can be used to identify possible durability issues associated with a given mix design. These tests will provide inputs for the mix design system as well as other research tracks, including process (quality) control.

Problem Statement MD 2.6. PCC Mix Compatibility Tests

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–10
Estimated Cost:	$2 M–$5 M

Mineral and chemical admixtures currently are available for improving the essential properties of a concrete mix (such as strength, permeability, and freeze-thaw resistance). However, these admixtures often are used in combination in a PCC paving mix without a thorough understanding of the materials' interaction or compatibility. For example, while a proper air void system is essential for durable concrete, excessive air voids reduce the effective cross-sectional area of concrete elements, decreasing concrete strength. Supplementary cementitious materials can cause further complications by creating an unstable air void system in freshly mixed concrete. This problem worsens when certain chemical admixtures also are used in the concrete. Research is needed to study the interaction and compatibility of various admixtures in PCC mixes and the effects that incompatibility may have on concrete properties and pavement performance. Research is also needed to develop accelerated testing methods that more accurately predict incompatibilities and their effects on long-term strength, durability, and performance. These tests will allow the owner-agency or contractor to evaluate the mix design before construction and ensure compatibility of mixture components before concrete placement.

Tasks:

1. Identify known compatibility problems among PCC admixtures, including the effects admixtures have on concrete properties, such as workability and the air void system.
2. Conduct laboratory testing to identify further compatibility problems.
3. Determine the effects of incompatible materials on pavement performance.
4. Determine the limits on proportions of incompatible materials.
5. Develop AASHTO-formatted test procedures and associated equipment that can identify incompatibilities in concrete mixes in the lab.
6. Integrate the lab test procedures into the mix design system to allow users to avoid mixture incompatibilities during the mix design process.

Benefits:	Practical and accurate test procedures for identifying incompatibilities that will reduce cost and improve concrete paving performance; avoiding the increasing possibility of incompatibility from newer constituents added to concrete mixtures and due to conditions during placement, such as climate.
Products:	Various AASHTO-formatted test procedures capable of identifying compatibility problems within a mixture or between the mixture and the paving environment.
Implementation:	Guidelines and test procedures/equipment that identify potential incompatible materials in PCC paving mixes will result. These tests can be used during the mix design process as well as for QC during construction.

Problem Statement MD 2.7. PCC Mix Property Test Development

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 2–8
Estimated Cost:	$2 M–$5 M

Mix properties affect both the constructability and long-term performance of PCC pavements. While this broad research will require significant definition during the framework stage, some of the essential mix properties that may warrant investigation include water-cement ratio, permeability, air void system, and workability. While several tests that measure most of these properties currently exist, many of these test procedures are still somewhat crude or time-consuming and give varied results. For example, while it is simple to calculate water-cement ratio based on batch weights, this calculation may not accurately indicate the actual in place water-cement ratio due to addition of water at the job site, inaccurate estimates of aggregate moisture content, or water evaporation during transportation. Thin sections can be used to estimate the water-cement ratio of the hardened concrete, but this is time-consuming and generally occurs long after paving is finished. Research is needed to investigate essential mix properties and develop or further refine procedures for measuring these mix properties quickly and accurately. This research will identify essential mix properties affecting both constructability and pavement performance and develop testing equipment for measuring these properties.

Tasks:

1. Identify essential mix properties that affect pavement constructability and performance.
2. Identify and develop AASHTO-formatted test procedures and associated equipment for measuring these properties.
3. Develop new equipment that can be used to measure essential mix properties in the lab and in the field quickly and accurately.
4. Develop recommendations for deploying mix property testing equipment.

Benefits:	New test procedures for measuring concrete mix properties that constitute a critical component of the mix design system, providing the data necessary by the models for optimization.
Products:	Various AASHTO-formatted test procedures capable of quickly measuring concrete mix properties in a repeatable and reproducible fashion.
Implementation:	This work will result in test equipment that will quickly and accurately measure essential mix properties. The test equipment can be used for trial batching during the mix design process and for QC during construction.

Problem Statement MD 2.8. PCC Mix Thermal Tests

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 3–6
Estimated Cost:	$500 k–$1 M

The FHWA HIPERPAV™ program is among a number of recent initiatives that have underscored the importance of heat development in concrete pavements. A concrete mixture generally can be characterized by a unique signature representing the amount and rate of heat generated through the hydration process. Measuring this characteristic requires a calorimeter, commonly isothermal, adiabatic, or semi-adiabatic. While the importance of this concrete characteristic has been demonstrated and accepted, no accepted standard for measurement yet exists. This research will develop a nonproprietary test standard suitable for AASHTO adoption. If both practical and cost effective, the standard should spur widespread acceptance of this test for characterizing a concrete mixture. A second goal in developing the specification should be to develop a test rugged enough for use in the field for routine QC. Finally, if the heat signature test is found to be sensitive to pavement performance, tests for other thermal properties should be developed during this task, including tests for the specific heat and thermal conductivity of the PCC. A precedent currently exists for evaluating these parameters within the *Mechanistic-Empirical Pavement Design Guide*.(1)

Tasks:

1. Identify the mix thermal properties that are most sensitive for predicting concrete pavement behavior and performance.
2. Identify existing lab tests to evaluate the most sensitive properties. Evaluation criteria should include ease of use, proprietary nature, cost, ruggedness, repeatability, and reproducibility.
3. Select candidate lab tests and perform a structured evaluation of the equipment, comparing the test results to known standards, if possible.
4. Develop specifications suitable for adoption by AASHTO.

Benefits:	Test procedures for thermal properties of concrete mixes that allow the industry to quantify the impact of the hydration process on both the early-age behavior and long-term performance of the concrete pavement.
Products:	AASHTO-formatted test procedures for measuring critical thermodynamic properties of a concrete mix, including calorimetry and thermal transport properties.
Implementation:	A number of tests will result that can identify the thermal properties of concrete mixes. These tests will provide inputs for the mix design system as well as other research tracks, including process (quality) control and intelligent construction systems (ICS).

Problem Statement MD 2.9. PCC Mix Performance Testing Equipment

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 5–10
Estimated Cost:	$2 M–$5 M

Mix performance is one of the most important factors in determining pavement performance, particularly in the long term. Some essential performance properties include freeze-thaw resistance, abrasion resistance, and sulfate-attack resistance, among others. Understanding mix performance will help contractors and owner-agencies develop mixes that meet the design life requirements. Performance problems may not necessarily be caused by durability problems, such as material incompatibility and freeze-thaw resistance, but may simply result from improper mixture proportioning or material selection. This research will examine factors that affect mix performance and thereby affect pavement performance. Testing equipment will be developed to help predict mix performance quickly during the mix design process in the laboratory.

Tasks:

1. Identify factors (e.g., mix proportions and materials) that affect mixture performance.
2. Identify equipment or test procedures that can be used to predict mix performance.
3. Refine existing equipment or develop new testing equipment that can be used to predict mix performance quickly.
4. Work with contractors and owner-agencies to evaluate the test equipment.
5. Develop AASHTO-formatted specifications and associated recommendations for deploying new testing equipment.

Benefits:	Increased concrete pavement quality through tracking the properties that are the most relevant to concrete pavement performance.
Products:	AASHTO-formatted test procedures for new equipment (or a combination of existing equipment) capable of assessing the performance potential of a concrete mix (e.g., susceptibility to fatigue cracking or spalling).
Implementation:	Testing procedures and equipment that can predict mix performance in the laboratory will result. The testing equipment can be used by contractors and owner-agencies during the mix design process and for QC testing.

Problem Statement MD 2.10. PCC Mix Functional Testing Equipment

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 7–10
Estimated Cost:	$2 M–$5 M

Some properties of PCC mixes can affect the functional performance of PCC pavements, including mix placeability (which affects ride quality and tire-pavement noise), abrasion resistance (which affects ride quality and safety), and skid resistance (which affects safety). These PCC mix properties ultimately influence roadway user satisfaction, particularly regarding users' safety and driving comfort. While these issues may not affect pavement performance directly, significant consequences can result if they are overlooked. For example, a pavement that is too noisy may require expensive sound walls, while a pavement with poor abrasion resistance may rut under studded tires and require costly rehabilitation. Research is needed to investigate the essential functional properties of PCC paving mixes and develop tests for measuring these properties. The tests should allow the contractor or owner-agency to predict functional performance during the mix design process quickly so adjustments can be made before construction.

Tasks:

1. Identify important properties of PCC mixes that ultimately tie into functional pavement performance.
2. Identify test procedures and equipment that can be used to measure these properties.
3. Modify existing equipment or develop new equipment that quickly and accurately can measure the properties that predict pavement functional performance.
4. Develop AASHTO-formatted specifications and associated recommendations for deploying functional testing equipment.

Benefits:	Increased concrete pavement quality through tracking the properties that are the most relevant to concrete pavement performance.
Products:	AASHTO-formatted test procedures for new equipment (or a combination of existing equipment) capable of assessing the performance potential of a concrete mix (e.g., susceptibility to fatigue cracking or spalling).
Implementation:	This work will result in testing procedures and equipment that can measure mix properties to predict pavement functional performance. The tests can be used during the mix design process and for QC during construction.

Problem Statement MD 2.11. Expert System for PCC Mixes

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 2. PCC Mix Design Laboratory Testing and Equipment
Approximate Phasing:	Years 3–10
Estimated Cost:	$1 M–$2 M

Recent concerns about early deterioration of concrete pavement indicate a need for tools that predict concrete durability problems during mixture proportioning and design. No limitations usually exist on the combination of materials that can produce workable and durable concrete. However, constituent materials with certain chemical attributes, such as high levels of alkali, may develop mixture durability problems. Data for long-term tests of concrete mixtures, such as the prism test and screening tests for such constituents as aggregate, are available from many States. Compiling these data into a large database could provide the foundation for an expert system to predict durability problems. This system could indicate the potential for material combination problems and guide engineers and contractors in developing mix designs for pavement projects.

Because of the rapid increase in the number of concrete production materials available, it is important to develop a national database that collects and synthesizes information about all concrete mixes used throughout the United States, from mix design to durability in the field. Clearly documenting the mixes that are successful for a particular application and set of materials and those that are unsuccessful will provide States and others a means to assess their own mixes without having to perform extensive and costly laboratory testing. The database will allow users to determine whether a certain mix design will be successful or unsuccessful. More specifically, this national database will contain information about the concrete materials, mix proportions, locations of use, pavement designs, fresh and hardened concrete properties, construction methods, and the long-term durability performance of the concrete mixes. It also will detail issues such as whether ASR, sulfate attack, freeze-thaw resistance, or any other fresh or hardened concrete property was inappropriate for a particular mixture and site condition.

Tasks:

1. Identify available sources of information for the expert system, including existing syntheses, expert personnel, and existing databases.
2. Identify a structure for the expert system that allows users intuitive access to the information and rapid and efficient population of the information during development.
3. Develop a beta version of the system and establish a peer review process.
4. Refine the expert system and prepare a form suitable for rapid implementation (e.g., consideration should be made for Internet deployment to keep the system dynamic).

Benefits:	Preservation of institutional memory, which is fading as many industry experts retire; a system that captures their experience in a form that is easily accessible.
Products:	A robust computerized expert system with an intuitive interface that allows users to access best practices and troubleshoot.
Implementation:	An expert system will be developed that includes an extensive database of experience and other data related to paving concrete mixtures and their performance. This information should be kept dynamic with ongoing updates and feedback.

SUBTRACK MD 3. PCC MIX DESIGN MODELING

This subtrack addresses the modeling needed to predict slab performance using the laboratory test results identified in the previous subtrack. The modeling also must be coordinated fully throughout this entire track. The research in the following problem statements will develop, improve, adapt, calibrate, and validate PCC pavement models. Table 4 provides an overview of this subtrack.

Table 4. Subtrack MD 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
MD 3.0. Framework for PCC Mix Design Modeling (Subtrack MD 3)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
MD 3.1. Aggregate Models for Optimizing PCC Mixtures	$250 k–$500 k	Thoroughly documented models, also in computerized form, that can be used to optimize the sizing and blending of aggregate stockpiles for a concrete mix.	Models that optimize the aggregate structure within a concrete mix that have been shown to improve a wide variety of fresh and hardened concrete properties.
MD 3.2. Fresh PCC Pavement Behavior Models	$1 M–$2 M	Thoroughly documented models, also in computerized form, that can be used to predict the behavior of fresh concrete (e.g., rheology).	Models that predict critical fresh concrete properties as a function of the mix to allow the mix design system to consider these factors more objectively.
MD 3.3. Hardened PCC Pavement Behavior Models	$250 k–$500 k	Thoroughly documented models, also in computerized form, that can be used to predict the behavior of hardened concrete.	Characterization of hardened concrete properties and behavior to optimize the mix design system for performance.
MD 3.4. Improved PCC Pavement Performance Models Adaptation	$250 k–$500 k	Thoroughly documented models, also in computerized form, that can be used to predict the structural performance (e.g., faulting) of a concrete pavement as a function of mix properties.	Performance models predicting the linkage between concrete pavement performance and mix properties in the mix design system; supplements for other ongoing efforts to develop these models.
MD 3.5. Functional PCC Pavement Models Adaptation	$250 k–$500 k	Thoroughly documented models, also in computerized form, that can be used to predict the functional performance (e.g., smoothness) of a concrete pavement as a function of mix properties.	Functional models predicting the linkage between concrete pavement function (e.g., smoothness, safety, noise) and mix properties in the mix design system; supplements for other ongoing efforts to develop these models.
MD 3.6. Characterizing Concrete Materials Variability	$250 k–$500 k	Thorough documentation of each of the sources and degrees of variability in the concrete making process.	Understanding variability well enough to quantify it objectively, thus remaining cost effective in design.
MD 3.7. PCC Mix Model Calibration	$1 M–$2 M	A calibration report of the various models used to predict concrete mix behavior and concrete pavement performance; adjustments to the various models as needed.	Proper calibration of the numerous models developed and assembled as part of this research track before widespread distribution of the system.
MD 3.8. PCC Mix Model Validation	$500 k–$1 M	A validation report of the various models used to predict concrete mix behavior and concrete pavement performance; adjustments to the various models as needed.	A validation effort conducted before release of the mix design system that assesses the predictive ability of the system in situations independent of the development and calibration activities.

Problem Statement MD 3.0. Framework for PCC Mix Design Modeling (Subtrack MD 3)

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack MD 3 (PCC Mix Design Modeling) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack MD 3 (PCC Mix Design Modeling), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack MD 3 (PCC Mix Design Modeling).

Problem Statement MD 3.1. Aggregate Models for Optimizing PCC Mixtures

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 2–4
Estimated Cost:	$250 k–$500 k

Aggregate packing is an important consideration for optimizing concrete mixtures. Aggregate packing is used to determine the optimal proportions of aggregate for a specific concrete mix, given the aggregates available for a particular project. The goal of aggregate packing is to minimize the voids in the aggregate skeleton, thereby minimizing the amount of cement paste needed. This not only strengthens the mix by maximizing the amount of aggregate, but also minimizes shrinkage, permeability, and porosity.

Additionally, minimizing the amount of cement paste reduces the cost of the mix, as cementitious materials are generally the most expensive component in concrete mixes. Research is needed to develop a method for characterizing the aggregate packing behavior in a concrete mixture based on the aggregate shape and gradation.

Tasks:

1. Identify existing models suitable for predicting the optimum aggregate structure within a concrete mixture.
2. Determine the suitability of the existing models for paving mixtures and conduct research to make necessary adjustments.
3. Develop a beta version of the model through a stand-alone interface and evaluate the predictions against lab and field data.
4. Develop the final model in a form suitable for rapid incorporation into the mix design system.

Benefits:	Models that optimize the aggregate structure within a concrete mix that have been shown to improve a wide variety of fresh and hardened concrete properties.
Products:	Computerized models that can be used to optimize the sizing and blending of aggregate stockpiles for a concrete mix; model documentation.
Implementation:	The model developed under this effort will be used in the various predictive modes of the mix design system.

Problem Statement MD 3.2. Fresh PCC Pavement Behavior Models

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 3–7
Estimated Cost:	$1 M–$2 M

Fresh PCC behavior affects the constructability and performance of PCC pavements, properties that significantly impact the cost and quality of the finished product. Ensuring optimal fresh PCC properties for a paving operation will improve paving efficiency, reduce labor costs, increase paving speed, and result in a finished product that meets durability and functional requirements. Concrete moisture variations, for example, significantly affect most concrete properties, such as strength and shrinkage. For example, distresses such as plastic shrinkage cracking, delamination spalling, and drying shrinkage cracking result from excessive moisture loss during construction. Likewise, the air void system significantly affects pavement constructability and durability. Modeling can predict fresh PCC behavior and pavement performance efficiently based on fresh PCC properties. Modeling also allows virtual adjustments to be made to PCC mixes before trial batching. Multiscale models are needed to predict and guide the entire concrete paving process, from microstructure to performance. More fundamental models will be developed that tie fresh PCC properties to constructability and performance, and those properties selected for accurate, reliable, and inexpensive field evaluation. These models will take into account various material properties, climatic conditions, admixtures, and construction techniques available for paving operations. The models will then be incorporated into easy-to-use software for both contractors and owner-agencies that can be incorporated into the broader mix design system developed in this research track.

Tasks:

1. Identify existing models suitable for predicting the behavior of a fresh concrete mixture.
2. Determine the suitability of the existing models to paving mixtures and conduct research to make necessary adjustments.
3. Develop a beta version of the model through a stand-alone interface and evaluate the predictions against lab and field data.
4. Develop the final model in a form suitable for rapid incorporation into the mix design system.

Benefits:	Models that predict critical fresh concrete properties as a function of the mix to allow the mix design system to consider these factors more objectively.
Products:	Computerized models that can be used to predict the behavior of fresh concrete (e.g., rheology); model documentation.
Implementation:	This work will result in models that can be used to predict constructability and pavement performance based on fresh PCC properties. The models can be used both during the mix design process and as a replacement or supplement to QC tests during construction.

Problem Statement MD 3.3. Hardened PCC Pavement Behavior Models

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 3–8
Estimated Cost:	$250 k–500 k

Understanding pavement behavior is essential for the pavement design process, as pavement behavior influences pavement characteristics (e.g., thickness, slab length), joint design, mix design, and construction techniques. Modeling pavement behavior is an efficient way to ensure that the pavement design is adequate for the given conditions. Improved models for understanding hardened PCC pavement behavior are needed to predict critical aspects such as curling and warping, joint functionality, and others. These models should take into account material properties, mix properties, construction conditions, and pavement characteristics. The models should also account for hardened PCC properties, such as creep, coefficient of thermal expansion, zero-stress temperature, slab temperature gradients, pavement support, and environmental conditions, among others. These new models will allow designers, contractors, and owner-agencies to make necessary adjustments to pavement design characteristics during the design process, well in advance of construction, as well as during construction.

Tasks:

1. Identify existing models suitable for predicting hardened concrete behavior. The models selected should be used in concert with ongoing work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement).
2. Determine the suitability of the existing models for paving mixtures and conduct research to make necessary adjustments.
3. Develop a beta version of the models through a stand-alone interface and evaluate the predictions against lab and field data.
4. Develop the final models in a form suitable for rapid incorporation into the mix design system.

Benefits:	Characterization of hardened concrete properties and behavior to optimize the mix design system for performance.
Products:	Computerized models that can be used to predict the behavior of hardened concrete; model documentation.
Implementation:	This work will result in models that predict hardened PCC pavement behavior, presented in the form of easy-to-use software. The models can be employed both during the design process and to make design adjustments during construction. This work assumes that the research done in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement) has been completed. The estimated cost for this research is above and beyond that in track 2.

Problem Statement MD 3.4. Improved PCC Pavement Performance Models Adaptation

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 3–7
Estimated Cost:	$250 k–$500 k

When designing a PCC pavement, the pavement engineer specifies performance goals for both the plastic and hardened concrete. The owner and contractor want to predict this performance to ensure that what is specified and placed will meet the long-term goals. This research will develop new models or refine existing ones to evaluate the characteristics of given mix designs and thus predict long-term pavement performance. The models will take into account the mix properties as well as site characteristics and construction techniques to predict pavement performance. These models will be suitable for use during both the mix design process and construction so that necessary adjustments can be made quickly.

Tasks:

1. Identify existing models suitable for predicting concrete pavement performance as a function of the concrete mixture. The models selected should be used in concert with ongoing work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement).
2. Determine the suitability of existing models to paving mixtures and conduct research to make necessary adjustments.
3. Develop beta versions of the models through a stand-alone interface and evaluate the predictions against lab and field data.
4. Develop the final models in a form suitable for rapid incorporation into the mix design system.

Benefits:	Performance models predicting the linkage between concrete pavement performance and mix properties in the mix design system; supplements for other ongoing efforts to develop these models.
Products:	Computerized models that can be used to predict the structural performance (e.g., faulting) of a concrete pavement as a function of mix properties; model documentation.
Implementation:	This work will result in models that predict long-term pavement performance based on mix properties. The models will be usable at the mix design stage as well as during construction to rapidly assess the mixes being placed. This work assumes that the research done in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement) has been completed. The estimated cost for this research is above and beyond that in track 2.

Problem Statement MD 3.5. Functional PCC Pavement Models Adaptation

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 4–9
Estimated Cost:	$250 k–$500 k

Functional PCC pavement performance ensures user satisfaction and pavement durability. Smoother pavements, for example, are not only more desirable to the user, but also reduce dynamic loading on the pavement, increasing pavement life. However, smoothness is not the only functional performance aspect. Tire-pavement noise and skid resistance are also key functional performance factors. The concrete mixture impacts these functional performance factors. Mixes that are difficult to place, for example, can result in rough pavements. Models are needed to predict functional performance during the mix design process. Predicting functional performance will allow contractors or owner-agencies to adjust the mix design so that the finished pavement will meet the functional requirements. The new models will also allow contractors to adjust the mix design as materials or construction conditions change during pavement placement.

Tasks:

1. Identify existing models suitable for predicting the functional properties of a concrete pavement as a function of the concrete mixture. The models selected should be used in concert with ongoing work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement).
2. Determine the suitability of the existing models to paving mixtures and conduct research to make adjustments necessary
3. Develop beta versions of the models through a stand-alone interface and evaluate the predictions against lab and field data.
4. Develop the final models in a form suitable for rapid incorporation into the mix design system.

Benefits:	Functional models predicting the linkage between concrete pavement function (e.g., smoothness, safety, noise) and mix properties in the mix design system; supplements for other ongoing efforts to develop these models.
Products:	Computerized models that can be used to predict the functional performance (e.g., smoothness) of a concrete pavement as a function of mix properties; model documentation.
Implementation:	This work will result in models to predict pavement functional performance based on mix design properties and materials. The models can be used during both the mix design process and construction. This work assumes that the research done in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement) has been completed. The estimated cost for this research is above and beyond that in track 2.

Problem Statement MD 3.6. Characterizing Concrete Materials Variability

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 2–7
Estimated Cost:	$250 k–$500 k

This research will document the sources of and solutions to concrete pavement variability. A better understanding of variability in current PCC pavement construction is needed, including stockpiles, batching, transport, placement, finishing, and curing. Following a synthesis of work done in this area, the researcher should advance strategies to minimize variability through improved equipment, measuring devices, and operator influences. The impact of reducing variability should be assessed for: (1) contractor profitability, (2) specification tolerances, and (3) design safety factors. By reducing variability, modern pavement design procedures can be used, resulting in more cost effective designs that also improve overall pavement performance. The overall influence of variability on design safety and product acceptance must be better understood, especially product acceptance as it relates to the size of the product sample.

Tasks:

1. Identify information sources for assessing the variability of concrete mixtures and other elements of the concrete paving process. This work should be done in concert with ongoing work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement).
2. Synthesize variability information and collect additional information as needed.
3. Identify inputs for the mix design system that variability information would affect, considering the most appropriate means to consider risk and reliability in the mix design procedure.

Benefits:	Understanding variability well enough to quantify it objectively, thus remaining cost effective in design.
Products:	Thorough documentation of each of the sources and degrees of variability in the concrete-making process.
Implementation:	This research will result in a better understanding of the sources of variability in the concrete paving process. This information, in turn, can be used in the mix design system to develop more reliable and cost effective designs. This work assumes that the research done in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavement) has been completed. The estimated cost for this research is above and beyond that in track 2.

Problem Statement MD 3.7. PCC Mix Model Calibration

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 4–8
Estimated Cost:	$1 M–$2 M

Developing the sophisticated PCC mix design system proposed in this research track will require numerous models and components that are based on varying degrees of calibrated relationships. Integrating these components into a larger system, however, introduces the need for an overall calibration. This calibration is required if users are to have confidence in the mix design system's predictions. This research will organize a calibration effort that will evaluate a wide range of materials, site conditions, climates, construction techniques, pavement characteristics, and other variables. The result will be recommendations for adjustments to the mix design procedure that will increase the reliability of the predictions.

Tasks:

1. Identify variables for calibration, such as materials, site conditions, and climates.
2. Identify typical ranges for each variable.
3. Perform laboratory calibrations for the different variables that can be tested in the lab.
4. Perform onsite calibration tests where needed.
5. Calibrate models for deployment.

Benefits:	Proper calibration of the numerous models developed and assembled as part of this research track before widespread distribution of the system.
Products:	A calibration report of the various models used to predict concrete mix behavior and concrete pavement performance; adjustments to the various models as needed.
Implementation:	This work will result in calibrated models for the mix design system, considering a wide range of materials, site conditions, climates, construction techniques, and pavement characteristics.

Problem Statement MD 3.8. PCC Mix Model Validation

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 3. PCC Mix Design Modeling
Approximate Phasing:	Years 5–10
Estimated Cost:	$500 k–$1 M

Although the PCC mix design system models will be calibrated for a wide range of materials, site conditions, climates, construction techniques, and pavement characteristics, validation using actual paving projects is required for the system to gain wide acceptance. This research will organize and conduct independent validation studies of the mix design system on actual paving projects. The projects will be selected to ensure that a wide variety of materials and conditions exists between projects.

Tasks:

1. Identify possible candidate paving projects for model validation under varied conditions.
2. Implement the mix design system during the paving project mix design process.
3. Track problems or issues in the mix design system during paving operations.
4. Based on the validation projects, make necessary modifications to the mix design system.

Benefits:	A validation effort conducted before releasing the mix design system that assesses the predictive ability of the system in situations independent of the development and calibration activities.
Products:	A validation report of the various models used to predict concrete mix behavior and concrete pavement performance; adjustments to the various models as needed.
Implementation:	This work will result in a validated mix design system that is ready for incorporation into owner-agency pavement mix design practices.

SUBTRACK MD 4. PCC MIX DESIGN EVALUATION AND IMPLEMENTATION

This subtrack addresses field evaluation and implementation procedures, provides a mechanism for user feedback, and prepares the products from this research track to be adopted. The following problem statements outline mix design system conferences and workshops, mobile laboratory demonstrations, Web-based training, and other technology transfer activities. Table 5 provides an overview of this subtrack.

Table 5. Subtrack MD 4 overview.

Problem Statement	Estimated Costs	Products	Benefits
MD 4.0. Framework for PCC Mix Design Evaluation and Implementation (Subtrack MD 4)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
MD 4.1. PCC Pavement Mix Design System Conferences and Workshops	$2 M–$5 M	A series of conferences and workshops that include presenting the proper use of the new mix design system along with a background of the development.	Workshops and conferences that provide vital components of the technology transfer for the performance-based mix design system; activities that offer users hands-on experience with the mix design system at various stages; valuable feedback for developing the system.
MD 4.2. Support for FHWA Mobile Concrete Laboratory Demonstrations	$1 M–$2 M	A series of conferences and workshops that present the proper use of the new mix design system along with a background of the development; further demonstration of the Mobile Concrete Research Laboratory nationwide.	A mobile concrete laboratory that allows potential users a firsthand look at available technology; an instrumental component in technology transfer; demonstrations of the performance-based mix design system along with the requisite laboratory tests.
MD 4.3. Standardized Databases and Electronic Communications Protocols for the Concrete Pavement Industry	$250 k–$500 k	Industry standards for nomenclature and for measuring and reporting information and data used by the concrete paving industry.	Industry standards that allow data to be assembled in a common format, resulting in a more efficient development effort; standardized system for the multifaceted concrete pavement industry to use in pooling materials, equipment, and other disciplines.
MD 4.4. Web-Based Training System for Implementation of PCC Research Products	$500 k–$1 M	A Web-based training system capable of effectively training potential users of the numerous products developed under the performance-based mix design track.	Mix design system training from remote locations; a feasible and cost effective training medium for an age in which broadband Internet access is becoming standard.
MD 4.5. PCC Mix Design Equipment for States	$1 M–$2 M	Funding for purchasing the equipment recommended for use in the performance-based mix design system.	Funding made available to allow State agencies to use the new equipment recommended as part of the mix design system.

Problem Statement MD 4.0. Framework for PCC Mix Design Evaluation and Implementation (Subtrack MD 4)

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 4. PCC Mix Design Evaluation and Implementation
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack MD 4 (PCC Mix Design Evaluation and Implementation) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack MD 4 (PCC Mix Design Evaluation and Implementation), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack MD 4 (PCC Mix Design Evaluation and Implementation).

Problem Statement MD 4.1. PCC Pavement Mix Design System Conferences and Workshops

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 4. PCC Mix Design Evaluation and Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	$2 M–$5 M

Transportation agencies are often slow to adopt new technologies and techniques because they are unfamiliar with these innovations and lack resources for research. Workshops and conferences will provide an ideal environment for familiarizing and training agencies in the PCC pavement mix design system. These technology transfer activities will allow both contractors and owner-agencies to better understand the aspects of the mix design system and the benefits this system will provide for pavement construction and performance.

Tasks:

1. Identify States and/or industry representatives willing to host mix design system workshops and conferences.
2. Assemble pertinent information on the mix design system components.
3. Conduct workshops and conferences, presenting mix design system information and providing hands-on training for the mix design software.

Benefits:	Workshops and conferences that provide vital components of the technology transfer for the performance-based mix design system; activities that offer users hands-on experience with the mix design system at various stages; valuable feedback for developing the system.
Products:	A series of conferences and workshops that include presenting the proper use of the new mix design system along with a background of the development.
Implementation:	This research will result in numerous workshops and conferences on the PCC pavement mix design system at various venues throughout the United States.

Problem Statement MD 4.2. Support for FHWA Mobile Concrete Laboratory Demonstrations

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 4. PCC Mix Design Evaluation and Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	$1 M–$2 M

The FHWA Mobile Concrete Laboratory brings the lab to the jobsite to introduce contractors and owner-agencies to concrete mix design and testing technology. With the development of a new mix design system and new testing equipment and procedures, onsite demonstrations using the Mobile Concrete Laboratory are necessary for introducing this new technology to contractors and owner-agencies. For this purpose, this research will provide funding to send the Mobile Concrete Research Laboratory to various projects throughout the United States.

Tasks:

1. Identify potential projects and contractors and owner-agencies interested in Mobile Concrete Laboratory demonstrations.
2. Demonstrate the mix design system and new concrete testing equipment at these project locations.

Benefits:	A mobile concrete laboratory that allows potential users a firsthand look at available technology; an instrumental component in technology transfer; demonstrations of the performance-based mix design system along with the requisite laboratory tests.
Products:	A series of conferences and workshops that presents the proper use of the new mix design system along with a background of the development; further demonstration of the Mobile Concrete Laboratory nationwide.
Implementation:	This research will provide continued funding for sending the Mobile Concrete Laboratory to PCC paving projects throughout the country.

Problem Statement MD 4.3. Standardized Databases and Electronic Communications Protocols for the Concrete Pavement Industry

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 4. PCC Mix Design Evaluation and Implementation
Approximate Phasing:	Years 2–10
Estimated Cost:	\$250 k–\$500 k

Successfully implementing all research products and practices depends on effective communication. Ineffective communication often delays concrete products bound for the market, delays and duplicates paperwork between suppliers and vendors, reduces management efficiency, loses the value added when concrete-related computerized guidelines work together, and decreases data accuracy due to transaction/conversion between incompatible systems or formats, among other problems.

As computing and Internet technologies advance, electronic communication forms become ubiquitous and convenient modes of effective communication. Extensible Markup Language (XML), originally designed to satisfy the demands of large-scale electronic publishing, has become an open standard for exchanging a wide variety of Web data. XML facilitates data generation and reading and ensures that the data structure is unambiguous. The benefits of using a common XML schema in the concrete pavement industries include distributing information (e.g., concrete mixture design specifications, concrete research findings, pavement design/construction information) through the Web or any electronic publishing and syndication service; processing commerce transactions electronically (concrete batch tickets, concrete lab test results); providing transparent management control in a multivendor environment (various contractors, concrete testing labs); formulating queries to obtain desired information (e.g., mix design alternatives, pros and cons of specific practices) from knowledge-based systems; and providing interoperability among various computerized concrete design guidelines/analyses. Both the PCA/NRMCA and ACI committee 235 have initiated XML schema for the concrete industries. However, a lack of funding and resources limited progress. NCHRP Project 20–64, "XML Schemas for Exchange of Transportation Data (TransXML)," is currently being conducted.

This work will result in a ConcreteXML schema based on the World Wide Web Consortium XML schema design principles and requirements. This ConcreteXML schema, with its own namespace, then can be merged into the TransXML under the overall XML schema framework by the consortium. In developing this working schema, an important task will include standardizing terms and XML vocabularies in all concrete pavement-related industries (e.g., State pavement management, State specifications, cement producers, admixture producers, aggregate suppliers, concrete testing labs, mix design firms, concrete batch plants, material delivery, paving companies, financial/inventory). Thus, any XML documents based in ConcreteXML can be validated easily and automated for quick and error-proof electronic data exchange.

Tasks:

1. Identify systems for standardizing databases and electronic communications, such as XML.
2. Standardize terms and XML vocabularies in all concrete paving-related industries.
3. Implement a standard ConcreteXML or comparable system for all databases and electronic communications.

Benefits:	Industry standards that allow data to be assembled in a common format, resulting in a more efficient development effort; standardized system for the multifaceted concrete pavement industry to use in pooling materials, equipment, and other disciplines.
Products:	Industry standards for nomenclature and for measuring and reporting information and data used by the concrete paving industry.
Implementation:	This work will result in a standardized protocol for databases and electronic communications for the concrete pavement industries.

Problem Statement MD 4.4. Web-Based Training System for Implementation of PCC Research Products

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 4. PCC Mix Design Evaluation and Implementation
Approximate Phasing:	Years 6–10
Estimated Cost:	$500 k–$1 M

Research project results often are implemented inadequately and thus are used incompletely. A mechanism for adequate research product technology transfer is therefore necessary. A Web-based service that contains information about research products from different research organizations should be developed. This Web-based service should include actual case studies, online software applications, documentation, and other resources to make research findings more accessible to the paving community.

Tasks:

1. Compile information about new testing equipment and procedures and mix design software, including thorough documentation, case studies, downloadable software applications, photos, and video, if necessary.
2. Develop Web-based training modules for the software and testing equipment.
3. Create and maintain a Web site for accessing the training modules, providing updates for new products or refinements to existing products.

Benefits:	Mix design system training from remote locations; a feasible and cost effective training medium for an age in which broadband Internet access is becoming standard.
Products:	A Web-based training system capable of effectively training potential users of the numerous products developed under the performance-based mix design track.
Implementation:	This research will result in Web-based training modules for new mix design software and testing equipment.

Problem Statement MD 4.5. PCC Mix Design Equipment for States

Track:	1. Performance-Based Concrete Pavement Mix Design System (MD)
Subtrack:	MD 4. PCC Mix Design Evaluation and Implementation
Approximate Phasing:	Years 6–10
Estimated Cost:	$1 M–$2 M

Most States lack the funding necessary to purchase their own new and advanced equipment. Moreover, many contractors are reluctant to invest large amounts of capital in new equipment unless they are sure it will be profitable. Therefore, a vehicle that helps States purchase needed equipment should be established to promote such equipment for mix design testing.

Task:	Establish requirements for helping States purchase advanced equipment to test mix designs.
Benefits:	Funding made available to allow State agencies to use the new equipment recommended as part of the mix design system.
Products:	Funding for purchasing the equipment recommended for use in the performance-based mix design system.
Implementation:	This work will result in a vehicle that helps States purchase advanced equipment for PCC pavement mix design testing.

Track 2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)

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TRACK 2 (DG) OVERVIEW

Under this track, the concrete pavement research community will attempt to develop a mechanistic approach to pavement restoration and preservation strategies. This track builds off of the excellent comprehensive work done under NCHRP 1–37A (development of the *Mechanistic-Empirical Pavement Design Guide*).[(1)] The problem statements below will continuously improve the models, designs, rehabilitation efforts, and all aspects of the work done under NCHRP 1–37A. This track relies on a detailed understanding the *Mechanistic-Empirical Pavement Design Guide*, committing researchers to the power of modeling and predictions.[(1)] However, the CP Road Map also identifies the need for simplified mix design procedures for cities and counties, as well as a design catalog approach. Because many materials properties are important to design success, it is critical that the research conducted under this track be coordinated closely with the work in track 1 (Performance-Based Concrete Pavement Mix Design System).

Empirical approaches to concrete pavement design are effective when the conditions remain basically the same, the focus is on structural design, and the attention is not on understanding and managing distress or failure modes. The pavement design practice of today is primarily empirical, though the state of the practice is moving toward mechanistic approaches. The primary source of much of today's pavement design is still the American Association of State Highway Officials' (AASHO) road test of the 1950s. This one subgrade, one base, one climate, limited traffic design guide was constructed using better-than-normal construction practices. Data analysis techniques were also fairly basic and the incorporation of reliability was insufficiently understood. Moreover, the AASHO road test did not incorporate many of the concepts and products used in concrete pavement practice today, including concrete overlays, permeable bases, different cements, dowel bar retrofits (DBR), and other necessary repairs.

The state of the practice today is moving rapidly toward M-E approaches, particularly with the release of the *Mechanistic-Empirical Pavement Design Guide* and the expressed interest of many States.[(1)] These M-E approaches will allow the designer to account for new design features and characteristics, many materials properties, changing traffic characteristics, and differing construction procedures (such as curing and day/night construction). The designer now can consider additional design features and focus more on pavement performance, including limiting key distress types.

In continuing this work, this track not only looks to the next generation of modeling improvements, but seriously considers integrating design with materials, construction, presentation, and surface characteristics. This track also explores the development of new high-speed computer analysis tools for optimizing pavement design that can address changes to multiple inputs and thus offer better data on potential life cycle costs and reliability.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

Mechanistic-based concrete pavement designs will be reliable, economical, constructible, and maintainable throughout their design life and meet or exceed the multiple needs of the traveling public, taxpayers, and the owning highway agencies. The advanced technology developed under this track will increase concrete pavement reliability and durability (with fewer early failures and lane closures) and help develop cost effective pavement design and rehabilitation.

Track Objectives

1. Develop viable (e.g., reliable, economical, constructible, and maintainable) concrete pavement options for all classes of streets, low-volume roads, highways, and special applications.
2. Improve concrete pavement design reliability, enhance design features, reduce life cycle costs, and reduce lane closures over the design life by maximizing the use of fundamental engineering principles through mechanistic relationships.
3. Integrate pavement designs with materials, construction, traffic loading, climate, preservation treatments, rehabilitation, and performance requirements to produce reliable, economical, and functional (noise, spray, aesthetics, friction, texture, illumination) designs.
4. Integrate traditional structural pavement design with materials, construction, traffic loading, climate, preservation treatments, rehabilitation, and performance inputs that will produce reliable, economical, and functional (noise, spray, aesthetics, friction, texture, illumination) designs.
5. Design preservation and rehabilitation treatments and strategies using mechanistic-based procedures that use in place materials from the pavement structure to minimize life cycle costs and construction and maintenance lane closures.
6. Develop and evaluate new and innovative concrete pavement designs for specific needs (e.g., high traffic, residential traffic, parkways).

Research Gaps

- Insufficient understanding of factors that improve design reliability.
- Pavement designs that lack design reliability for all occasions.
- Insufficient information to design low-volume local jurisdictions effectively.
- Lack of design integration with materials, construction, and rehabilitation factors.
- Lack of methods for conducting multiple high-speed design analyses and sensitivity studies.
- Lack of fundamental relationships for preservation and rehabilitation designs.
- Insufficient understanding of pavement foundations and the proper selection of base, subbase, and subdrainage elements.
- Lack of new and innovative concrete pavement designs.
- Insufficient understanding of the issues surrounding multiple traffic lane design.

Research Challenges

- Consider all significant variabilities and uncertainties properly, develop M-E pavement design reliability methodology that considers all sources of variability directly, and produce concrete pavement designs that meet the desired reliability level (not over or under designed).
- Design pavements reliably and with innovations for unconventional concrete pavement needs, such as concrete overlays, low-volume solutions, very heavy traffic, stage construction with low initial costs, and tunnels.
- Obtain design, materials, traffic, and performance data for low-volume roads to help calibrate and validate the design procedure.
- Understand fundamental material properties using appropriate test procedures, develop improved pavement response and distress models, and understand and model complicated relationships between structural design, mix designs, and construction factors.
- Determine the impact of the design changes proposed in the *Mechanistic-Empirical Pavement Design Guide* developed under NCHRP 1–37A, develop high-speed computer analyses to better implement an incremental damage approach, and encourage users to continue developing mechanistic concepts.[1]

- Reduce reliance on empirical relationships, more fully consider the existing subgrade and pavement design and condition and the options for dealing with it in structural rehabilitation design, and model the impact of preservation treatments and rehabilitation treatments.
- Understand and more fully capture the 20 years of experience with permeable bases and drains, better understand erodibility and bonding, identify the times when subdrainage and layer permeability are needed and when outlets for the permeable layer (e.g., daylighting) must be improved, and improve environmental stewardship by using recycled materials in the foundation.
- Establish a clear rationale for new and innovative design sections; overcome the incremental improvement mentality for wholesale rethinking; and build, test, and evaluate innovative sections.
- Determine the number of lanes and shoulders that can be tied together for given projects and determine tie bar design for specific project conditions.

Research Track 2 (DG) Phasing

The horizontal bar chart in figure 2 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

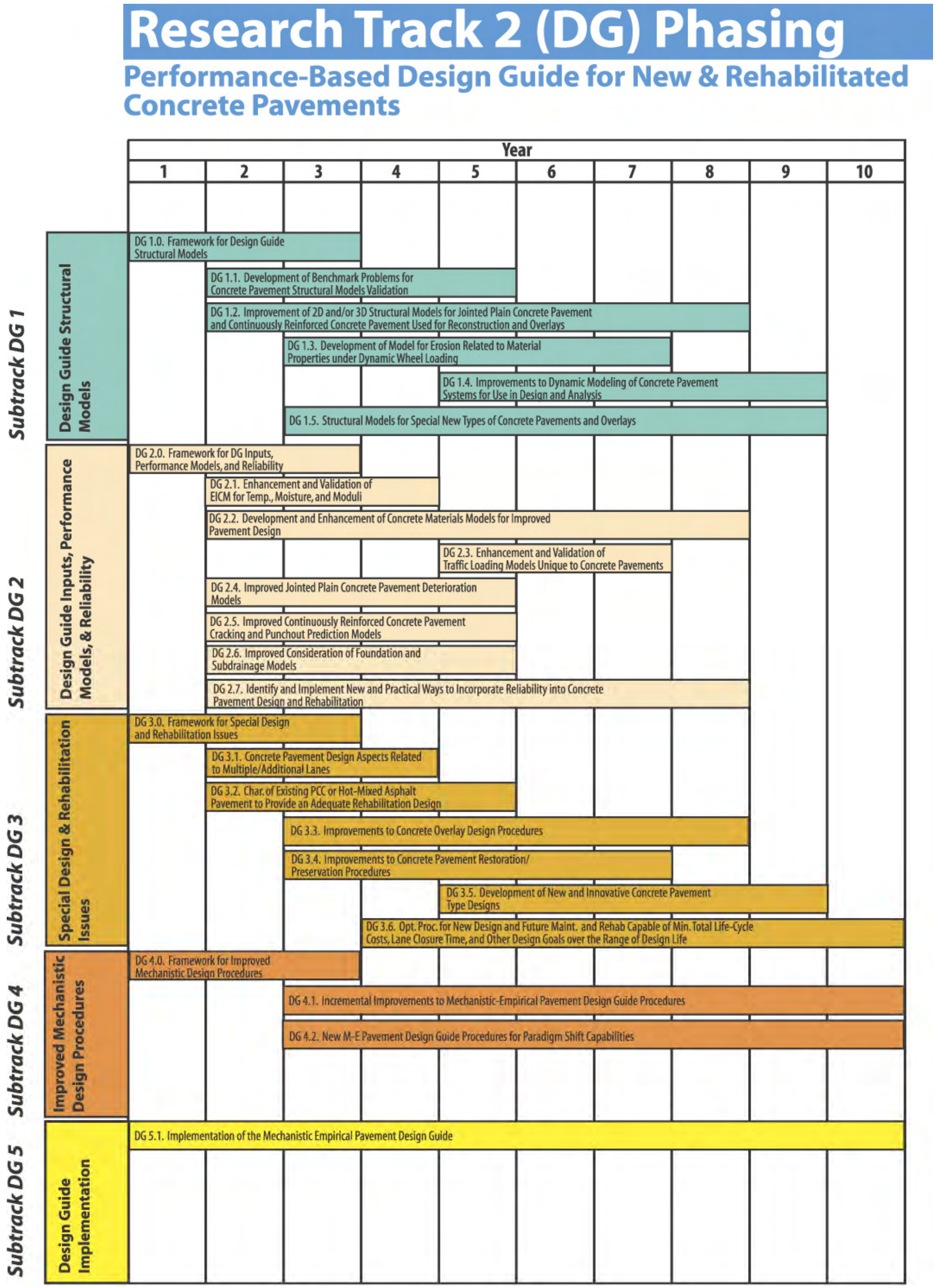

Figure 2. Track 2 (DG) subtrack and problem statement phasing chart.

Research Track 2 (DG) Estimated Costs

Table 6 shows the estimated costs for this research track.

Table 6. Research track 2 (DG) estimated costs.

Problem Statement	Estimated Cost
Subtrack DG 1. Design Guide Structural Models	
DG 1.0. Framework for Design Guide Structural Models (Subtrack DG 1)	$250 k
DG 1.1. Development of Benchmark Problems for Concrete Pavement Structural Models Validation	$500 k–$700 k
DG 1.2. Improvement of Two-Dimensional (2D) and/or Three-Dimensional (3D) Structural Models for Jointed Plain Concrete Pavement and Continuously Reinforced Concrete Pavement Used for Reconstruction and Overlays	$5 M–$6 M
DG 1.3. Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading	$800 k–$1.2 M
DG 1.4. Improvements to Dynamic Modeling of Concrete Pavement Systems for Use in Design and Analysis	$800 k–$1.2 M
DG 1.5. Structural Models for Special New Types of Concrete Pavements and Overlays	$1 M–$2 M
Subtrack DG 2. Design Guide Inputs, Performance Models, and Reliability	
DG 2.0. Framework for Design Guide Inputs, Performance Models, and Reliability (Subtrack DG 2)	$300 k
DG 2.1. Enhancement and Validation of Enhanced Integrated Climatic Models for Temperature, Moisture, and Moduli	$1 M–$2 M
DG 2.2. Development and Enhancement of Concrete Materials Models for Improved Pavement Design	$5 M–$6 M
DG 2.3. Enhancement and Validation of Traffic Loading Models Unique to Concrete Pavements	$600 k–$1 M
DG 2.4. Improved Jointed Plain Concrete Pavement Deterioration Models	$1.5 M–$2.5 M
DG 2.5. Improved Continuously Reinforced Concrete Pavement Cracking and Punchout Prediction Models	$1.5 M–$2.5 M
DG 2.6. Improved Consideration of Foundation and Subdrainage Models	$1 M–$1.5 M
DG 2.7. Identify and Implement New and Practical Ways to Incorporate Reliability into Concrete Pavement Design and Rehabilitation	$3 M–$5 M
Subtrack DG 3. Special Design and Rehabilitation Issues	
DG 3.0. Framework for Special Design and Rehabilitation Issues (Subtrack DG 3)	$150 k
DG 3.1. Concrete Pavement Design Aspects Related to Multiple/Additional Lanes	$800 k–$1.5 M
DG 3.2. Characterization of Existing PCC or Hot-Mix Asphalt (HMA) Pavement to Provide an Adequate Rehabilitation Design	$3.5 M–$4.5 M
DG 3.3. Improvements to Concrete Overlay Design Procedures	$4 M–$4.5 M
DG 3.4. Improvements to Concrete Pavement Restoration (CPR)/Preservation Procedures	$2 M–$3 M
DG 3.5. Development of New and Innovative Concrete Pavement Type Designs	$1 M–$2 M
DG 3.6. Optimizing Procedure for New Design and Future Maintenance and Rehabilitation Capable of Minimizing Total Life Cycle Costs, Lane Closure Time, and Other Design Goals over the Range of Design Life	$1 M–$2 M
Subtrack DG 4. Improved Mechanistic Design Procedures	
DG 4.0. Framework for Improved Mechanistic Design Procedures (Subtrack DG 4)	$300 k
DG 4.1. Incremental Improvements to *Mechanistic-Empirical Pavement Design Guide* Procedures	$1.5 M–$2.5 M
DG 4.2. New *Mechanistic-Empirical Pavement Design Guide* Procedures for Paradigm Shift Capabilities	$2 M–$4 M
Subtrack DG 5. Design Guide Implementation	
DG 5.1. Implementation of the *Mechanistic-Empirical Pavement Design Guide*	$2 M–$3 M
Track 2 (DG)	
Total	$40.5 M–$59.6 M

Track Organization: Subtracks and Problem Statements

Track 2 (DG) problem statements are grouped into five subtracks:

- Subtrack DG 1. Design Guide Structural Models.
- Subtrack DG 2. Design Guide Inputs, Performance Models, and Reliability.
- Subtrack DG 3. Special Design and Rehabilitation Issues.
- Subtrack DG 4. Improved Mechanistic Design Procedures.
- Subtrack DG 5. Design Guide Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK DG 1. DESIGN GUIDE STRUCTURAL MODELS

This subtrack identifies and frames the next generation of structural models for conventional pavements as well as the models needed for new and innovative structures. This subtrack is tied closely to the output from the *Mechanistic-Empirical Pavement Design Guide*.[1] Table 7 provides an overview of this subtrack.

Table 7. Subtrack DG 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
DG 1.0 Framework for Design Guide Structural Models (Subtrack DG 1)	$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
DG 1.1 Development of Benchmark Problems for Concrete Pavement Structural Models Validation	$500 k–$700 k	Data that validates current and future structural models for concrete pavements; accurate structural models that improve the performance prediction of concrete pavements.	Accurate structural models that improve the performance prediction of concrete pavements.
DG 1.2 Improvement of 2D and/or 3D Structural Models for Jointed Plain Concrete Pavement and Continuously Reinforced Concrete Pavement Used for Reconstruction and Overlays	$5 M–$6 M	Improved 2D and later 3D finite-element model (FEM) that provides significantly improved computation of stresses and deflections for jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) used in reconstruction and as overlays; pavement performance prediction models that more accurately predict pavement distress and life for incorporation into a new version of the pavement design guide.	Improved characterization of design features, interlayer relationships, and material properties; FEMs incorporated into new versions of the pavement design guide.
DG 1.3. Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading	$800 k–$1.2 M	A comprehensive base/subgrade erosion test and model capable of predicting vertical as well as horizontal displacement of fine particles as a function of traffic loading and climatic conditions; a more efficiently designed base and subbase course for specific site conditions.	More reliable and cost effective base and subbase course support for specific site conditions.
DG 1.4. Improvements to Dynamic Modeling of Concrete Pavement Systems for Use in Design and Analysis	$800 k–$1.2 M	A structural model that considers dynamic loading of concrete pavements.	A structural model that considers dynamic loading of concrete pavements that will model traffic loadings more realistically and that can be incorporated into the pavement design guide's advanced version.
DG 1.5 Structural Models for Special New Types of Concrete Pavements and Overlays	$1 M–$2 M	FEM models that accurately predict structural responses for the slab and supporting layers in selected structural systems.	The ability to consider new and innovative concrete pavement structures for more cost effective conventional or special design applications.

Problem Statement DG 1.0. Framework for Design Guide Structural Models (Subtrack DG 1)

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 1. Design Guide Structural Models
Approximate Phasing:	Years 1–3
Estimated Cost:	$250 k

Subtrack DG 1 (Design Guide Structural Models) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack DG 1 (Design Guide Structural Models), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack DG 1 (Design Guide Structural Models).

Problem Statement DG 1.1. Development of Benchmark Problems for Concrete Pavement Structural Models Validation

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 1. Design Guide Structural Models
Approximate Phasing:	Years 2–5
Estimated Cost:	$500 k–$700 k

The *Mechanistic-Empirical Pavement Design Guide* uses a mechanistic model to calculate critical stresses and deflections from traffic and climate factors in JPCP and CRCP. These stresses and deflections are used to predict key distress. The *Mechanistic-Empirical Pavement Design Guide* development contract (NCHRP 37–A) could not fully validate these critical stresses and deflections, and concern exists that these stresses and deflections may not be computed accurately by the underlying FEM.(1)

Research performed at various locations over the years has compared measured and predicted strains and deflections (e.g., AASHO road test, Minnesota Road Research Project (MnROAD)). Some of the structural models used include Westergaard, ILLISLAB, JSLAB, and ISLAB2000. Discrepancies between the calculated and measured strains and deflections have always been evident but need additional research attention. Loading speed should be considered fully.

Tasks:

1. Identify and document available benchmark solutions of measured stresses (strains) and deflections in the slab and other layers to evaluate the current structural models (including the ISLAB2000 used in the *Mechanistic-Empirical Pavement Design Guide*) and determine how closely they predict measured values.(1)
2. Conduct full-scale experiments and measure structural responses for unavailable but key design situations. Consider future improved structural models (e.g., 3D FEM) in planning and conducting these benchmark solutions.

Benefits:	Accurate structural models that improve the performance prediction of concrete pavements.
Products:	Data that validates current and future structural models for concrete pavements; accurate structural models that improve the performance prediction of concrete pavements.
Implementation:	This research will help establish the accuracy of structural response models. Structural responses are used to calculate the design procedure.

Problem Statement DG 1.2. Improvement of 2D and/or 3D Structural Models for Jointed Plain Concrete Pavement and Continuously Reinforced Concrete Pavement Used for Reconstruction and Overlays

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 1. Design Guide Structural Models
Approximate Phasing:	Years 2–8
Estimated Cost:	$5 M–$6 M

The *Mechanistic-Empirical Pavement Design Guide* uses the ISLAB2000 FEM to structurally model JPCP and CRCP that are built new and used as overlays.[1] The FEM calculates critical stresses and deflections from traffic and climate factors and then uses them to predict damage and distress. While this is a good state-of-the-art FEM for design use, models must be developed that will more accurately calculate stresses in all types of concrete pavements and rehabilitation situations.

Tasks:

1. Include capability to consider both loading and thermal gradients in a layered system with discontinuities (joints and cracks).
2. Model all types of concrete pavements and overlays over all types of existing pavement conditions (multiple layers and discontinuities).
3. Model the effect of all types of bases/subbases and widths on structural responses at joints and other locations.
4. Model the effect of horizontal restraint (friction) on joint and crack openings and structural responses.
5. Model the effect of separation layers on structural responses.
6. Improve modeling of subgrade support for new and rehabilitation designs.
7. Test and validate the FEMs using the benchmark problems developed under this design track.

Benefits:	Far better characterization of design features, interlayer relationships, and material properties; FEMs incorporated into new versions of the pavement design guide.
Products:	Improved 2D and later 3D FEM that provides significantly improved computation of stresses and deflections for JPCP and CRCP used in reconstruction and as overlays; pavement performance prediction models that more accurately predict pavement distress and life for incorporation into a new version of the pavement design guide.
Implementation:	The FEM will be incorporated into design procedure as soon as completed. It also will be used for parameter and sensitivity studies.

Problem Statement DG 1.3. Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 1. Design Guide Structural Models
Approximate Phasing:	Years 3–7
Estimated Cost:	$800 k–$1.2 M

When excess moisture exists in a pavement with an erodible base or underlying fine-grained subgrade material, repeated vehicle loadings typically force the mixture of water and fine material (fines) from beneath the leave slab corner and eject it to the surface through the transverse joint or along the shoulder. This process, commonly referred to as pumping, eventually results in a void below the leave slab corner. In addition, some of the fines that are not ejected are deposited under the approach slab corner, causing the approach slab to rise. Combined, this buildup of material beneath the approach corner and the loss of support under the leave corner can cause significant joint faulting, especially for JPCP without dowels. Significant joint faulting increases the life cycle cost of the pavement through early rehabilitation and vehicle operating costs. Voids also can develop along the edge of a CRCP.

The *Mechanistic-Empirical Pavement Design Guide* level one classification of material erodibility is based on the material type and test results from an appropriate laboratory test that realistically simulates erosion beneath a PCC slab.(1) However, suitable tests that would accurately assess erosion under various concrete pavement types are currently unavailable. Levels two and three rely on strength tests or otherwise inadequate descriptions of base materials. The M-E models relate erosion potential with PCC corner slab deflections. This mechanistic parameter, however, only indirectly indicates erosion potential, because it does not reflect horizontal movements of the fine particles in the base/subgrade. Moreover, the available erodibility classification methods cannot account mechanistically for the erodibility of the base and subgrade as a function of traffic loading and climatic conditions.

Tasks:

1. Evaluate all available erosion tests and their applicability to mechanistic-based concrete pavement design. Adopt, modify, or develop an erosion test that can consider all types of base and subbase materials used for concrete pavements. Validate the test using partial or full-scale testing in the lab and field.
2. Develop an erosion model that considers the mechanics of erosion beneath JPCP, CRCP, and other types of concrete pavements for use in an incremental mechanistic concrete pavement design procedure.
3. Provide detailed guidelines and recommendations for using the test to design in the mechanistic-based design procedure.

Benefits:	More reliable and cost effective base and subbase course support for specific site conditions.
Products:	A comprehensive base/subgrade erosion test and model capable of predicting vertical as well as horizontal displacement of fine particles as a function of traffic loading and climatic conditions; a more efficiently designed base and subbase course for specific site conditions.
Implementation:	This problem statement will generate an important, currently missing part of the concrete pavement design guide. The model resulting from this research will be able to be incorporated into the design procedure immediately.

Problem Statement DG 1.4. Improvements to Dynamic Modeling of Concrete Pavement Systems for Use in Design and Analysis

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 1. Design Guide Structural Models
Approximate Phasing:	Years 5–9
Estimated Cost:	$800 k–$1.2 M

Traffic loadings are almost always moving when they impact the pavement surface. If these loads are moving quickly and the pavement is reasonably smooth, these loads cause deflections that are often less than static. However, as roughness increases, impact loading can develop, which may significantly exceed static loading. Modeling concrete pavement dynamically would provide more realistic loading and speed effects on structural behavior and improve accuracy in predicting key stresses and deflections.

Tasks:

1. Evaluate existing dynamic FEMs and identify those most applicable to concrete pavement structures.
2. Using the best available FEM developed under this track (track 2), incorporate the ability to consider dynamic loadings into the model.
3. Test and validate the dynamic FEM using the developed benchmark problems.

Benefits:	A structural model that considers dynamic loading of concrete pavements that will more realistically model traffic loadings and that can be incorporated into the pavement design guide’s advanced version.
Products:	A structural model that considers dynamic loading of concrete pavements.
Implementation:	Dynamic loading impacts pavements every day. Improved understanding may lead to better performance prediction. Results obtained will be implemented immediately into design procedures.

Problem Statement DG 1.5. Structural Models for Special New Types of Concrete Pavements and Overlays

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 1. Design Guide Structural Models
Approximate Phasing:	Years 3–9
Estimated Cost:	$1 M–$2 M

Continually seeking improved and more cost effective concrete pavement designs is important. New and innovative alternative designs have been constructed, and others will be proposed over time. As an initial step, it is important to have a capable structural model that accurately calculates stress and deformation of these pavement types. This research will expand or modify the latest FEM to model different types of concrete pavements structurally.

Task:	Expand or modify FEMs to model the following concrete pavement types and their layered systems beneath the slabs: 1. Precast jointed concrete pavement (JCP). 2. Structurally reinforced concrete pavement. 3. Concrete overlays. 4. Other new and innovative types identified.
Benefits:	The ability to consider new and innovative concrete pavement structures for more cost effective conventional or special design applications.
Products:	FEM models that accurately predict structural responses for the slab and supporting layers in selected structural systems.
Implementation:	The effects of new and innovative designs cannot be established without structural models. These structural models will be implemented into design procedures as soon as the feasibility of special designs is established.

SUBTRACK DG 2. DESIGN GUIDE INPUTS, PERFORMANCE MODELS, AND RELIABILITY

This subtrack develops specific improvements to environmental models, long-term concrete properties, the next generation of traffic models, distress models, and easy-to-use reliability analysis tools. Table 8 provides an overview of this subtrack. Table 8 provides an overview of this subtrack.

Table 8. Subtrack DG 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
DG 2.0 Framework for Design Guide Inputs, Performance Models, and Reliability (Subtrack DG 2)	$300 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
DG 2.1 Enhancement and Validation of Enhanced Integrated Climatic Models for Temperature, Moisture, and Moduli	$1 M–$2 M	A more capable and accurate enhanced integrated climatic model (EICM) for use with concrete pavements to provide detailed hourly temperature, moisture, subdrainage, and other inputs for the incremental design process.	Full and accurate consideration of climatic factors that provide more cost effective and reliable concrete pavement designs.
DG 2.2 Development and Enhancement of Concrete Materials Models for Improved Pavement Design	$5 M–$6 M	A better understanding of concrete materials models that will be incorporated into current and advanced versions of the pavement design guide, making it more reliable and cost effective.	Better quantification of long-term concrete properties to consider these factors in design more accurately. This research will help determine the impact of various key construction aspects on slab behavior and performance and the concrete fatigue of full-scale slabs under various conditions.
DG 2.3 Enhancement and Validation of Traffic Loading Models Unique to Concrete Pavements	$600 k–$1 M	Improved traffic characterization for use in concrete pavement design.	Far better characterization of traffic loadings for use in concrete pavement design.
DG 2.4 Improved Jointed Plain Concrete Pavement Deterioration Models	$1.5 M–$2.5 M	Improved and more comprehensive distress and smoothness prediction models for JPCP, including JCPC on low-volume roadways.	Reduced prediction uncertainty, resulting in a more cost effective design for a given level of reliability for JPCP; improved validation of JPCP design for low-volume roadways.
DG 2.5 Improved Continuously Reinforced Concrete Pavement Cracking and Punchout Prediction Models	$1.5 M–$2.5 M	Improved and more comprehensive distress and smoothness prediction models for CRCP.	Reduced prediction uncertainty, resulting in a more cost effective design for a given level of reliability for CRCP.
DG 2.6 Improved Consideration of Foundation and Subdrainage Models	$1 M–$1.5 M	An improved and more comprehensive design procedure that considers the base layer, subbase layers, subgrade, and subdrainage of concrete pavements more fully; guidelines that will be implemented into a future version of the pavement design guide.	Improved consideration of the foundation and subdrainage that will be implemented into the pavement design guide to produce more reliable and cost effective designs.
DG 2.7 Identify and Implement New and Practical Ways to Incorporate Reliability into Concrete Pavement Design and Rehabilitation	$3 M–$5 M	Improved and more comprehensive reliability methodology that considers individual input, model, and other variabilities for concrete pavement mechanistic design.	Improved procedures that will reduce first costs and improve credibility of the mechanistic design approach, since design reliability critically affects pavement costs and performance.

Problem Statement DG 2.0. Framework for Design Guide Inputs, Performance Models, and Reliability (Subtrack DG 2)

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 1–3
Estimated Cost:	$300 k

Subtrack DG 2 (Design Guide Inputs, Performance Models, and Reliability) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack DG 2 (Design Guide Inputs, Performance Models, and Reliability), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack DG 2 (Design Guide Inputs, Performance Models, and Reliability).

Problem Statement DG 2.1. Enhancement and Validation of Enhanced Integrated Climatic Models for Temperature, Moisture, and Moduli

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 2–4
Estimated Cost:	$1 M–$2 M

The EICMs in the *Mechanistic-Empirical Pavement Design Guide* are a major step toward considering the many climate factors in concrete pavement design.[1] The EICM receives the following hourly data from weather stations: solar radiation, temperature, precipitation, windspeed, and cloud cover. The software then applies this weather data to the pavement section under consideration to predict pavement temperature and moisture at various points within each pavement layer and in the subgrade. These temperatures and moistures serve many purposes, including calculation of stress and curling using temperature gradients through the slab, estimation of layer modulus using moisture contents in unbound materials, estimation of the dynamic modulus of asphalt-bound materials, estimation of the frost line and modulus below and above the line, and computation of the load transfer efficiency (LTE) using joint and crack openings. While the EICM is an extremely valuable tool, certain aspects must be improved to support more advanced climatic modeling of concrete pavements.

Tasks:

1. Further validation of moisture contents in unbound materials.
2. Further validation of temperature gradients and moisture gradients in concrete slabs.
3. Wider system capability to handle subdrainage in 2D or 3D pavement systems.
4. Further validation of various thermal and hydraulic inputs for various materials.

Benefits:	Full and accurate consideration of climatic factors that provide more cost effective and reliable concrete pavement designs.
Products:	A more capable and accurate EICM for use with concrete pavements to provide detailed hourly temperature, moisture, subdrainage, and other inputs for the incremental design process.
Implementation:	The EICM is the heart of the design procedure, and any improvements will be implemented immediately.

Problem Statement DG 2.2. Development and Enhancement of Concrete Materials Models for Improved Pavement Design

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 2–8
Estimated Cost:	$5 M–$6 M

Concrete materials properties significantly affect concrete pavement performance. Improving the characterization of slab concrete will more reliably predict pavement performance. This research will address many key aspects of improving PCC materials and construction.

Tasks:

1. Consider in the design stage that several concrete material properties vary over time, including strength, modulus, shrinkage, creep, and others. Provide further data on these properties.
2. Determine the effect of construction factors on concrete materials properties in the slab. This minimally would include the following: slab curing, slab zero-stress temperature, built-in curling (thermal gradient through slab as it solidifies), and differential slab shrinkage.
3. Conduct PCC slab repeated load testing. This would include major studies into full-scale slab fatigue characteristics that consider curling, warping, support, strength, modulus, support conditions, and coefficient of thermal expansion. Accelerated loading facility (ALF) testing would be appropriate for these studies. Develop fracture models of concrete fatigue for both top-down and bottom-up slab cracking.
4. Develop new tests for characterizing concrete strength and modulus that better reflect field behavior than current tests.

Benefits:	Better quantification of long-term concrete properties to consider these factors in design more accurately. This research will help determine the impact of various key construction aspects on slab behavior and performance and the concrete fatigue of full-scale slabs under various conditions.
Products:	A better understanding of concrete materials models that will be incorporated into current and advanced versions of the pavement design guide, making it more reliable and cost effective.
Implementation:	The concrete materials models resulting from this research will be immediately incorporated into improved concrete pavement design procedures.

Problem Statement DG 2.3. Enhancement and Validation of Traffic Loading Models Unique to Concrete Pavements

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 5–7
Estimated Cost:	$600 k–$1 M

Traffic loading on concrete pavements varies from very low to extremely heavy. A typical concrete pavement located on a major highway could carry from 50,000 (on a very low-volume road) to more than 200,000,000 (on an urban freeway) heavy trucks over its 30- to 40-year lifetime. Accurately characterizing traffic loadings is critical to good design.

The *Mechanistic-Empirical Pavement Design Guide* significantly improved traffic loading characterization by considering the full axle spectrum for each type of axle (i.e., single, tandem, tridem, and quads).[1] However, improvement is needed.

Tasks:

1. Determine the effect of traffic speed on performance.
2. Determine the critical traffic loadings for fatigue cracking.
3. Determine how to model tandem, tridem, and quad axles and improve modeling of their distribution.
4. Evaluate the type of loading that contributes to top-down slab cracking where axles are spaced about 3 to 6 meters (m) (10 to 20 feet (ft)) apart and load the slab at each transverse joint, causing a negative cantilever effect with high top-of-slab stresses.

Benefits:	Improved characterization of traffic loadings for use in concrete pavement design.
Products:	Improved traffic characterization for use in concrete pavement design.
Implementation:	The traffic loading models resulting from this research will be immediately incorporated into concrete pavement design procedures.

Problem Statement DG 2.4. Improved Jointed Plain Concrete Pavement Deterioration Models

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 2–5
Estimated Cost:	$1.5 M–$2.5 M

Used in all levels of streets and highways from very low to very high traffic volumes, JPCP is by far the most popular type of concrete built in the world. This popularity is due to its relative cost-effectiveness and its reliability. The JPCP design has significantly improved through increased knowledge over the past several decades.

Tasks:

1. Improve the top-down and bottom-up transverse cracking models for new and rehabilitated pavements developed under the *Mechanistic-Empirical Pavement Design Guide*.(1) Include models for JPCP designs located on low-volume rural and urban roadways as well as on higher volume roadways.
2. Predict crack deterioration. When JPCP cracks, some of these cracks do not deteriorate, while others deteriorate significantly. These deteriorating cracks require maintenance and cause roughness. A study will investigate the causes of crack deterioration and develop models to be used in design that predict crack deterioration. The effects of preventive maintenance on crack deterioration rate also will be studied.
3. Study longitudinal cracking (fatigue related). Some longitudinal cracking in JPCP could not be explained by traditional fatigue cracking calculations. A major study will determine the circumstances under which fatigue-based longitudinal cracking could occur. The effect of widened slabs also will be investigated.
4. Improve joint faulting and spalling models for new construction and overlays. The existing models will be considered and improved to model faulting for all design types and model rehabilitation situations needed for design. An improved joint opening/closing model may also be needed. The models should include JPCP designs located on low-volume rural and urban roadways as well as on higher volume roadways.
5. Develop improved smoothness (international roughness index (IRI)) models for JPCP.

Benefits:	Reduced prediction uncertainty, resulting in a more cost effective design for a given level of reliability for JPCP; improved validation of JPCP design for low-volume roadways.
Products:	Greatly improved and more comprehensive distress and smoothness prediction models for JPCP, including JCPC on low-volume roadways.
Implementation:	The JCPC deterioration models resulting from this research will be incorporated immediately into improved concrete pavement design procedures.

Problem Statement DG 2.5. Improved Continuously Reinforced Concrete Pavement Cracking and Punchout Prediction Models

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 2–5
Estimated Cost:	$1.5 M–$2.5 M

Several States and other countries use CRCP, especially for heavily trafficked highways. In Long-Term Pavement Performance (LTPP) program testing, it has proven to be the smoothest of all pavement types for more than 30 years, due to its ability to handle very high traffic loadings over a long period. CRCP design has improved significantly through increased knowledge over the past several decades.

Tasks:

1. Improve the crack spacing, crack width, and crack load deterioration models developed under the *Mechanistic-Empirical Pavement Design Guide*.[1] An improved crack opening/closing model may be needed.
2. Improve the prediction of edge-top-down structural punchouts developed under *Mechanistic-Empirical Pavement Design Guide*.[1]
3. Investigate the occurrence of punchouts from the bottom-up, especially for widened slab CRCP designs.
4. Develop an improved smoothness (IRI) prediction model for CRCP.

Benefits:	Reduced prediction uncertainty, resulting in a more cost effective design for a given level of reliability for CRCP.
Products:	Significantly improved and more comprehensive distress and smoothness prediction models for CRCP.
Implementation:	The CRCP cracking and punchout prediction models resulting from this research will be incorporated immediately into improved concrete pavement design procedures.

Problem Statement DG 2.6. Improved Consideration of Foundation and Subdrainage Models

Track: 2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack: DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing: Years 2–5
Estimated Cost: $1 M–$1.5 M

The base course, subbase courses, and the subgrade are very important to the performance of any type of concrete pavement. Imbedded in the foundation is pavement structure subdrainage, as well as a significant portion of the entire concrete pavement cost. The sublayers affect both the structural aspects (deflection, stress) in the slab and critical load transfer across joints and cracks (e.g., the base layer affects the LTE of the joint or crack). In addition, the friction between the slab and base is extremely important for initiating cracks at the joints and, in CRCP, the transverse shrinkage cracks. Many examples have shown that sublayer and subdrainage failures have led to concrete slab failure. Improvements are needed to produce more reliable and cost effective sublayer designs for concrete pavement.

Tasks:

1. Identify key practical aspects of sublayers, such as materials and construction that relate to concrete pavement subdrainage, performance, and cost. Determine how various subgrade situations (from soft, wet soils to near-surface bedrock) affect performance, and develop improved guidelines for preparing concrete pavement foundations and sublayers.
2. Develop improved inputs for designing the parameters that characterize concrete pavement sublayers. These would include time-dependent moduli (seasonal changes), hydraulic permeability, and other parameters.
3. Develop improved inputs for slab/base friction characteristics of various base layer types.
4. Determine the impact of JPCP and CRCP on sublayers and subgrade performance using the mechanistic-based design procedure. Develop guidelines on selection of base types, subbase types, subdrainage, and subgrade treatments to produce cost effective yet good performance of concrete pavements.
5. Consider the likelihood and impact of distress propagation and interaction due to cracks in the base course.
6. Evaluate subdrainage needs for all concrete pavement levels and develop improved impact projections of subdrainage or lack of subdrainage on performance. Develop new and more reliable and cost effective ways to drain concrete pavements.

Benefits: Improved consideration of the foundation and subdrainage that will be implemented into the pavement design guide to produce more reliable and cost effective designs.

Products: An improved and more comprehensive design procedure that considers the base layer, subbase layers, subgrade, and subdrainage of concrete pavements more fully; guidelines that will be implemented into a future version of the pavement design guide.

Implementation: The foundation and subdrainage models resulting from this research will be incorporated immediately into improved concrete pavement design procedures. See also DG 1.3 (Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading) on erosion.

Problem Statement DG 2.7. Identify and Implement New and Practical Ways to Incorporate Reliability into Concrete Pavement Design and Rehabilitation

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 2. Design Guide Inputs, Performance Models, and Reliability
Approximate Phasing:	Years 2–8
Estimated Cost:	$3 M–$5 M

Reliability is a critical area of design for which very little knowledge exists. Nearly everything associated with pavements (as well as most other structures) is variable or uncertain. This includes factors such as traffic loading estimates, climate prediction estimates, subgrade soils along a project, paving materials variations, construction process variations, and design procedure inadequacies. Designers must consider these uncertainties and variations to produce a design with a chance of success greater than 50–50.

The Texas DOT (TxDOT) first incorporated design reliability into pavement design in the early 1970s, and these procedures were used successfully for more than 2 decades. The 1986 *AASHTO Pavement Design Guide* made use of similar but expanded concepts to incorporate design reliability into the asphalt and PCC pavement design procedures.[2] The new mechanistic-based *Mechanistic-Empirical Pavement Design Guide* incorporated design reliability into the pavement design process differently, using the residual error in the prediction of sections used for calibration.[1]

All of these approaches have significant limitations and inadequacies. Design reliability significantly impacts both performance and pavement structure costs. Some feel that the current AASHTO procedures over design for higher levels of traffic because of the large effect of the multiplier on traffic (e.g., design traffic is 3 to 6 times the mean estimated traffic). Extensive research has been conducted on the design reliability of other structures, such as buildings, retaining walls, foundations, and hydraulic structures. However, very little research has been done on pavement design reliability. Any improvement to the procedure, therefore, would impact cost and PCC pavements performance significantly.

Tasks:

1. Review how design reliability has been incorporated into various structural design procedures. Identify the most promising approaches and concepts for use in concrete pavement mechanistic design.
2. Develop a practical procedure for incorporating design reliability into the *Mechanistic-Empirical Pavement Design Guide*'s mechanistic-based design procedure.[1] This methodology will allow designers to input the means, standard deviations, and distributions of many of the key input variables.
3. Estimate the magnitudes of variability and uncertainty and their distributions that will be used in the reliability-based design procedure. These estimates will be based on collected data.

Benefits:	Improved procedures that will reduce first costs and improve credibility of the mechanistic design approach, since design reliability critically affects pavement costs and performance.
Products:	Significantly improved and comprehensive reliability methodology that considers individual input, model, and other variabilities for concrete pavement mechanistic design.
Implementation:	The results of this research will be incorporated immediately into improved concrete pavement design and rehabilitation procedures for greater reliability.

SUBTRACK DG 3. SPECIAL DESIGN AND REHABILITATION ISSUES

This subtrack addresses the design details from tied shoulders, tie bars, and pavement preservation, and considers better ways to analyze alternative design features using more streamlined computer software. Table 9 provides an overview of this subtrack.

Table 9. Subtrack DG 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
DG 3.0 Framework for Special Design and Rehabilitation Issues (Subtrack DG 3)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
DG 3.1 Concrete Pavement Design Aspects Related to Multiple/Additional Lanes	$800 k–$1.5 M	Specific design methodology, guidelines, and standards for tying together multiple traffic lanes and shoulders.	Fewer unexpected incidents of longitudinal cracking that result from tying too many lanes together or widening longitudinal joints that had been left untied.
DG 3.2 Characterization of Existing PCC or Hot-Mix Asphalt Pavement to Provide an Adequate Rehabilitation Design	$3.5 M–$4.5 M	Improved characterization of existing pavements; improved estimates of remaining life that will be useful for selecting from alternative rehabilitations; identification of solutions for overcoming existing poor design and material situations; improved support for unbonded concrete overlay design.	Proper characterization of the existing pavement critical to reliable and cost effective rehabilitation design; rehabilitation design improvements to the pavement design guide.
DG 3.3 Improvements to Concrete Overlay Design Procedures	$4 M–$4.5 M	Improved guidelines and design procedures for several types of concrete overlays, including concrete overlays of difficult existing pavements, ultrathin slab design that includes improved concrete-to-asphalt bonding procedures, improved layering modeling for unbonded concrete overlays, characterization of underlying PCC slab design and condition for unbonded overlays, and improved bonding between thin PCC overlay and existing PCC slabs.	Concrete overlays of difficult existing pavements; ultrathin slab design, including improved concrete-to-asphalt bonding procedures; improved layering modeling for unbonded concrete overlays; characterization of underlying PCC slab design and condition for unbonded overlays; improved bonding between thin PCC overlay and existing PCC slabs.
DG 3.4 Improvements to Concrete Pavement Restoration/Preservation Procedures	$2 M–$3 M	Improved guidelines and design procedures for several types of concrete overlays that improve their reliability, viability, and cost-effectiveness.	Improved guidelines and design procedures for the several activities involved with restoring and preserving existing concrete pavements, resulting in improved decisionmaking for potential CPR projects in terms of selecting needed treatments (such as DBR), predicting remaining life, and further validating CPR as a reliable alternative.

Table 9. Subtrack DG 3 overview, continued.

Problem Statement	Estimated Cost	Products	Benefits
DG 3.5 Development of New and Innovative Concrete Pavement Type Designs	$1 M–$2 M	New and innovative types of concrete pavement and a working design procedure for use; demonstrations of new concrete pavement types performed under track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction) and track 8 (Long Life Concrete Pavements).	Improved options to consider for the design; cost effective and reliable concrete pavement designs.
DG 3.6 Optimizing Procedure for New Design and Future Maintenance and Rehabilitation Capable of Minimizing Total Life Cycle Costs, Lane Closure Time, and Other Design Goals over the Range of Design Life	$1 M–$2 M	A comprehensive system that, for a given design project, analyzes a number of alternative initial designs, future preservation treatments, and rehabilitation options; and determines the optimum combination to minimize life cycle costs, initial construction cost, the cost of shoulders and widened slabs, or lane closure time, and to address other needs of the designer. Such a system could handle varying design lives from 8 to more than 60 years.	New and innovative designs that will improve options to consider for the design and provide more cost effective and reliable concrete pavement designs.

Problem Statement DG 3.0. Framework for Special Design and Rehabilitation Issues (Subtrack DG 3)

Track: 2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack: DG 3. Special Design and Rehabilitation Issues
Approximate Phasing: Years 1–3
Estimated Cost: $150 k

Subtrack DG 3 (Special Design and Rehabilitation Issues) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack DG 3 (Special Design and Rehabilitation Issues), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.
Products: A validated, sequenced, and detailed research framework for this subtrack.
Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack DG 3 (Special Design and Rehabilitation Issues).

Problem Statement DG 3.1. Concrete Pavement Design Aspects Related to Multiple/Additional Lanes

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 3. Special Design and Rehabilitation Issues
Approximate Phasing:	Years 2–4
Estimated Cost:	$800 k–$1.5 M

There are many design situations where multiple traffic lanes and concrete shoulders are adjacent. For example, a design situation with three lanes in one direction and two tied shoulders on each side would result in a concrete pavement more than 15 m (50 ft) wide. Also, several critical design decisions must be made regarding the longitudinal joints. The common practice is to tie the shoulders and lanes together with deformed tie bars, but are they always needed? And if needed, what are their proper bar diameters, spacings, and embedment lengths?

Too many tied joints possibly could contribute to longitudinal random cracking. But how many is too many for a given design situation? How many lanes/shoulders can be tied together? What should be done if the base course is an unbound aggregate? What should be done if the base course is permeable asphalt? What should be done if the pavement is constructed during wide swings in ambient temperature?
There is not enough research knowledge regarding these issues. This research will consider these questions to develop a design procedure for multiple traffic lanes and adjacent concrete shoulders.
Tasks:

1. Develop an analytical model that accurately calculates the stresses and deformations in concrete pavement slabs when tied together in multiple lanes and shoulders.
2. Develop a tie bar design procedure for multiple lanes and shoulders on a variety of base courses.
3. Address key design issues and provide guidelines for adding lanes, widening narrow lanes, and replacing shoulders.
4. Evaluate the need for longitudinal joint LTE for various design situations.

Benefits:	Fewer unexpected incidents of longitudinal cracking that result from tying too many lanes together or widening longitudinal joints that had been left untied.
Products:	Specific design methodology, guidelines, and standards for tying together multiple traffic lanes and shoulders.
Implementation:	The design methodology, guidelines, and standards resulting from this research will be incorporated immediately into improved concrete pavement design procedures.

Problem Statement DG 3.2. Characterization of Existing PCC or Hot-Mix Asphalt Pavement to Provide an Adequate Rehabilitation Design

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 3. Special Design and Rehabilitation Issues
Approximate Phasing:	Years 2–5
Estimated Cost:	$3.5 M–$4.5 M

The United States contains a huge infrastructure of existing highway pavements. Every day, designers grapple with ways to develop an adequate design that will carry traffic reliably over the next design period. To accomplish this task, researchers must characterize or evaluate the existing pavement adequately and overcome its inherent deficiencies with a sufficient rehabilitation design. Several end products related to the characterization of existing PCC or HMA pavement will result from these research tasks. Improved characterization of existing pavements will be the most significant and valuable accomplishment. Improved estimates of remaining pavement life will be useful for selecting alternative rehabilitations. Identifying and providing solutions to overcome several existing poor design and material situations will be extremely valuable. Finally, improving key unbonded concrete overlay design procedures will lead to greater reliability and cost-effectiveness.

Tasks:

1. Develop improved procedures for characterizing an existing PCC or HMA pavement to provide an adequate rehabilitation design.
2. Develop a procedure for rapidly determining the remaining life of an existing PCC pavement. The procedure should allow a designer to make remaining pavement life determinations by integrating data on current design features; accumulated and future environmental and loading data; data on existing conditions obtained through visual surveys; field and laboratory testing; in place sensors; and advanced pavement performance modeling techniques. This will help determine the best alternative rehabilitation designs.
3. Identify the key rehabilitation design issues related to overcoming a poor existing design and materials for rehabilitation.
4. Develop improved procedures and technology for unbonded concrete overlays:
5. Determine the effect of the existing PCC slab on unbonded overlay performance.
6. Identify the interface conditions, for various surface preparations and treatments, necessary for achieving optimal performance based on field studies of in place pavements.
7. Develop guidelines for selecting the separation layer that will be used to design unbonded overlays, considering the existing pavement condition, type and design of the overlay, climate, and traffic loadings. Evaluate the effects of interface degradation or improvements over time.

Benefits:	Proper characterization of the existing pavement critical to reliable and cost effective rehabilitation design; rehabilitation design improvements to the pavement design guide.
Products:	Improved characterization of existing pavements; improved estimates of remaining life that will be useful for selecting from alternative rehabilitations; identification of solutions for overcoming existing poor design and material situations; improved support for unbonded concrete overlay design.
Implementation:	Good rehabilitation requires good evaluation. The results of this research will be implemented immediately into improved concrete overlay rehabilitation design procedure.

Problem Statement DG 3.3. Improvements to Concrete Overlay Design Procedures

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 3. Special Design and Rehabilitation Issues
Approximate Phasing:	Years 3–8
Estimated Cost:	\$4 M–\$4.5 M

Reliably designing all types of concrete overlays is essential to highway agencies. However, existing procedures lack a number of capabilities. This research will address a variety of those needs for both bonded and separated concrete overlay designs and for both existing PCC and HMA pavements.

Tasks:

1. Develop guidelines and procedures for designing concrete overlays and widening existing narrow slabs.
2. Develop reliable design procedures for ultrathin slabs placed on existing PCC or HMA layers. For this, improved evaluation techniques of the existing pavement and improved bonding and design procedures are needed.
3. Develop improved layering and jointing models to consider unbonded concrete overlays and the underlying layers.
4. Develop technology to estimate the required design inputs for considering the design and condition of the existing PCC pavement.
5. Develop improved bonding techniques for bonding PCC layers over existing PCC slabs.

Benefits:	Concrete overlays of difficult existing pavements; ultrathin slab design, including improved concrete-to-asphalt bonding procedures; improved layering modeling for unbonded concrete overlays; characterization of underlying PCC slab design and condition for unbonded overlays; improved bonding between thin PCC overlay and existing PCC slabs.
Products:	Improved guidelines and design procedures for several types of concrete overlays, including concrete overlays of difficult existing pavements, ultrathin slab design that includes improved concrete-to-asphalt bonding procedures, improved layering modeling for unbonded concrete overlays, characterization of underlying PCC slab design and condition for unbonded overlays, and improved bonding between thin PCC overlay and existing PCC slabs.
Implementation:	Concrete overlays must be designed more cost effectively to compete with alternatives. The results of this research will be implemented immediately into concrete pavement design procedures.

Problem Statement DG 3.4. Improvements to Concrete Pavement Restoration/Preservation Procedures

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 3. Special Design and Rehabilitation Issues
Approximate Phasing:	Years 3–7
Estimated Cost:	$2 M–$3 M

Many State highway agencies currently apply preservation techniques to all types of pavements, including concrete. As the Nation's interstate highways age, more effective CPR and preservation techniques have become daily activities for many State highway agencies, techniques such as joint repair, dowel retrofitting, shoulder replacement that includes retrofitting with tied PCC, slab replacement, full-depth patching with PCC, grouting and fill of voids, and diamond grinding.

Though several guidelines explain these tasks, very few mechanistic-based procedures evaluate the effectiveness of such repairs in preventing or delaying future distress and its progression. One design procedure that uses mechanistic-based procedures to evaluate and determine the feasibility of CPR is found in the *Mechanistic-Empirical Pavement Design Guide*.[1]

Tasks:

1. Evaluate the *Mechanistic-Empirical Pavement Design Guide* mechanistic-based procedures for assessing the effectiveness of JPCP subjected to CPR.[1]
2. Enhance the *Mechanistic-Empirical Pavement Design Guide* JPCP procedures and develop new procedures for evaluating CPR performed on other concrete pavement types, such as CRCP and jointed reinforced concrete pavement (JRCP).[1] At minimum, the procedure should consider existing pavement design features, climatic conditions, traffic loading, existing distress conditions that include materials durability, future loadings data, and advanced M-E modeling to determine future CPR pavement performance based on key performance indicators.
3. Develop improved guidelines and procedures for designing CPR/preservation projects. These should include improved procedures that assess the window of opportunity for applying preservation techniques to existing concrete pavements.
4. Develop improved procedures for estimating the remaining life (both structural and functional) of existing concrete pavements so that improved restoration or concrete overlay decisions can be made.
5. Develop enhanced pavement management data to support cost effective pavement preservation.

Benefits:	Improved guidelines and design procedures for the activities involved with restoring and preserving existing concrete pavements, resulting in improved decisionmaking for potential CPR projects in terms of selecting needed treatments (such as DBR), predicting remaining life, and further validating CPR as a reliable alternative.
Products:	Improved guidelines and design procedures for several types of concrete overlays that improve their reliability, viability, and cost-effectiveness.
Implementation:	This research will provide practical technological improvements to CPR that will be implemented immediately into design procedures.

Problem Statement DG 3.5. Development of New and Innovative Concrete Pavement Type Designs

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 3. Special Design and Rehabilitation Issues
Approximate Phasing:	Years 5–9
Estimated Cost:	$1 M–$2 M

JPCP is the world's most widely constructed pavement. Many States and other countries also have constructed CRCP, which seems to be gaining in popularity. JRCP has been built extensively in the United States, but serious problems with joints and intermediate panel cracking have effectively halted their construction in any State or foreign country today. JPCP and CRCP pavement types also have problems and limitations. More innovative, cost effective, and reliable design alternatives need to be explored.

Tasks:

1. Conduct a study to explore many new and innovative options for concrete pavement designs. This study will involve both performing a literature search and contacting as many agencies as possible around the world to investigate the latest innovative designs. Evaluate these candidates for feasibility and recommend the most promising. Consider the following as a minimum:
   - Thin slab replacement for existing pavements. Many existing PCC or HMA pavements have thicknesses of 20 to 25 centimeters (cm) (8 to 10 inches). A cost effective solution is to remove this layer and replace it with a relatively thin concrete slab design especially suited for heavy traffic. Design procedures to accomplish this reliably and cost effectively are needed.
   - Design innovations for JPCP and CRCP. Design innovations should optimize the structural and material design of these pavements (e.g., trapezoidal cross sections).
   - Precast JCP design. These are being constructed at several projects, and a major research and development effort is underway to improve their design and construction. Placement speed is their main advantage, with no further curing time required.
   - Concrete overlays, reinforcement, and special surfacing designs. This includes two or more layers of paving materials (concrete, reinforcement, special materials) bonded together. Typical examples include two-layer construction (wet on wet) using layers with different properties, CRCP with special two-layer reinforcement, and special epoxy resin concrete surfacing materials.
   - Structurally reinforced concrete pavement design, including CRCP. A few of these pavements have been constructed in places such as Brazil and Columbia. One design built in Brazil uses two layers of steel in a slab placed on a prepared base course. Another design built in Columbia is essentially a reinforced concrete bridge deck with longitudinal, reinforced concrete beams placed in trenches (the slab is not on grade). The Netherlands has developed a similar system.
   - Prestressed, posttensioned concrete pavements. Several of these have been built in the United States and abroad over the past 30 years. However, the expansion joints often have failed and required maintenance.
2. Develop design procedures for the most promising type of concrete pavements using the existing mechanistic-based procedure as much as possible.

Benefits:	Improved options to consider for the design; cost effective and reliable concrete pavement designs.
Products:	New and innovative types of concrete pavement and a working design procedure for use; demonstrations of new concrete pavement types performed under track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction) and track 8 (Long Life Concrete Pavements).
Implementation:	The new and innovative concrete pavement types will be demonstrated and evaluated under track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction) and track 8 (Long Life Concrete Pavements) and incorporated into a future version of the pavement design guide.

Problem Statement DG 3.6. Optimizing Procedure for New Design and Future Maintenance and Rehabilitation Capable of Minimizing Total Life Cycle Costs, Lane Closure Time, and Other Design Goals over the Range of Design Life

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 3. Special Design and Rehabilitation Issues
Approximate Phasing:	Years 4–10
Estimated Cost:	$1 M–$2 M

The *Mechanistic-Empirical Pavement Design Guide* evaluates a trial design provided by the designer.[1] The proposed design must make several trial runs before an acceptable design is established, and this is only for the first performance period. The design procedure does not consider future rehabilitations, nor does it provide optimization procedures to minimize life cycle costs or even first costs. An optimization procedure to be incorporated into the current and future versions of the pavement design guide is needed.

Tasks:

1. Develop design procedure concepts that consider multiple initial trial designs and multiple optional rehabilitation alternatives and then select designs from among the initial ones that optimize (i.e., minimize or maximize) a desired factor. This factor could be life cycle costs, initial construction costs, future rehabilitation costs, user delay costs, among others. Design procedure concepts should be developed for shoulders, tied shoulders, and alternative shoulder materials.
2. Develop software to accomplish the optimization described above in the first task.
3. Validate the software using several actual projects provided by State highway agencies.

Benefits:	New and innovative design options that will improve options to consider for the design and provide more cost effective and reliable concrete pavement designs.
Products:	A comprehensive system that, for a given design project, analyzes a number of alternative initial designs, future preservation treatments, and rehabilitation options, and determines the optimum combination to minimize life cycle costs, initial construction cost, the cost of shoulders and widened slabs, or lane closure time, and to address other needs of the designer. Such a system could handle varying design lives from 8 to more than 60 years.
Implementation:	Current mechanistic-based procedures in the *Mechanistic-Empirical Pavement Design Guide* do not optimize.[1] This capability is needed and will be implemented into design procedures immediately.

SUBTRACK DG 4. IMPROVED MECHANISTIC DESIGN PROCEDURES

This subtrack develops the new generation design procedure and a comprehensive database of performance data needed for calibration and validation. Table 10 provides an overview of this subtrack.

Table 10. Subtrack DG 4 overview.

Problem Statement	Estimated Cost	Products	Benefits
DG 4.0 Framework for Improved Mechanistic Design Procedures (Subtrack DG 4)	$300 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
DG 4.1 Incremental Improvements to *Mechanistic-Empirical Pavement Design Guide* Procedures	$1.5 M–$2.5 M	An improved and implementable design procedure for new and rehabilitated JPCP and CRCP designs.	A significantly improved pavement design guide that better considers many of its aspects and several new aspects of pavement design; new and rehabilitated designs that are more reliable and cost effective.
DG 4.2 New *Mechanistic-Empirical Pavement Design Guide* Procedures for Paradigm Shift Capabilities	$2 M–$4 M	New generation pavement design procedures that consider many improvements and new pavement design aspects; new and rehabilitated designs that are more reliable and cost effective.	An advanced paradigm shift in integrated concrete pavement design procedures for new and rehabilitated JPCP, CRCP, and other selected designs.

Problem Statement DG 4.0. Framework for Improved Mechanistic Design Procedures (Subtrack DG 4)

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 4. Improved Mechanistic Design Procedures
Approximate Phasing:	Years 1–3
Estimated Cost:	$300 k

Subtrack DG 4 (Improved Mechanistic Design Procedures) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack DG 4 (Improved Mechanistic Design Procedures), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack DG 4 (Improved Mechanistic Design Procedures).

Problem Statement DG 4.1. Incremental Improvements to *Mechanistic-Empirical Pavement Design Guide* Procedures

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 4. Improved Mechanistic Design Procedures
Approximate Phasing:	Year 3–10
Estimated Cost:	$1.5 M–$2.5 M

The initial *Mechanistic-Empirical Pavement Design Guide*, delivered to NCHRP in 2004 after 6 years of development, represents a paradigm shift in design capabilities.[1] Nevertheless, many aspects still require incremental improvements before the guide meets the concrete pavement design goal that aims for new and rehabilitated designs to be reliable, economical, constructible, and maintainable throughout their design life and to meet or exceed the multiple needs (in highways, urban streets, low-volume roads, and special applications, such as tunnels and ports) of the traveling public, taxpayers, and the owning highway agencies. Achieving this goal will require incorporating the results from each of the research studies into the pavement design guide.

Tasks:

1. Improve the FEM neural nets to consider more design and material features (e.g., thinner slabs and better layering capabilities, especially for concrete overlay design).
2. Develop better traffic characterization procedures, including loadings for top-down cracking and truck speed.
3. Predict temperature and moisture more accurately.
4. Incorporate improved base erosion models.
5. Improve JPCP and CRCP distress prediction models.
6. Improve JPCP and CRCP IRI prediction models.
7. Improve sublayer design of base, subbase, subgrade, and particularly subdrainage.
8. Incorporate an improved design reliability approach.
9. Improve the characterization of existing PCC and HMA pavements for use in PCC rehabilitated design.
10. Improve CPR procedures.
11. Improve concrete overlay design procedures.
12. Implement design guidelines and procedures related to multiple lanes, including those related to tie bar design and the number of lanes/shoulders to tie together.
13. Comprehensively calibrate the models using data collected from the ALFs and long-term test sections developed under track 9 (Concrete Pavement Accelerated and Long-Term Data Collection).
14. Validate studies with several State highway agencies.

Benefits:	A significantly improved pavement design guide that better considers many of its aspects and several new aspects of pavement design; new and rehabilitated designs that are more reliable and cost effective.
Products:	An improved implementable design procedure for new and rehabilitated JPCP and CRCP designs.
Implementation:	Many States and local governments will use this new pavement design guide; it can be improved incrementally.

Problem Statement DG 4.2. New *Mechanistic-Empirical Pavement Design Guide* Procedures for Paradigm Shift Capabilities

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 4. Improved Mechanistic Design Procedures
Approximate Phasing:	Years 3–10
Estimated Cost:	\$2 M–\$4 M

This research will develop an advanced version of the pavement design guide that includes major steps forward from the incrementally developed procedures in problem statement DG 4.1 (Incremental Improvements to *Mechanistic-Empirical Pavement Design Guide* Procedures). The new, more fully mechanistic-based procedures will require several years to develop (extending to the end of the 10-year period). The goal is to ensure that new and rehabilitated designs for concrete pavement will be more reliable, economical, constructible, and maintainable throughout their design life and meet or exceed the multiple needs (in highways, urban streets, low-volume roads, and special applications, such as tunnels and ports) of the traveling public, taxpayers, and the owning highway agencies. Achieving this goal will require incorporating the results from each of the research studies into the pavement design guide. The result will be a paradigm shift in 3D FEM, reliability control, incremental improvements, and advanced capabilities in layering, joints, reinforcement, and long life design.

Tasks:

1. Incorporate 3D structural FEMs into the design procedure. Consider implementing the dynamic FEM structural model into the design procedure.
2. Incorporate a more accurate integrated climatic model for temperature and moisture.
3. Develop new concrete materials characterization tests, including fatigue damage, strength, modulus, and many other inputs.
4. Incorporate more accurate long-term changes in material properties (e.g., PCC strength, modulus, shrinkage, and creep).
5. Predict key distress types in JPCP, CRCP, and other selected pavement types using a more intense incremental damage accumulation measurement (e.g., hourly over the entire design period).
6. Improve smoothness prediction models for JPCP and CRCP.
7. Model other functional surface characteristics, such as noise, friction, and spray, as available. This task will link to track 4 (Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements).
8. Include optimization capability to give the designer the tools to minimize life cycle costs or maximize smoothness over the design life.
9. Improve sublayer design of the base, subbase, subgrade, and particularly subdrainage.
10. Incorporate an improved design reliability approach.
11. Comprehensively calibrate the models using data collected from the ALFs and long-term test sections developed under track 9 (Concrete Pavement Accelerated and Long-Term Data Collection).
12. Validate studies with many State highway agencies.

Benefits:	An advanced paradigm shift in integrated concrete pavement design procedures for new and rehabilitated JPCP, CRCP, and other selected designs.
Products:	New generation pavement design procedures that consider many improvements and new pavement design aspects; more reliable and cost effective new and rehabilitated designs.
Implementation:	This research will result in a paradigm shift in pavement design that will produce technology needed to deal with critical problems years from now.

SUBTRACK DG 5. DESIGN GUIDE IMPLEMENTATION

This subtrack addresses implementing the new pavement design guide. Table 11 provides an overview of this subtrack.

Table 11. Subtrack DG 5 overview.

Problem Statement	Estimated Cost	Products	Benefits
DG 5.1 Implementation of the *Mechanistic-Empirical Pavement Design Guide*	\$2 M–\$3 M	Strong technology transfer to the workforce concerning the design of new and rehabilitated concrete pavements through workshops, conferences, and Web-based personnel training.	A workforce with the basic knowledge and understanding needed to design concrete pavements and rehabilitation projects using the design procedure properly.

Problem Statement DG 5.1. Implementation of the *Mechanistic-Empirical Pavement Design Guide*

Track:	2. Performance-Based Design Guide for New and Rehabilitated Concrete Pavements (DG)
Subtrack:	DG 5. Design Guide Implementation
Approximate Phasing:	Years 1–10
Estimated Cost:	\$2 M–\$3 M

Implementing a mechanistic-based design procedure fundamentally changes the way concrete pavement design is performed. Designers must develop additional skills in areas such as structural analysis, material characterization, local calibration, software usage, and existing pavement characterization. Successful implementation will require thousands of pavement designers to be extensively trained over a period of several years. Hands-on workshops, online training tools, and national workshops can accomplish this task.

Tasks:

1. Develop and present workshops dealing with many aspects of the mechanistic-based design process (structural modeling, materials characterization, distress and IRI prediction, overlays, restoration, optimization, traffic, climate, local calibration, etc.). Develop Web-based training in mechanistic-based design. Organize national workshops and conferences on mechanistic design.
2. Organize national conferences and workshops where States and other highway agencies share their findings on the mechanistic design process.
3. Develop Web-based training tools.

Benefits:	A workforce with the basic knowledge and understanding needed to design concrete pavements and rehabilitation projects using the design procedure properly.
Products:	Strong technology transfer to the workforce concerning the design of new and rehabilitated concrete pavements through workshops, conferences, and Web-based personnel training.
Implementation:	This research will result in technology sharing.

Track 3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)

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TRACK 3 (ND) OVERVIEW

The research community has studied various NDT technologies for nearly 20 years. While this technology is beginning to impact pavement management equipment and some hand-held test equipment in construction technology, NDT technology has not been applied extensively to concrete paving. The advancing technology could benefit both the construction and inspection teams in several key ways. The equipment industry faces both a technical challenge and the challenge of investing in a methodology without being certain of a market. Establishing a working group that properly frames the issues, agrees on the technologies, and prioritizes the work efforts is critical for overcoming this investment challenge. Both industry and government will benefit from NDT by reducing reliance on slow and sometimes poorly managed small-sample testing programs. NDT technology also can be incorporated into an ICS that adjusts the paving process automatically while informing contractors and inspectors of changes and/or deficiencies in construction. Continuous and real-time sampling will be configured to detect changes to the approved mix design and the preprogrammed line and grade values. NDT technology also will allow industry and government to use the data collected for long-term pavement management and evaluation. In this regard, track 3 has significant links to track 10 (Concrete Pavement Performance).

The NDT/ICS methods developed in this track can measure the following properties that impact concrete pavement durability and performance:

- Pavement depth.
- Horizontal and vertical slab alignment.
- Subgrade support and variability.
- Steel location (dowels and tie bars).
- Concrete strength through the slab.
- Concrete temperature through the slab.
- Moisture loss.
- Smoothness.
- Tire/pavement noise potential.
- Air.

Many problem statements in this track relate to track 1 (Performance-Based Concrete Pavement Mix Design System) and track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). Software standards will also ensure that the public can link to any software that the private sector produces.

Finally, human factors are critical for both researching and implementing this track. Pavement engineers, materials testers, and contractors need to understand NDT fundamentals to avoid the black box syndrome—that is, trying to get a technology to do something that they do not understand in principle. The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

High-speed nondestructive QC can continuously monitor pavement properties during construction to provide rapid feedback. As a result, automatic adjustments can ensure a high-quality finished product that meets performance specifications.

Track Objectives

1. Perform NDT QC tests and procedures that use continuous and real-time sampling to monitor performance-related concrete mix properties and reduce the number of human inspectors.
2. Improve construction operations by providing continuous and rapid feedback to make changes automatically.
3. Integrate data collection with materials management and pavement management systems (PMS) to solve future problems and evaluate performance.

Research Gaps

- Lack of an overall coordinated plan and government and industry partnerships.
- Lack of financial incentives and favorable investment economics.
- Insufficient understanding of NDT.
- Insufficient understanding of testing variability.

Research Challenges

- Involve both industry and government to create the market and the funding to make this track's goal feasible.
- Develop affordable testing equipment for contractors and owner-agencies, considering both initial and life cycle costs.
- Help contractors and civil engineers understand and simplify the use of NDT in wide-scale concrete pavement operations.
- Develop testing equipment with a low degree of variability to achieve repeatable and reliable results in the field.

Research Track 3 (ND) Phasing

The horizontal bar chart in figure 3 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

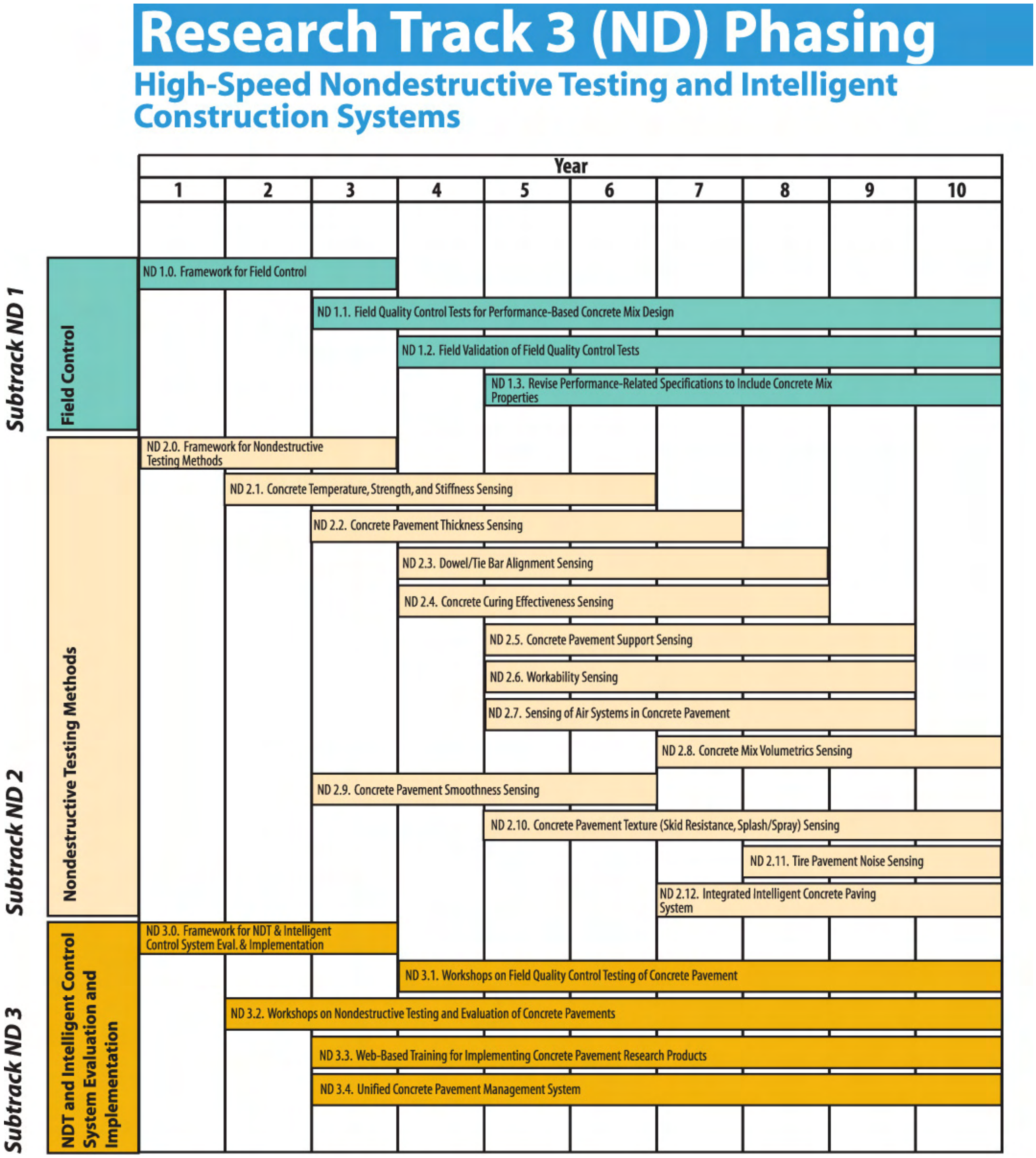

Figure 3. Track 3 (ND) subtrack and problem statement phasing chart.

Research Track 3 (ND) Estimated Costs

Table 12 shows the estimated costs for this research track.

Table 12. Research track 3 (ND) estimated costs.

Problem Statement	Estimated Cost
Subtrack ND 1. Field Control	
ND 1.0. Framework for Field Control (Subtrack ND 1)	$350 k
ND 1.1. Field Quality Control/Quality Assurance Tests for Performance-Based Concrete Mix Design	$2 M–$5 M
ND 1.2. Field Validation of Field Quality Control/Quality Assurance Tests	$2 M–$5 M
ND 1.3. Revise Performance-Related Specifications (PRS) to Include Concrete Mix Properties	$500 k–$1 M
Subtrack ND 2. Nondestructive Testing Methods	
ND 2.0. Framework for Nondestructive Testing Methods (Subtrack ND 2)	$600 k
ND 2.1. Concrete Temperature and Moisture Sensing	$1 M–$2 M
ND 2.2. Concrete Pavement Thickness Sensing	$500 k–$1 M
ND 2.3. Dowel/Tie Bar Alignment Sensing	$1 M–$2 M
ND 2.4. Concrete Curing Effectiveness Sensing	$500 k–$1 M
ND 2.5. Concrete Pavement Support Sensing	$1 M–$2 M
ND 2.6. Workability Sensing	$500 k–$1 M
ND 2.7. Sensing of Air Systems in Concrete Pavement	$1 M–$2 M
ND 2.8. Concrete Mix Density and Volumetrics Sensing	$1 M–$2 M
ND 2.9. Concrete Pavement Smoothness Sensing	$1 M–$2 M
ND 2.10. Concrete Pavement Texture (Skid Resistance, Splash/Spray) Sensing	$500 k–$1 M
ND 2.11. Tire-Pavement Noise Sensing	$500 k–$1 M
ND 2.12. Integrated Intelligent Concrete Paving System	$2 M–$5 M
Subtrack ND 3. Nondestructive Testing and Intelligent Control Systems Evaluation and Implementation	
ND 3.0. Framework for Nondestructive Testing and Intelligent Control Systems Evaluation and Implementation (Subtrack ND 3)	$150 k
ND 3.1. Workshops on Field Quality Control Testing of Concrete Pavement	$1 M–$2 M
ND 3.2. Workshops on Nondestructive Testing and Evaluation of Concrete Pavement	$1 M–$2 M
ND 3.3. Web-Based Training for Implementing Concrete Pavement Research Products	$500 k–$1 M
ND 3.4. Unified Concrete Pavement Management System	$1 M–$2 M
Track 3 (ND)	
Total	$19.6 M–$41.1 M

Track Organization: Subtracks and Problem Statements

Track 3 (ND) problem statements are grouped into three subtracks:

- Subtrack ND 1. Field Control.
- Subtrack ND 2. Nondestructive Testing Methods.
- Subtrack ND 3. Nondestructive Testing and Intelligent Control Systems Evaluation and Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements then follow.

SUBTRACK ND 1. FIELD CONTROL

This subtrack frames the actual field testing research, identifies key QC factors, and pools all the information into a PRS framework linking the information with track 1 (Performance-Based Concrete Pavement Mix Design System) and track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). Table 13 provides an overview of this subtrack.

Table 13. Subtrack ND 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
ND 1.0. Framework for Field Control (Subtrack ND 1)	$350 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
ND 1.1. Field Quality Control/Quality Assurance Tests for Performance-Based Concrete Mix Design	$2 M–$5 M	Testing techniques/devices for QC field testing of performance-based mix designs.	Performance-based concrete mix properties for projects constructed using performance-based mix designs that owner-agencies can verify.
ND 1.2. Field Validation of Field Quality Control/Quality Assurance Tests	$2 M–$5 M	Best practice guides and recommendations for field QC tests.	A guide for implementing and using field QC tests for performance-based mix designs that will be given to owner-agencies.
ND 1.3. Revise Performance-Related Specifications to Include Concrete Mix Properties	$500 k–$1 M	Recommended PRS for mix design properties.	A guide for incorporating concrete mix design properties into PRS that will be given to owner-agencies.

Problem Statement ND 1.0. Framework for Field Control (Subtrack ND 1)

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 1. Field Control
Approximate Phasing:	Years 1–3
Estimated Cost:	$350 k

Subtrack ND 1 (Field Control) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack ND 1 (Field Control), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack ND 1 (Field Control).

Problem Statement ND 1.1. Field Quality Control/Quality Assurance Tests for Performance-Based Concrete Mix Design

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 1. Field Control
Approximate Phasing:	Years 3–10
Estimated Cost:	\$2 M–\$5 M

As performance-based mix designs replace method-based and QC/quality assurance (QA)-based specifications, tests that properly measure mix properties in the field will be required. Examples of these properties for which practical field tests must be developed include heat signature, workability, water-cement ratio, and air content (size and spacing). While heat signature data can be derived in the laboratory, there is a need to develop and implement a field-ready version of the adiabatic calorimeter. Workability affects concrete placeability, affecting both paver performance and finished pavement ride quality. Water-cement ratio, a key concrete mix property, is the primary factor affecting concrete strength and permeability, significantly influencing early-age performance and long-term durability. Unfortunately, the water-cement ratio specified for a job is rarely achieved when the concrete is placed, due to the water added to achieve workability and numerous other factors. Therefore, a quick, reliable test procedure that determines the water-cement ratio shortly before concrete placement as a QA check is needed. Air content (size and spacing of bubbles) also affects permeability and pavement performance (freeze-thaw performance), and should be measured after the concrete has been placed. The air void analyzer has provided reliable results and should be used as a routine QC tool for paving projects. QC devices for field testing performance-based mix design should be rugged, inexpensive, and capable of reproducing the data that current laboratory devices can provide.

Tasks:

1. Identify performance-based concrete mix design properties.
2. Determine suitable limits for performance-based mix design properties.
3. Identify techniques/devices that can determine the desired mix design properties.
4. Modify existing devices/techniques or develop new devices for measuring the mix design parameters accurately in the field, producing the same results as laboratory tests.
5. Develop recommendations for deploying field tests on projects using performance-based mix designs.

Benefits:	Performance-based concrete mix properties for projects constructed using performance-based mix designs that owner-agencies can verify.
Products:	Testing techniques/devices for QC field testing of performance-based mix designs.
Implementation:	This work will result in testing techniques/devices for field testing performance-based mix design properties.

Problem Statement ND 1.2. Field Validation of Field Quality Control/Quality Assurance Tests

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 1. Field Control
Approximate Phasing:	Years 4–10
Estimated Cost:	$2 M–$5 M

Before deploying QC tests in the field, extensive field validation testing will be required. Field validation should be completed under all conceivable conditions expected during future testing, including varying climatic conditions, material properties, pavement types, construction techniques, and mix designs. Best practices should be developed for each of the tests. The repeatability, reliability, and variability of the test results should be checked during the field validation process.

Tasks:

1. Identify all tests required for field validation.
2. Work with owner-agencies to identify test validation locations that represent different climatic conditions, materials, pavement types, construction procedures, and mix designs.
3. Work with contractors and owner-agencies to perform validation testing at various field sites.
4. Evaluate repeatability, reliability, and variability for each test.
5. Recommend improvements to test equipment and procedures.
6. Document the best practices for performing field validation tests.

Benefits:	A guide for implementing and using field QC tests for performance-based mix designs that will be given to owner-agencies.
Products:	Best practice guides and recommendations for field QC tests.
Implementation:	This work will result in best practice guidelines and/or needed improvements to field QC tests.

Problem Statement ND 1.3. Revise Performance-Related Specifications to Include Concrete Mix Properties

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 1. Field Control
Approximate Phasing:	Years 5–10
Estimated Cost:	$500 k–$1 M

FHWA has had an ongoing research program studying PRS for rigid pavements to ensure the construction of high-performance concrete pavements. States are advancing through the continuum of methods specifications, from QC/QA specifications to PRS-based specifications. Because the relationship between concrete mix properties and pavement performance has become better understood, PRS-based specifications should include mix properties. Workability and air content/spacing are two basic mix properties known to affect pavement construction and performance; these should be included in PRS-based specifications. As with other PRS-based specifications, determining and setting limits on performance parameters is the first step in the development process. The next step will be to determine NDTs for the various concrete properties that can be used for QC/QA in the field.

Tasks:

1. Identify the concrete properties shown to affect concrete pavement performance, including parameters indirectly affecting performance (i.e., properties that may affect constructability and thereby affect pavement performance).
2. Determine limits for performance-based properties.
3. Identify practical field tests for measuring mix properties.
4. Develop recommendations concerning PRS for mix properties.

Benefits:	A guide for incorporating concrete mix design properties into PRS that will be given to owner-agencies.
Products:	Recommended PRS for mix design properties.
Implementation:	This work will result in recommended PRS for concrete pavement mix properties.

SUBTRACK ND 2. NONDESTRUCTIVE TESTING METHODS

This subtrack addresses the specific research needed to develop the actual NDT elements of the new intelligent control system. Table 14 provides an overview of this subtrack.

Table 14. Subtrack ND 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
ND 2.0. Framework for Nondestructive Testing Methods (Subtrack ND 2)	$600 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
ND 2.1. Concrete Temperature and Moisture Sensing	$1 M–$2 M	Devices for monitoring concrete temperature and moisture during construction.	Quick determination and short notice adjustment of the optimal time for surface texturing, joint sawing/cutting, and opening to traffic, resulting in high-quality pavement that can be opened quickly to traffic.
ND 2.2. Concrete Pavement Thickness Sensing	$500 k–$1 M	Nondestructive techniques/devices for measuring pavement thickness during construction.	Techniques/devices that provide continuous real-time pavement thickness measurements without removing cores from the slab, resulting in better QA for owner-agencies.
ND 2.3. Dowel/Tie Bar Alignment Sensing	$1 M–$2 M	Devices for detecting dowel and tie bar misalignment during construction.	Paver adjustment and gross misalignment correction during construction, resulting from the detection of dowel and tie bar misalignment behind the paver; better joint and pavement performance.
ND 2.4. Concrete Curing Effectiveness Sensing	$500 k–$1 M	Devices for sensing concrete curing effectiveness during construction.	Automatic adjustment to curing methods during and immediately after the paving operation, resulting from continuous monitoring of curing effectiveness after concrete placement; high-quality concrete pavement.
ND 2.5. Concrete Pavement Support Sensing	$1 M–$2 M	Devices for measuring pavement support during construction.	Automatic adjustments to the mix design, slab thickness, and joint spacing during construction, resulting from continuous monitoring of pavement support in front of the paving operation; high-quality pavements constructed precisely for the support over which they are placed.
ND 2.6. Workability Sensing	$500 k–$1 M	Equipment for continuously monitoring concrete workability during construction.	Automatic adjustments to the concrete mix design and paver operating parameters during construction, resulting from continuous concrete workability monitoring during placement; durable, high-quality concrete pavement placed under optimal operating conditions for the mix.
ND 2.7. Sensing of Air Systems in Concrete Pavement	$1 M–$2 M	Nondestructive equipment for measuring air content/properties.	Automatic adjustments to the concrete mix and paver operating parameters during construction, resulting from continuous air content monitoring (quantity and spacing) behind the paver; high-quality concrete pavement with the proper air content to meet the durability requirements for the climate in which it is constructed.

Table 14. Subtrack ND 2 overview, continued.

Problem Statement	Estimated Cost	Products	Benefits
ND 2.8. Concrete Mix Density and Volumetrics Sensing	$1 M–$2 M	Nondestructive equipment for monitoring volumetric proportions of mix constituents.	Continuous monitoring of the volumetric proportions of mix constituents to allow contractors and inspectors to ensure the proper mix proportions are being used; high-quality concrete pavement with the proper mix proportions.
ND 2.9. Concrete Pavement Smoothness Sensing	$1 M–$2 M	Wet smoothness-sensing equipment.	Pavement smoothness monitored behind the paver, permitting surface deviations to be corrected while the concrete is still plastic and allowing the paver or batching operation to be adjusted to prevent further surface deviations; smoother as-constructed pavements that do not require additional measures (diamond grinding) to meet smoothness specifications.
ND 2.10. Concrete Pavement Texture (Skid Resistance, Splash/ Spray) Sensing	$500 k–$1 M	Equipment for predicting skid resistance and splash/spray potential.	Continuously monitored surface texture, permitting real-time prediction of skid resistance and splash/spray potential; automatic adjustments to finishing and texturing processes to achieve the desired skid resistance and splash/spray characteristics, resulting in as-constructed pavements that meet surface texture requirements without the need for additional texturing measures.
ND 2.11. Tire-Pavement Noise Sensing	$500 k–$1 M	Equipment for predicting pavement noise characteristics during construction.	Prediction of tire-pavement noise potential during construction, allowing surface textures to be corrected while the concrete is still plastic and automatic adjustments to the surface texturing process to meet the tire-pavement noise restrictions; as-constructed pavements that meet stringent tire-pavement noise restrictions without the need for additional noise mitigation.
ND 2.12. Integrated Intelligent Concrete Paving System	$2 M–$5 M	An integrated intelligent paving system to predict future pavement performance.	An integrated intelligent paving system that will predict future pavement performance during the construction process, allowing contractors and owner-agencies to adjust the paving process automatically to achieve the pavement performance requirements; high-quality concrete pavements that will achieve the intended 30-, 40-, or 50-year (or more) design life.

Problem Statement ND 2.0. Framework for Nondestructive Methods (Subtrack ND 2)

Track: 3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack: ND 2. Nondestructive Methods
Approximate Phasing: Years 1–3
Estimated Cost: $600 k

Subtrack ND 2 (Nondestructive Methods) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack ND 2 (Nondestructive Methods), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.
Products: A validated, sequenced, and detailed research framework for this subtrack.
Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack ND 2 (Nondestructive Methods).

Problem Statement ND 2.1. Concrete Temperature and Moisture Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 2–6
Estimated Cost:	$1 M–$2 M

NDT methods for temperature and moisture sensing are important QC checks for concrete placement and early-age monitoring. Temperature can significantly affect pavement performance, prompting many transportation departments to limit concrete temperature during placement. Additionally, moisture sensing not only is a surrogate for curing effectiveness, but also is a direct indication of the hydration process. New devices will allow inspectors to monitor the concrete temperature and moisture history to ensure that limits are not exceeded. Using maturity methods, concrete temperature and moisture can be related to concrete strength, allowing contractors to assess quickly the time before the pavement can be opened to traffic. However, more precise guidelines for the maturity measurement interval, accuracy, and monitoring locations are needed. In addition, guidelines for installing sensors should be developed, addressing concerns such as the effect of mounting sensors on steel dowels or reinforcement and the minimum cover required for proper temperature measurement. Predicting stiffness using the temperature and moisture history can benefit concrete pavement construction by permitting contractors to assess the proper timing for applying surface texture and cutting joints. All NDT devices used for these purposes should be economical and practical for field use.

Tasks:

1. Identify NDT methods and devices for temperature and moisture sensing.
2. Determine the reliability and variability of the test methods and devices under field conditions.
3. Modify existing devices or develop practical new devices that accurately monitor temperature and moisture during pavement construction.
4. Develop recommendations for deploying NDT techniques/devices for temperature and moisture monitoring.

Benefits:	Quick determination and short notice adjustment of the optimal time for surface texturing, joint sawing/cutting, and opening to traffic, resulting in high-quality pavement that can be opened quickly to traffic.
Products:	Devices for monitoring concrete temperature and moisture during construction.
Implementation:	This work will result in reliable, practical, and economical techniques/devices for monitoring concrete temperature and moisture during pavement construction.

Problem Statement ND 2.2. Concrete Pavement Thickness Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 3–7
Estimated Cost:	$500 k–$1 M

As-constructed pavement thickness must be assessed during construction to determine pay factors and to ensure that the owner-agency gets what it pays for. Current practice for verifying concrete pavement thickness is to remove cores from the pavement and measure their length with calipers. This is a time-consuming and costly process. Several agencies are attempting to use nondestructive techniques, such as physical probes, impact-echo, and ground-penetrating radar equipment, to eliminate the need for core sampling. A systematic evaluation of these and other alternatives is needed to determine their accuracy and potential for use in concrete paving specifications. When using coring to sample thickness, a limited number of thickness measurements are feasible because the cost for each sample is high. The goal of new NDT is to increase the number of samples while decreasing the cost of testing and eliminating the core removal.

Tasks:

1. Identify existing NDT techniques that determine pavement thickness.
2. Determine the variability of existing methods and assess whether this variability is acceptable for QC testing.
3. Modify existing nondestructive techniques or develop new techniques that measure slab thickness at intervals as short at 30.5 cm (1 ft) quickly, accurately, and cost effectively.
4. Develop recommendations for deploying nondestructive thickness sensing devices.

Benefits:	Techniques/devices that provide continuous real-time pavement thickness measurements without removing cores from the slab, resulting in better QA for owner-agencies.
Products:	Nondestructive techniques/devices for measuring pavement thickness during construction.
Implementation:	This work will result in nondestructive techniques/devices for measuring pavement thickness quickly at short intervals.

Problem Statement ND 2.3. Dowel/Tie Bar Alignment Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 4–8
Estimated Cost:	$1 M–$2 M

Many transportation agencies use dowel and tie bars to ensure adequate load transfer across joints in concrete pavements. If constructed properly, dowel bars should be exactly parallel to both the surface and centerline of the hardened slab. Unfortunately, this is not always the case, as misalignment can occur from either misplacement (incorrect initial positioning of the dowels), displacement (movement during the paving operation), or both. Tie bars should be centered over a longitudinal joint to secure adjacent slabs effectively. Misaligned dowel bars can cause joints to lock-up or even fault, and thus significantly affect pavement performance. There is no clear consensus among agencies on the level of practical limits on dowel placement tolerances. Normally, a maximum allowable alignment error of 0.64 cm (0.25 inch) per 45.7 cm (18 inches) length of dowel bar is specified, although the Georgia DOT specifies an allowable tolerance of 7.2 cm (3 inches) per 2.4 m (8 ft) both horizontally and vertically, and several other agencies specify an allowable tolerance of 2.5 cm (1 inch) per 1.2 m (4 ft) both horizontally and vertically. Unfortunately, these specifications are difficult to enforce because there is no efficient and reliable technique for determining in situ dowel misalignment. However, recent development of the MIT-SCAN-2 and MIT-SCAN-2F devices has provided an opportunity to obtain accurate dowel position information efficiently and cost effectively.

Research is needed that either modifies existing dowel bar alignment sensing equipment or develops new equipment for use during the paving process. Real-time measurements of dowel bar alignment immediately behind the paving operation will alert the contractor and inspectors to alignment problems, allowing for paver adjustments and possible corrections to misaligned dowel bars.

Tasks:

1. Identify existing nondestructive dowel and tie bar alignment sensing devices.
2. Modify existing devices or develop new devices that permit testing during the paving operation.
3. Evaluate the accuracy of the devices on actual pavement sections and make recommendations for deploying the devices for concrete paving construction projects.

Benefits:	Paver adjustment and gross misalignment correction during construction, resulting from the detection of dowel and tie bar misalignment behind the paver; better joint and pavement performance.
Products:	Devices for detecting dowel and tie bar misalignment during construction.
Implementation:	This work will result in dowel and tie bar alignment sensing devices that can be used to assess dowel and tie bar alignment rapidly during construction.

Problem Statement ND 2.4. Concrete Curing Effectiveness Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 4–8
Estimated Cost:	$500 k–$1 M

The effectiveness of curing methods used during concrete paving is an important factor that can affect pavement service life. Curing affects slab warping behavior, and rapid moisture loss at the surface also can weaken surface strength. While standard laboratory test methods for evaluating the effectiveness of curing compound exist, no test or device is widely used in the field. This research will identify an NDT that will allow for continuous monitoring of curing method effectiveness during and after concrete placement. Ideally, the test/device will be fully automated and will alert the inspector or contractor if additional curing measures are needed. The test/device could also be linked to automated curing equipment that would adjust curing depending on the amount of moisture loss detected in the slab. Such devices should be portable, economical, and unobtrusive and be capable of monitoring curing effectiveness at several locations along a day's worth of pavement placement.

Tasks:

1. Identify existing moisture sensors or other devices that measure curing effectiveness.
2. Modify existing devices or develop new devices to monitor curing effectiveness.
3. Validate curing effectiveness detection devices on paving projects.
4. Develop recommendations for deploying curing effectiveness detection devices.

Benefits:	Automatic adjustment to curing methods during and immediately after the paving operation, resulting from continuous monitoring of curing effectiveness after concrete placement; high-quality concrete pavement.
Products:	Devices for sensing concrete curing effectiveness during construction.
Implementation:	This work will result in a device that senses curing effectiveness during and after concrete placement.

Problem Statement ND 2.5. Concrete Pavement Support Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 5–9
Estimated Cost:	$1 M–$2 M

The support structure beneath PCC pavements significantly affects pavement design characteristics, such as thickness, joint spacing, and mix design. Unfortunately, when most pavements are designed, the variability of the supporting structure along the length of the pavement can be significant. Automated, nondestructive support-sensing devices would allow the support structure to be assessed continuously along the length of the pavement during the paving operation. Support-sensing devices could be fixed to the paving equipment to determine the stiffness of the support structure at the time of placement and as the paving operation progresses. Automated support-sensing devices could send support information to automated batching and paving equipment, causing the batching equipment to adjust the paving mix or the paver to adjust slab thickness or load transfer (joint spacing) automatically.

Tasks:

1. Identify existing nondestructive support-sensing devices.
2. Modify existing devices or develop new devices that continuously monitor pavement support layers.
3. Integrate support-sensing devices into the paving operation to make adjustments automatically.
4. Validate support-sensing equipment on actual paving projects.
5. Develop recommendations for deploying support-sensing equipment on paving projects.

Benefits:	Automatic adjustments to the mix design, slab thickness, and joint spacing during construction, resulting from continuous monitoring of pavement support in front of the paving operation; high-quality pavements constructed precisely for the support over which they are placed.
Products:	Devices for measuring pavement support during construction.
Implementation:	This work will result in automated support-sensing equipment that can measure pavement support continuously during construction.

Problem Statement ND 2.6. Workability Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 5–9
Estimated Cost:	$500 k–$1 M

Fresh concrete workability can affect significantly the paving process and the quality of the finished product. Workability can dictate both the speed and efficiency (i.e., energy consumption) of the paving process as well as the finishability of the pavement, affecting both ride quality and surface texture. The process is commonly controlled in the field with routine sampling and testing of the concrete for strength, slump, and sometimes air content (or unit weight). While these measures provide critical feedback, they are not always timely or reliable. This research will investigate techniques that evaluate paving concrete properties—specifically rheological properties such as workability—more rapidly and continuously. With continuous workability monitoring, the batch plant could adjust mix proportions more quickly and reliably and the paving operator could adjust the paver operating parameters more quickly.

Tasks:

1. Identify techniques/equipment for measuring concrete workability.
2. Modify existing equipment or develop new equipment that continuously monitors mix workability.
3. Validate workability sensing equipment on actual paving projects.
4. Integrate workability sensing equipment with automated batching and paving equipment.
5. Develop recommendations for deploying workability sensing equipment.

Benefits:	Automatic adjustments to the concrete mix design and paver operating parameters during construction, resulting from continuous concrete workability monitoring during placement; durable, high-quality concrete pavement placed under optimal operating conditions for the mix.
Products:	Equipment for continuously monitoring concrete workability during construction.
Implementation:	This work will result in equipment for continuously sensing concrete workability that can be tied into automated batching and paving equipment.

Problem Statement ND 2.7. Sensing of Air Systems in Concrete Pavement

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 5–9
Estimated Cost:	$1 M–$2 M

Placement activities, such as slipform paving, reduce the quantity of entrained air in concrete by as much as 2 percent. Air tests are not currently taken after slipform paving, but rather are taken from samples either at the plant or in front of the paving machine. However, this testing procedure systematically ignores the impact of the pavement placement operation on air content. Durability studies have revealed problems with freeze-thaw damage due to an inadequate quantity of entrained air. Studies also show that both the amount of entrained air and the spacing between the air bubbles is important. Air tests are not taken behind the paving machine primarily because these tests are destructive. The current testing standard, ASTM C 231, would require removing concrete from the finished slab.

This research will develop a test method or procedure to determine the air content (amount and spacing of bubbles) of plastic concrete after paving. Although the air void analyzer has been shown to indicate air content (amount and spacing of bubbles) accurately, it still usually requires that concrete be removed from the finished surface, and the testing apparatus is not necessarily suited for field applications. This research will identify appropriate technology to create accurate and durable test equipment that can determine air content properties quickly, permitting automatic adjustments to mix proportions.

Tasks:

1. Identify existing equipment for classifying air content (quantity and bubble spacing) accurately.
2. Modify existing equipment or develop new durable and economical automated equipment/sensors that can assess air content behind the paver quickly.
3. Validate air sensing equipment on actual paving projects.
4. Integrate automated air sensing equipment/sensors with batching and paving equipment.
5. Develop recommendations for deploying air sensing equipment for paving operations.

Benefits:	Automatic adjustments to the concrete mix and paver operating parameters during construction, resulting from continuous air content monitoring (quantity and spacing) behind the paver; high-quality concrete pavement with the proper air content to meet the durability requirements for the climate in which it is constructed.
Products:	Nondestructive equipment for measuring air content/properties.
Implementation:	This work will result in air sensing equipment that can quickly and accurately assess the air content and spacing behind the paver.

Problem Statement ND 2.8. Concrete Mix Density and Volumetrics Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 7–10
Estimated Cost:	$1 M–$2 M

During typical paving operations, process controls measure such concrete properties as slump, air content, and strength. However, density is checked rarely, and volumetric proportions seldom are checked to determine whether the proper proportions are being batched. For this purpose, nondestructive equipment for sensing the density and volumetric proportions of the material onsite is needed. The equipment should determine both the density and the volumetric proportions of constituents quickly and continuously throughout the paving operation. Automated equipment could alert inspectors or the batch plant to adjust the mix.

Tasks:

1. Develop sensing equipment that can determine the density of the mixture and volumetric proportions of concrete constituents quickly.
2. Validate density and volumetric sensing equipment on an actual paving project.
3. Develop recommendations for deploying automated sensing equipment.

Benefits:	Continuous monitoring of the density and volumetric proportions of mix constituents to allow contractors and inspectors to ensure the proper mix proportions are being used; high-quality concrete pavement with the proper mix proportions.
Products:	Nondestructive equipment for monitoring mixture density and volumetric proportions of mix constituents.
Implementation:	This work will result in nondestructive density and mix volumetric sensing equipment.

Problem Statement ND 2.9. Concrete Pavement Smoothness Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 3–6
Estimated Cost:	$1 M–$2 M

The California Profilograph is the equipment most commonly used to measure pavement smoothness, providing information to the contractor in as little as 4 to 6 hours after placing conventional concrete pavement. While this is the fastest available method for providing smoothness information, it is not fast enough to indicate bumps or dips to the paving crew during finishing operations. Wet smoothness-measuring devices that can be mounted to slipform machines or a trailing construction bridge are needed. These devices will provide direct feedback to the paving finishing crew and to automated paving equipment. The crew can then eliminate surface deviations while the concrete remains plastic, and the paving machine could adjust to correct smoothness irregularities caused by the paver. This method will provide a uniform surface and eliminate areas that must be ground after construction.

This research will develop a wet smoothness-measuring device that produces information translatable to the California Profile Index or IRI. Evaluating the accuracy of the smoothness-measuring device will be necessary to demonstrate its accuracy relative to the California Profilograph. In addition, a manual describing the testing equipment and indexing procedure should be developed to implement this equipment and procedure.

Tasks:

1. Identify wet smoothness-measuring devices.
2. Adapt the smoothness-measuring devices to slipform paving operations.
3. Develop a system that combines the new smoothness measurements with software that automatically calculates the simulated California Profile Index and IRI.
4. Validate the wet smoothness measurements on an actual paving project.
5. Develop recommendations for deploying the smoothness-sensing equipment during the paving operation.

Benefits:	Pavement smoothness monitored behind the paver, permitting surface deviations to be corrected while the concrete is still plastic and allowing the paver or batching operation to be adjusted to prevent further surface deviations; smoother as-constructed pavements that do not require additional measures (diamond grinding) to meet smoothness specifications.
Products:	Wet smoothness-sensing equipment.
Implementation:	This work will result in wet smoothness-sensing equipment that can be adapted to slipform paving operations.

Problem Statement ND 2.10. Concrete Pavement Texture (Skid Resistance, Splash/Spray) Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 5–10
Estimated Cost:	\$500 k–\$1 M

The primary purpose of pavement surface texture is to improve friction (skid resistance). However, reducing splash and spray also must be considered, as these can affect driver visibility. Predicting both skid resistance and splash/spray potential during pavement construction can ensure that an adequate and safe surface texture is applied. Because skid resistance and splash/spray potential are difficult to measure or quantify on fresh concrete surfaces, surface texture (type and depth), skid resistance, and splash/spray potential may need to be correlated. Measuring surface texture properties during construction will allow the contractor to adjust the paving equipment to improve surface texture and possibly correct still-plastic in place concrete. Surface texture sensing equipment could be mounted on the paving train immediately behind the finishing and texturing processes to determine texture properties in real time. The sensing equipment would provide instant results for a large enough section of pavement to indicate the whole surface adequately.

Tasks:

1. Identify surface texture measurement equipment/techniques that can be used on fresh (plastic) concrete to determine skid resistance and splash/spray potential.
2. Identify correlations between surface texture measurements, skid resistance, and splash/spray potential.
3. Modify existing equipment or develop new sensing equipment that measures surface texture properties on fresh concrete.
4. Develop necessary correlations between surface texture properties, skid resistance, and splash/spray potential.
5. Validate surface texture measurement equipment on actual paving projects.
6. Develop recommendations for deploying surface texture sensing equipment.

Benefits:	Continuously monitored surface texture, permitting real-time prediction of skid resistance and splash/spray potential; automatic adjustments to finishing and texturing processes to achieve the desired skid resistance and splash/spray characteristics, resulting in as-constructed pavements that meet surface texture requirements without the need for additional texturing measures.
Products:	Equipment for predicting skid resistance and splash/spray potential.
Implementation:	This work will result in equipment that can predict the skid resistance and splash/spray potential of fresh concrete pavement.

Problem Statement ND 2.11. Tire-Pavement Noise Sensing

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 8–10
Estimated Cost:	$500 k–$1 M

Tire-pavement noise is very important to consider in concrete pavement construction, and many States have implemented noise-level restrictions on new pavement construction. Tire-pavement noise can increase the cost of a paving project significantly if noise mitigation measures are required. Therefore, determining potential tire-pavement noise during construction is important if measures are to be taken to reduce noise levels. Research to develop techniques and equipment for measuring pavement noise potential during construction is needed. Sensing equipment mounted to the paving train immediately behind the finishing and texturing operations could sense and predict noise potential in real time. This information would allow the contractor to adjust the paving equipment to reduce noise potential and perhaps correct in place concrete that is still plastic. Noise-sensing equipment will provide instant results for a large enough section of pavement to indicate the noise potential for whole surface adequately.

Tasks:

1. Identify surface texture measurement techniques/equipment that can predict tire-pavement noise.
2. Modify existing equipment or develop new techniques/equipment that predict tire-pavement noise from surface texture measurements on fresh concrete.
3. Develop necessary correlations between surface texture measurement and pavement noise.
4. Validate noise-sensing equipment on actual paving projects.
5. Develop recommendations for deploying noise-sensing equipment.

Benefits:	Prediction of tire-pavement noise potential during construction, allowing surface textures to be corrected while the concrete is still plastic and automatic adjustments to the surface texturing process to meet the tire-pavement noise restrictions; as-constructed pavements that meet stringent tire-pavement noise restrictions without the need for additional noise mitigation.
Products:	Equipment for predicting pavement noise characteristics during construction.
Implementation:	This work will result in noise-sensing equipment that can be used for new PCC pavement construction.

Problem Statement ND 2.12. Integrated Intelligent Concrete Paving System

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 2. Nondestructive Methods
Approximate Phasing:	Years 7–10
Estimated Cost:	\$2 M–\$5 M

Pavement performance often can be linked to construction practices or problems encountered during construction. For this reason, an integrated intelligent paving system that predicts future pavement performance behind the paving operation in real time is needed. The intelligent paving system will predict concrete pavement performance using various sensors and equipment on and around the paving operations. The intelligent paving system minimally would incorporate monitoring of the following: concrete and ambient temperatures, workability, air properties, mix constituent proportions, strength, slab thickness, dowel bar alignment, curing effectiveness, pavement support, smoothness, texture (skid resistance and splash/spray potential), and noise potential. The intelligent paving system could allow contractors and inspectors to make adjustments automatically to improve future pavement performance and increase pay factors or performance-based incentives.

Tasks:

1. Identify models that have been shown to predict concrete pavement performance based on construction variables.
2. Identify sensing equipment that could be incorporated into the intelligent paving system.
3. Integrate sensors/equipment and models into the intelligent paving system.
4. Validate the intelligent paving system on actual paving projects.
5. Develop recommendations for deploying the intelligent paving system.

Benefits:	An integrated intelligent paving system that will predict future pavement performance during the construction process, allowing contractors and owner-agencies to adjust the paving process automatically to achieve the pavement performance requirements; high-quality concrete pavements that will achieve the intended 30-, 40-, or 50-year (or more) design life.
Products:	An integrated intelligent paving system to predict future pavement performance.
Implementation:	This work will result in an intelligent paving system that can predict future pavement performance during construction.

SUBTRACK ND 3. NONDESTRUCTIVE TESTING AND INTELLIGENT CONTROL SYSTEM EVALUATION AND IMPLEMENTATION

This subtrack addresses the field evaluation and implementation elements of the track. Table 15 provides an overview of this subtrack.

Table 15. Subtrack ND 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
ND 3.0. Framework for Nondestructive Testing and Intelligent Control Systems Evaluation and Implementation (Subtrack ND 3)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
ND 3.1. Workshops on Field Quality Control Testing of Concrete Pavement	$1 M–$2 M	Workshops that provide QC field testing.	Technology transfer on QC field testing for performance-based mix designs through workshops that are a minor investment for owner-agencies.
ND 3.2. Workshops on Nondestructive Testing and Evaluation of Concrete Pavements	$1 M–$2 M	Workshops on NDT equipment and evaluation.	Technology transfer for NDT equipment and evaluation through workshops that are a minor investment for owner-agencies.
ND 3.3. Web-Based Training for Implementing Concrete Pavement Research Products	$500 k–$1 M	Web-based training modules and a continuously maintained Web site for new NDT and ICS products and technologies.	Technology transfer for implementable NDT and ICS products that is accessible to anyone with an Internet-ready computer.
ND 3.4. Unified Concrete Pavement Management System	$1 M–$2 M	A concrete PMS that includes records for construction, materials, performance, and maintenance.	A unified management system for concrete pavements that significantly improves design and construction operations, with a direct link between these factors and the observed inservice performance and maintenance requirements.

Problem Statement ND 3.0. Framework for Nondestructive Testing and Intelligent Control System Evaluation and Implementation (Subtrack ND 3)

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 3. Nondestructive Testing and Intelligent Control System Evaluation and Implementation
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

ND 3 (Nondestructive Testing and Intelligent Control System Evaluation and Implementation) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack ND 3 (Nondestructive Testing and Intelligent Control System Evaluation and Implementation), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack ND 3 (Nondestructive Testing and Intelligent Control System Evaluation and Implementation).

Problem Statement ND 3.1. Workshops on Field Quality Control Testing of Concrete Pavement

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 3. Nondestructive Testing and Intelligent Control System Evaluation and Implementation
Approximate Phasing:	Years 4–10
Estimated Cost:	$1 M–$2 M

Before implementing performance-based specifications, owner-agencies must recognize which tests can monitor performance-related properties during concrete pavement construction. While new tests and equipment are constantly being developed, transportation agencies are often slow to adopt new techniques due to unfamiliarity with new technologies and a lack of research resources. Workshops provide an environment ideal for familiarizing and training agencies in new tests and equipment. These workshops will give an overall view of QC testing in the field, with an emphasis on monitoring performance-based properties, and introduce new tests and equipment for QC field testing.

Tasks:

1. Compile information on QC field tests and equipment, particularly for monitoring performance-based properties.
2. Develop workshops and present material on QC field testing.

Benefits:	Technology transfer on QC field testing for performance-based mix designs through workshops that are a minor investment for owner-agencies.
Products:	Workshops that provide QC field testing of concrete pavement.
Implementation:	This project will result in numerous workshops on QC field testing at various venues throughout the United States.

Problem Statement ND 3.2. Workshops on Nondestructive Testing and Evaluation of Concrete Pavements

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 3. Nondestructive Testing and Intelligent Control System Evaluation and Implementation
Approximate Phasing:	Years 2–10
Estimated Cost:	$1 M–$2 M

While new NDTs and equipment constantly are being developed, transportation agencies often are slow to adopt new techniques due to unfamiliarity with these new technologies and a lack of research resources. Workshops provide an ideal environment for familiarizing and training agencies in new NDTs and equipment, as well as evaluation procedures for using these tests. Workshops will be developed to provide technology transfer of concrete pavement NDT techniques.

Tasks:

1. Compile information on NDTs and equipment for PCC pavement construction.
2. Develop workshops to introduce NDT equipment and evaluation procedures to contractors and owner-agencies.

Benefits:	Technology transfer for NDT equipment and evaluation through workshops that are a minor investment for owner-agencies.
Products:	Workshops on NDT equipment and evaluation.
Implementation:	This project will result in numerous workshops on NDT equipment and evaluation procedures at various venues throughout the United States.

Problem Statement ND 3.3. Web-Based Training for Implementing Concrete Pavement Research Products

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 3. Nondestructive Testing and Intelligent Control System Evaluation and Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	$500 k–$1 M

While many new products and technologies are developed and ready for implementation every year, transportation agencies are often slow to adopt new products and technologies due to unfamiliarity with these new technologies and a lack of research resources. Workshops offer contractors and owner-agencies the opportunity to learn about new products and technologies, but often agencies cannot afford to send employees to workshops or may be restricted from traveling to a workshop outside the home State. Fortunately, with Web-based training, contractors, designers, and owner-agencies can explore new products and technologies from any computer with Internet access. On-demand Web-based training can use features such as video streaming to visually demonstrate new products and technologies.

Tasks:

1. Compile information on NDT and ICS products and technologies ready for implementation, including thorough descriptions, photos, and video.
2. Develop Web-based training modules for each new product or technology.
3. Create a Web site for accessing the training modules and maintain the Web site with updates or refinements for new and existing products.

Benefits:	Technology transfer for implementable NDT and ICS products that is accessible to anyone with an Internet-ready computer.
Products:	Web-based training modules and a continuously maintained Web site for new NDT and ICS products and technologies.
Implementation:	This research will result in Web-based training modules for new NDT and ICS products and technologies related to concrete pavements.

Problem Statement ND 3.4. Unified Concrete Pavement Management System

Track:	3. High-Speed Nondestructive Testing and Intelligent Construction Systems (ND)
Subtrack:	ND 3. Nondestructive Testing and Intelligent Control System Evaluation and Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	$1 M–$2 M

For concrete pavements, independent management systems currently exist for materials, construction, performance, and maintenance. This research will combine these management systems into a unified system, producing a database capable of linking the materials and construction used on a specific pavement segment to the segment's observed performance. This will allow for more informed decisions to be made in selecting optimum design and construction features.

Tasks:

1. Structure a unified concrete PMS that considers user needs.
2. Identify the databases for concrete pavements currently in use and the potential links between these databases.
3. Develop a prototype system and populate it with a limited set of data. Evaluate this system and update it as necessary.
4. Develop and deploy the final unified concrete PMS.

Benefits:	A unified management system for concrete pavements that significantly improves design and construction operations, with a direct link between these factors and the observed inservice performance and maintenance requirements.
Products:	A concrete PMS that includes records for construction, materials, performance, and maintenance.
Implementation:	This project will result in a unified PMS that can be used to improve concrete pavement design and construction practices.

Track 4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)

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TRACK 4 (SC) OVERVIEW

FHWA and State highway agencies have learned from sophisticated opinion polling that American drivers value the quality of their ride experience. Over the past 2 decades, concrete pavement engineers have focused on improving pavement smoothness without jeopardizing surface friction or surface drainage characteristics. This difficult but important balancing act has led to advancements in smoothness indices, longitudinal tining, and measurement equipment, among other areas. However, the relationship between surface texture and surface characteristics, as well as concrete pavement performance, has yet to develop fully. While smoother concrete pavements are being constructed, the relationships between texture, noise, splash and spray, and friction require further study before widely accepted solutions become available.

In some areas of the United States, drivers and residents have demanded quieter rides and living experiences. These demands often eliminate concrete pavement as a construction option, and in some cases has even led to the overlay of recently constructed concrete pavements. In the Phoenix, AZ, metropolitan area, for example, concrete pavements that have a harsh transverse texture make up nearly all of the freeway system. Because of noise complaints, these pavements are now being overlaid with an open-graded asphalt rubber wearing course. While this may seem radical to some, the approach is not new. Noise has been a major problem in some of the most densely populated areas of Europe for more than a decade; as a result, concrete pavement construction has been impeded there.

Most European nations now place thin asphalt-based wearing courses over their concrete pavements immediately after construction. However, some concrete surfacing solutions have been used successfully. These include thin, open-graded (porous) concrete wearing surfaces and exposed aggregate surfaces. Textures such as fine longitudinal burlap drag and diamond grinding also are used to reduce noise.

To address noise impacts to highway abutters, FHWA regulations currently dictate the noise mitigation efforts required, if any, for new or expanded highway facilities. To date, these regulations have resulted in questions about whether noise walls are necessary, and if so, what their design should be. At the same time, automobile and tire makers have developed designs that meet more stringent friction (braking) demands, while at the same time reducing interior noise. In the near future, pavement will be looked to for help in noise reduction. This will require concrete pavement engineers to take responsibility for finding innovative materials and optimizing pavement textures.

To meet this responsibility, concrete pavement engineers must balance smoothness, friction, surface drainage, splash and spray, and noise to develop economical and long-lasting solutions for concrete pavement surfaces. Any long-term solution must include research and experimentation that examines the integration of these elements into an array of viable incremental solutions. One consideration is developing standardized noise measurement and analysis techniques. Pavement engineers also must understand fundamental engineering properties better to assess noise, friction, and smoothness, isolating improved texturing options and tailoring solutions to location, traffic, and renewal requirements. Pavement engineers must understand the functional and structural performance of various solutions over time, as the data from many studies are sufficient to examine the relationships between noise and the other surface characteristics, including pavement durability.

Research must aim to develop various standardized measurement techniques, understand the tire-pavement interaction with various texturing options, predict the life expectancy of any solution, and identify possible repair and rehabilitation strategies for these pavements. Moreover, if noise criteria are ever imposed as design-build criteria, integration with national noise mitigation standards must be considered, and rational and achievable construction specification language must be developed.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

A better understanding of concrete pavement surface characteristics will provide the traveling public with concrete pavement surfaces that meet or exceed predetermined requirements for friction/safety, tire-pavement noise, smoothness, splash and spray, light reflection, rolling resistance, and durability (longevity).

Track Objectives

1. Develop reliable, economical, constructible, and maintainable concrete pavement surface characteristics that meet or exceed highway user requirements for all classes of streets, low-volume roads, highways, and special applications.
2. Develop, field test, and validate concrete pavement designs and construction methods that produce consistent surface characteristics that meet or exceed highway user requirements for friction/safety, tire-pavement noise, smoothness, splash and spray, light reflection, rolling resistance, and durability (longevity).
3. Define the relationship between wet weather accident rates, pavement texture, and friction demand levels.
4. Determine the design materials and construction methods that produce different levels of short- and long-term surface microtexture, macrotexture, megatexture, and unevenness.
5. Determine the relationship between pavement texture levels (microtexture, macrotexture, megatexture, and unevenness) and surface characteristic performance levels (friction, noise, smoothness, splash and spray, rolling resistance, and light reflectivity).
6. Evaluate and develop high-speed, continuous measurement equipment and procedures for measuring texture, friction, noise, smoothness, splash and spray, rolling resistance, and other key surface characteristics.
7. Develop design and construction guidelines for concrete pavement surface characteristics, protocols, guide specifications, and associated technology transfer products.

Research Gaps

- Lack of a validated method that thoroughly characterizes pavement friction (e.g., wet versus dry and tangent versus cornering).
- Insufficient understanding of the relationship between surface texture, wet weather accidents, and friction demand. Threats of litigation, real or perceived, have otherwise prevented research from being conducted.
- Lack of concrete aggregate tests that relate very well to long-term texture and frictional stability (performance).
- Insufficient understanding of the relationship between the design/construction methods and materials and the as-built surface texture.
- Insufficient understanding of the relationship between the as-built surface texture and the initial and long-term functional performance.
- Insufficient understanding of the relationship between the design/construction material properties and methods and the long-term functional performance.
- Lack of a mechanistic understanding of the relationships between texture and tire-pavement noise, roadway noise, effective friction, splash, spray, and other functional indicators.
- Lack of understanding of unconventional texturing methods (e.g., exposed aggregate and porous PCC).

- Lack of equipment that efficiently and accurately measures all key surface characteristics.
- Lack of standard protocols for measuring all key surface characteristics.

Research Challenges

- Identify the critical factors in friction demand, obtain the data necessary to define and quantify the friction demand factors, and develop a standard method for quantifying friction demand.
- Obtain the existing and new data necessary to define relationships between wet weather accident rates, texture, and friction.
- Define the material-related factors that control texture and frictional stability, identify tests that quantify these factors, and relate test results to variations in long-term performance.
- Obtain the aggregate, design, construction, texture, and performance data necessary to define the relationships among these factors.
- Assemble a complete set of design, construction, texture, and long-term performance data. Add to the macrotexture data available and develop a direct, high-speed method for measuring microtexture.
- Model the difficult and complex relationships, deriving mechanistic or M-E solutions when possible.
- Obtain test section data from long-term performance studies in other countries, considering inexperienced contractors constructing as-designed test section pavements.
- Develop procedures and techniques to determine optimal surface characteristics that consider factors such as pavement/tire noise, friction, smoothness, wearout, and clogging of porous surfaces.
- Develop comprehensive protocols, convincing agencies and countries of the benefits of change.

Research Track 4 (SC) Phasing

The horizontal bar chart in figure 4 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

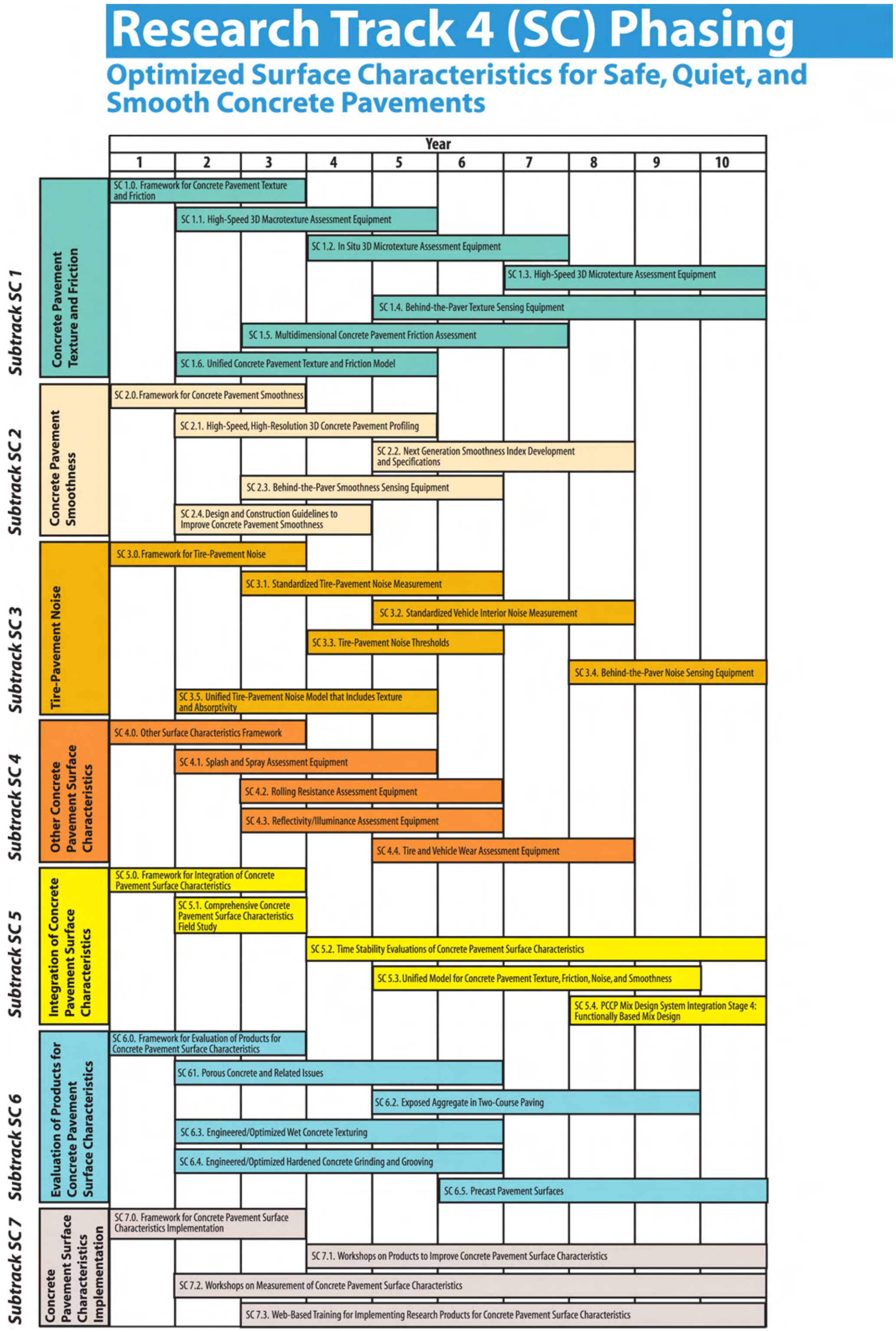

Figure 4. Track 4 (SC) subtrack and problem statement phasing chart.

Research Track 4 (SC) Estimated Costs

Table 16 shows the estimated costs for this research track.

Table 16. Research track 4 (SC) estimated costs.

Problem Statement	Estimated Cost
Subtrack SC 1. Concrete Pavement Texture and Friction	
SC 1.0. Framework for Concrete Pavement Texture and Friction (Subtrack SC 1)	\$100 k–\$250 k
SC 1.1. High-Speed 3D Macrotexture Assessment Equipment	\$2 M–\$5 M
SC 1.2. In Situ 3D Microtexture Assessment Equipment	\$500 k–\$1 M
SC 1.3. High-Speed 3D Microtexture Assessment Equipment	\$2 M–\$5 M
SC 1.4. Behind-the-Paver Texture Sensing Equipment	\$250 k–\$500 k
SC 1.5. Multidimensional Concrete Pavement Friction Assessment	\$1 M–\$2 M
SC 1.6. Unified Concrete Pavement Texture and Friction Model	\$500 k–\$1 M
Subtrack SC 2. Concrete Pavement Smoothness	
SC 2.0. Framework for Concrete Pavement Smoothness (Subtrack SC 2)	\$100 k–\$250 k
SC 2.1. High-Speed, High-Resolution 3D Pavement Profiling	\$2 M–\$5 M
SC 2.2. Next Generation Concrete Pavement Smoothness Index Development and Specifications	\$500 k–\$1 M
SC 2.3. Behind-the-Paver Smoothness Sensing Equipment	\$100 k–\$250 k
SC 2.4. Design and Construction Guidelines to Improve Concrete Pavement Smoothness	\$500 k–\$1 M
Subtrack SC 3. Tire-Pavement Noise	
SC 3.0. Framework for Tire-Pavement Noise (Subtrack SC 3)	\$100 k–\$250 k
SC 3.1. Standardized Tire-Pavement Noise Measurement	\$1 M–\$2 M
SC 3.2. Standardized Vehicle Interior Noise Measurement	\$250 k–\$500 k
SC 3.3. Tire-Pavement Noise Thresholds	\$500 k–\$1 M
SC 3.4. Behind-the-Paver Noise Sensing Equipment	\$100 k–\$250 k
SC 3.5. Unified Tire-Pavement Noise Model That Includes Texture and Absorptivity	\$500 k–\$1 M
Subtrack SC 4. Other Concrete Pavement Surface Characteristics	
SC 4.0. Framework for Other Concrete Pavement Surface Characteristics (Subtrack SC 4)	\$100 k–\$250 k
SC 4.1. Splash and Spray Assessment Equipment	\$1 M–\$2 M
SC 4.2. Rolling Resistance Assessment Equipment	\$1 M–\$2 M
SC 4.3. Reflectivity/Illuminance Assessment Equipment	\$1 M–\$2 M
SC 4.4. Tire and Vehicle Wear Assessment Equipment	\$1 M–\$2 M
Subtrack SC 5. Integration of Concrete Pavement Surface Characteristics	
SC 5.0. Framework for Integration of Concrete Pavement Surface Characteristics (Subtrack SC 5)	\$100 k–\$250 k
SC 5.1. Comprehensive Concrete Pavement Surface Characteristics Field Study	\$500 k–\$1 M
SC 5.2. Time Stability Evaluations of Concrete Pavement Surface Characteristics	\$500 k–\$1 M
SC 5.3. Unified Model for Concrete Pavement Texture, Friction, Noise, and Smoothness	\$500 k–\$1 M
SC 5.4. PCC Pavement Mix Design System Integration Stage 4: Functionally Based Mix Design	\$500 k–\$1 M
SC 5.5. Relating Pavement Surface Characteristics to Vehicle Accidents	\$1 M–\$2 M

Table 16. Research track 4 (SC) estimated costs, continued.

Problem Statement	Estimated Cost
Subtrack SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics	
SC 6.0. Framework for Evaluations of Products for Concrete Pavement Surface Characteristics (Subtrack SC 6)	$100 k–$250 k
SC 6.1. Porous Concrete and Related Issues	$1 M–$2 M
SC 6.2. Exposed Aggregate in Two-Course Paving	$250 k–$500 k
SC 6.3. Engineered/Optimized Wet Concrete Texturing	$1 M–$2 M
SC 6.4. Engineered/Optimized Hardened Concrete Grinding and Grooving	$1 M–$2 M
SC 6.5. Precast Pavement Surfaces	$250 k–$500 k
Subtrack SC 7. Concrete Pavement Surface Characteristics Implementation	
SC 7.0. Framework for Concrete Pavement Surface Characteristics Implementation (Subtrack SC 7)	$100 k–$250 k
SC 7.1. Workshops on Products to Improve Concrete Pavement Surface Characteristics	$1 M–$2 M
SC 7.2. Workshops on Measurement of Concrete Pavement Surface Characteristics	$1 M–$2 M
SC 7.3. Web-Based Training for Implementation of Research Products for Concrete Pavement Surface Characteristics	$500 k–$1 M
Track 4 (SC)	
Total	$25.4 M–$54.25 M

Track Organization: Subtracks and Problem Statements

Track 4 (SC) problem statements are grouped into seven subtracks:

- Subtrack SC 1. Concrete Pavement Texture and Friction.
- Subtrack SC 2. Concrete Pavement Smoothness.
- Subtrack SC 3. Tire-Pavement Noise.
- Subtrack SC 4. Other Concrete Pavement Surface Characteristics.
- Subtrack SC 5. Integration of Concrete Pavement Surface Characteristics.
- Subtrack SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics.
- Subtrack SC 7. Concrete Pavement Surface Characteristics Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK SC 1. CONCRETE PAVEMENT TEXTURE AND FRICTION

This subtrack focuses on issues related to texture and friction properties of concrete pavements. Table 17 provides an overview of this subtrack.

Table 17. Subtrack SC 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 1.0. Framework for Concrete Pavement Texture and Friction (Subtrack SC 1)	$100 k–$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 1.1. High-Speed 3D Macrotexture Assessment Equipment	$2 M–$5 M	Advanced, effective, high-speed 3D macrotexture assessment equipment with standards and specifications for its use.	Technology that can be a key component in assessing concrete pavement macrotexture in three dimensions; improved prediction of wet pavement friction.
SC 1.2. In Situ 3D Microtexture Assessment Equipment	$500 k–$1 M	Advanced and effective in situ 3D microtexture assessment equipment with standards and specifications for its use.	Automated method for measuring concrete pavement microtexture in situ.
SC 1.3. High-Speed 3D Microtexture Assessment Equipment	$2 M–$5 M	Advanced, effective high-speed 3D microtexture assessment equipment with standards and specifications for its use.	High-speed laser equipment that can measure concrete pavement microtexture at highway speeds.
SC 1.4. Behind-the-Paver Texture Sensing Equipment	$250 k–$500 k	Advanced, effective behind-the-paver texture sensing equipment with standards and specifications for its use.	Technology that can be a key component for measuring concrete pavement texture behind the paver; minimized instances of over- and under-texturing.
SC 1.5. Multidimensional Concrete Pavement Friction Assessment	$1 M–$2 M	Effective methods for multidimensional friction assessment with their respective standards and specifications.	Advancements in concrete pavement friction assessment that use multidimensional models.
SC 1.6. Unified Concrete Pavement Texture and Friction Model	$500 k–$1 M	A model that relates and integrates texture and friction characterization.	A model that advances the process of texture selection as it relates to friction, allowing improved prediction of friction resulting from texturing methods.

Problem Statement SC 1.0. Framework for Concrete Pavement Texture and Friction (Subtrack SC 1)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 1–3
Estimated Cost:	$100 k–$250 k

Subtrack SC 1 (Concrete Pavement Texture and Friction) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 1 (Concrete Pavement Texture and Friction), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack SC 1 (Concrete Pavement Texture and Friction).

Problem Statement SC 1.1. High-Speed 3D Macrotexture Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 2–5
Estimated Cost:	\$2 M–\$5 M (including \$500 k matching funds)

Measuring pavement macrotexture has been a common practice in Europe for many years. In the United States, the important role of pavement macrotexture in providing adequate surface friction increasingly is being recognized. Recent research indicates that the mean profile depth (MPD) parameter best describes macrotexture to predict wet pavement friction. One way of measuring MPD is to use high-speed, vehicle-mounted, laser-based measuring devices, such as the Road Surface Analyzer. The research in this problem statement will build off advancements such as this to develop effective, high-speed macrotexture assessment equipment that can scan a pavement surface in three dimensions, giving a picture of both longitudinal and transverse variation in macrotexture.

Tasks:

1. Synthesize related work and conduct a preliminary investigation to determine the best methods for quantifying macrotexture. Confirm that measuring macrotexture will advance the industry and meet the goals for track 4.
2. Identify available high-speed 3D laser equipment options.
3. Analyze the equipment for accuracy, precision, and ease of use.
4. Identify the most effective equipment based on cost, technological maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
5. Develop standards and specifications on the proper use of the equipment for assessing macrotexture.

Benefits:	Technology that can be a key component in assessing concrete pavement macrotexture in three dimensions; improved prediction of wet pavement friction.
Products:	Advanced, effective, high-speed 3D macrotexture assessment equipment with standards and specifications for its use.
Implementation:	The research in this problem statement will be coordinated closely with research done under problem statement SC 2.1 (High-Speed, High-Resolution 3D Concrete Pavement Profiling).

Problem Statement SC 1.2. In Situ 3D Microtexture Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 4–7
Estimated Cost:	\$500 k–\$1 M (including \$100 k matching funds)

Microtexture refers to fine-scale pavement roughness—much finer than macrotexture—largely determined by the fine aggregate in concrete mortar. Concrete pavement microtexture commonly is measured in the laboratory or estimated in the field using friction measurements. However, because of the fine resolution necessary, no automated method for measuring microtexture in situ exists, much less at highway speeds. The research in this problem statement will develop effective 3D microtexture assessment equipment that can be used in situ (static).

Tasks:

1. Synthesize related work and conduct a preliminary investigation to determine the best methods for quantifying microtexture in situ. Confirm that measuring microtexture in this way will advance the industry and meet the goals for track 4.
2. Identify available options for in situ 3D microtexture assessment equipment.
3. Analyze the equipment for accuracy, precision, and ease of use.
4. Identify the most effective equipment based on cost, technological maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
5. Develop standards and specifications on the proper equipment use for assessing microtexture.

Benefits:	Automated method for measuring concrete pavement microtexture in situ.
Products:	Advanced and effective in situ 3D microtexture assessment equipment with standards and specifications for its use.
Implementation:	The technology identified in this problem statement can be a key component to assess concrete pavement microtexture in situ.

Problem Statement SC 1.3. High-Speed 3D Microtexture Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 7–10
Estimated Cost:	\$2 M–\$5 M (including \$500 k matching funds)

No automated method for measuring concrete pavement microtexture at highway speeds currently exists. However, high-speed 3D laser equipment is expected to be available for measuring macrotexture at highway speeds. This technology can be adapted and improved (i.e., by increasing laser and computer processing power) to measure concrete pavement microtexture similarly at highway speeds. The research in this problem statement will develop this effective, high-speed 3D microtexture assessment equipment.

Tasks:

1. Synthesize related work and conduct a preliminary investigation to determine the best methods for quantifying microtexture. Confirm that the high-speed measurement of microtexture will advance the industry and meet the goals for track 4.
2. Identify the most effective high-speed laser equipment options for measuring concrete pavement microtexture and macrotexture, referring to problem statements SC 1.1 (High-Speed 3D Macrotexture Assessment Equipment) and SC 1.2 (In Situ 3D Microtexture Assessment Equipment).
3. Modify the equipment or develop additional equipment to measure concrete pavement microtexture at highway speeds.
4. Develop standards and specifications on the proper use of the equipment for assessing microtexture.

Benefits:	High-speed laser equipment that can measure concrete pavement microtexture at highway speeds.
Products:	Advanced, effective high-speed 3D microtexture assessment equipment with standards and specifications for its use.
Implementation:	The technology identified in this problem statement can be a key component in the high-speed assessment of concrete pavement microtexture.

Problem Statement SC 1.4. Behind-the-Paver Texture Sensing Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 5–10
Estimated Cost:	$250 k–$500 k

Many techniques indicate texture in plastic PCC pavements. However, current techniques are methods-based. And while the as-built texture is clearly important, texture rarely is verified due to a lack of testing equipment and expertise. Ideally, texture should be verified in situ and in real time as the paver (texturer) moves. Texture could thus be adjusted in real time, and over- or under-texturing could be minimized. The research in this problem statement will develop effective behind-the-paver equipment that measures concrete pavement texture during placement.

Tasks:

1. Identify available behind-the-paver texture sensing equipment or equipment components.
2. Analyze the equipment for accuracy, precision, and ease of use.
3. Identify the most effective equipment based on cost, maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
4. Develop standards and specifications for properly using the equipment to measure concrete pavement texture.

Benefits:	Technology that can be a key component for measuring concrete pavement texture behind the paver; minimized instances of over- and under-texturing.
Products:	Advanced, effective behind-the-paver texture sensing equipment with standards and specifications for its use.
Implementation:	The research in this problem statement will be coordinated closely with problem statement ND 2.10 (Concrete Pavement Texture (Skid Resistance, Splash/Spray) Sensing).

Problem Statement SC 1.5. Multidimensional Concrete Pavement Friction Assessment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 3–7
Estimated Cost:	$1 M–$2 M (including $200 k matching funds)

Roadway friction is a complex parameter. First, it commonly is assessed longitudinally along the direction of travel, essential for determining vehicle stopping distances. However, this assessment does not address situations in which vehicles slide sideways or diagonally into adjacent lanes, particularly while traversing horizontal curves. Furthermore, friction varies with the presence of water or other lubricating substances on the roadway. The research in this problem statement will capture these and other variables by developing a more effective method for assessing multidimensional friction.

Tasks:

1. Synthesize related work and conduct a preliminary investigation to determine the best methods for quantifying friction. Confirm that more sophisticated friction measurement will advance the industry and meet the goals for track 4.
2. Identify and analyze existing methods of assessing friction.
3. Develop additional methods as needed to allow for multidimensional friction assessment.
4. Develop standards and specifications to ensure proper procedures are followed for the respective methods.

Benefits:	Advancements in concrete pavement friction assessment that use multidimensional models.
Products:	Effective methods for multidimensional friction assessment with their respective standards and specifications.
Implementation:	The research in this problem statement will advance concrete pavement friction assessment.

Problem Statement SC 1.6. Unified Concrete Pavement Texture and Friction Model

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 1. Concrete Pavement Texture and Friction
Approximate Phasing:	Years 2–5
Estimated Cost:	\$500 k–\$1 M

Significant research demonstrates the sensitivity of friction to texture in various wavelength ranges and explains the fundamental mechanisms involved. However, little systematic information currently explains the sensitivity of friction to the specific dimensions of each type of texture, including directionality and variables such as aggregate size or channel width and depth. The research in this problem statement will develop a model to relate and integrate texture and friction.

Tasks:

1. Identify and analyze widely used texturing methods.
2. Analyze the respective relationships between these methods and pavement friction, tying this characterization to the research done under SC 1.5 (Multidimensional Concrete Pavement Friction Assessment) as necessary.
3. Develop preliminary models to relate and integrate texture and friction.
4. Adjust the models as necessary and develop a final model to relate and integrate texture and friction.

Benefits:	A model that advances the process of texture selection as it relates to friction, allowing for improved prediction of friction resulting from texturing methods.
Products:	A model that relates and integrates texture and friction characterization.
Implementation:	The research in this problem statement will advance texture selection as it relates to friction.

SUBTRACK SC 2. CONCRETE PAVEMENT SMOOTHNESS

This subtrack focuses on issues related to concrete pavement smoothness. Table 18 provides an overview of this subtrack.

Table 18. Subtrack SC 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 2.0. Framework for Concrete Pavement Smoothness (Subtrack SC 2)	\$100 k–\$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 2.1. High-Speed, High-Resolution 3D Pavement Profiling	\$2 M–\$5 M	Effective methods for high-speed, high-resolution 3D pavement profiling and their respective standards and specifications.	Pavement profiling methods that advance concrete pavement structure profiling.
SC 2.2. Next Generation Smoothness Index Development and Specifications	\$500 k–\$1 M	Recommended refinements to AASHTO provisional standards for pavement profiling and ride quality.	Methods and specifications that advance the construction and evaluation of pavement smoothness, ultimately enhancing ride quality for the traveling public.
SC 2.3. Behind-the-Paver Smoothness Sensing Equipment	\$100 k–\$250 k	Advanced, effective behind-the-paver smoothness sensing equipment with standards and specifications for its use.	Behind-the-paver technology that serves as a key component in sensing pavement smoothness, providing real-time information that can correct paving operations immediately.
SC 2.4. Design and Construction Guidelines to Improve Concrete Pavement Smoothness	\$500 k–\$1 M	Comprehensive and accurate guidelines in design and construction that help stakeholders improve concrete pavement smoothness.	Guidelines that advance design and construction practices to achieve smooth concrete pavements.

Problem Statement SC 2.0. Framework for Concrete Pavement Smoothness (Subtrack SC 2)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 2. Concrete Pavement Smoothness
Approximate Phasing:	Years 1–3
Estimated Cost:	$100 k–$250 k

Subtrack SC 2 (Concrete Pavement Smoothness) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 2 (Concrete Pavement Smoothness), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack SC 2 (Concrete Pavement Smoothness).

Problem Statement SC 2.1. High-Speed, High-Resolution 3D Concrete Pavement Profiling

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 2. Concrete Pavement Smoothness
Approximate Phasing:	Years 2–5
Estimated Cost:	$2 M–$5 M (including $500 k matching funds)

Current concrete pavement profiling technology commonly differentiates two categories of profiles: lateral and longitudinal. Lateral profiles allow for an assessment of rutting (e.g., from studded tire damage), superelevation of the road design, and other damage. More commonly analyzed are longitudinal profiles, which illustrate concrete pavement roughness and some forms of texture. While combining these two profiles can be beneficial, such combinations are rare, because piecing the two together is laborious and the resulting complete profile is often questionable. Ideal concrete pavement profiles would include methods for 3D measurement, which allow pavement distresses and directional features in the pavement surface to be detected and quantified readily. The research in this problem statement will develop effective methods for high-speed, high-resolution 3D pavement profiling.

Tasks:

1. Synthesize related work and conduct a preliminary investigation to determine the best methods for profiling concrete pavements. Confirm that more sophisticated pavement profiling techniques will advance the industry and meet the goals for track 4.
2. Identify and analyze existing methods for 3D pavement profiling.
3. Develop additional methods as needed for higher speed and higher resolution performance.
4. Develop standards and specifications to ensure proper procedures are followed for the respective methods.

Benefits:	Pavement profiling methods that advance concrete pavement structure profiling.
Products:	Effective methods for high-speed, high-resolution 3D pavement profiling and their respective standards and specifications.
Implementation:	The research in this problem statement will be coordinated closely with problem statement SC 1.1 (High-Speed 3D Macrotexture Assessment Equipment).

Problem Statement SC 2.2. Next Generation Smoothness Index Development and Specifications

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 2. Concrete Pavement Smoothness
Approximate Phasing:	Years 5–8
Estimated Cost:	$500 k–$1 M

There are four AASHTO provisional standards for assessing concrete pavement smoothness. These standards provide an excellent resource for implementing a smoothness QA program, but they must be reviewed and revised continuously as more is learned about pavement smoothness measurement and interpretation. Research is needed in various aspects of pavement smoothness to ensure that these specifications continue to provide smooth pavements. The research in this problem statement will aim to refine the AASHTO standards based on the results of research and development efforts both currently underway and conducted under this and other research programs.

Tasks:

1. Identify and analyze accurate and repeatable profiling methods and smoothness metrics. These should be as relevant to the comfort of vehicle occupants as possible.
2. Change the profiling specifications as needed. Suggested methods must provide relevant, understandable output and minimize the sensitivity of the process to measurement errors.
3. Suggest refinements to the specifications for smoothness pay factors, rationalizing the factors based on the costs involved with ride quality degradation.
4. Give these specification refinements to AASHTO for consideration only after formal peer review.

Benefits:	Methods and specifications that advance the construction and evaluation of pavement smoothness, ultimately enhancing ride quality for the traveling public.
Products:	Recommended refinements to AASHTO provisional standards for pavement profiling and ride quality.
Implementation:	The research in this problem statement will refine AASHTO provisional standards for assessing concrete pavement smoothness, thus advancing the construction and evaluation of concrete pavements.

Problem Statement SC 2.3. Behind-the-Paver Smoothness Sensing Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 2. Concrete Pavement Smoothness
Approximate Phasing:	Years 3–6
Estimated Cost:	$100 k–$250 k

Concrete pavement smoothness usually is assessed after the pavement has gained enough strength for pavement profilers to traverse the surface without damage. In this scenario, a pavement that does not meet the minimum required smoothness level would require costly remedial methods, or worse, rejection of the pavement. The frequency of these consequential actions can be minimized if pavement smoothness is assessed during paving. The smoothness level thus would be reported to interested parties while the concrete is still plastic. The research in this problem statement will develop effective and advanced behind-the-paver smoothness sensing equipment that can assess pavement smoothness during paving.

Tasks:

1. Identify available behind-the-paver smoothness sensing equipment.
2. Analyze the equipment for accuracy, precision, and ease of use.
3. Identify the most effective equipment based on cost, technological maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
4. Develop standards and specifications on the proper use of the equipment for sensing pavement smoothness.

Benefits:	Behind-the-paver technology that is a key component in sensing pavement smoothness, providing real-time information that can correct paving operations immediately.
Products:	Advanced, effective behind-the-paver smoothness sensing equipment with standards and specifications for its use.
Implementation:	The research in this problem statement will be coordinated closely with problem statement ND 2.9 (Concrete Pavement Smoothness Sensing).

Problem Statement SC 2.4. Design and Construction Guidelines to Improve Concrete Pavement Smoothness

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 2. Concrete Pavement Smoothness
Approximate Phasing:	Years 2–4
Estimated Cost:	$500 k–$1 M

Strong evidence supports the hypothesis that pavements that are smooth when built remain smooth longer than pavements that are initially rough. To provide smooth pavements, most State highway agencies have implemented smoothness specifications that offer incentives for very smooth pavements and impose penalties for unacceptably rough pavements. However, little specific guidance helps contractors improve smoothness during pavement construction. Similarly, little guidance is provided to pavement designers to achieve smoothness goals. The research in this problem statement will develop such guidance, synthesizing ongoing work in this area.

Tasks:

1. Develop an initial draft of smoothness guidelines by synthesizing existing best practices for design and construction of smooth concrete pavements.
2. Validate the draft guidelines by contacting agencies to identify recently constructed pavements of varying smoothness levels. Assess the ways in which the pavements were designed and built, and determine whether the draft guidelines remain valid under the varying situations.
3. Based on this validation, identify the need for additional (possibly structured) test sections to help refine the guidelines. Execute this validation work if necessary.
4. Develop a final set of design and construction guidelines to improve concrete pavement smoothness.

Benefits:	Guidelines that advance design and construction practices to achieve smooth concrete pavements.
Products:	Comprehensive and accurate guidelines in design and construction that help stakeholders improve concrete pavement smoothness.
Implementation:	The research in this problem statement will result in guidelines for achieving pavement smoothness goals.

SUBTRACK SC 3. TIRE-PAVEMENT NOISE

This subtrack focuses on issues related to tire-pavement noise generation, propagation, and mitigation related to concrete pavements. Table 19 provides an overview of this subtrack.

Table 19. Subtrack SC 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 3.0. Framework for Tire-Pavement Noise (Subtrack SC 3)	\$100 k–\$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 3.1. Standardized Tire-Pavement Noise Measurement	\$1 M–\$2 M	A standardized method or combination of methods for measuring tire-pavement noise.	Methods that advance the industry by allowing for a comparison of tire-pavement noise measurements made using different testing methods.
SC 3.2. Standardized Vehicle Interior Noise Measurement	\$250 k–\$500 k	A standardized method for measuring interior vehicle noise.	A method that advances procedures for measuring vehicle interior noise, improving decisions about the influence of tire-pavement noise on the traveling public.
SC 3.3. Tire-Pavement Noise Thresholds	\$500 k–\$1 M	A report defining tire-pavement noise thresholds that can be used to optimize concrete pavement surface characteristics.	Identified thresholds that advance the concrete pavement industry by providing rational methods for designing and constructing concrete pavements with acceptable friction and tire-pavement noise characteristics.
SC 3.4. Behind-the-Paver Noise Sensing Equipment	\$100 k–\$250 k	Advanced and effective equipment to measure concrete pavement noise and related surface characteristics behind the paver; standards and specifications for using the equipment.	Technology that serves as a key component in sensing concrete pavement noise and surface texture behind the paver.
SC 3.5. Unified Tire-Pavement Noise Model That Includes Texture and Absorptivity	\$500 k–\$1 M	A sophisticated model for predicting tire-pavement noise as a function of concrete pavement texture and other physical properties.	Models that predict tire-pavement noise as a function of its relationship to texture, materials characteristics, and other pavement features; a rational approach to predicting tire-pavement noise.

Problem Statement SC 3.0. Framework for Tire-Pavement Noise (Subtrack SC 3)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 3. Tire-Pavement Noise
Approximate Phasing:	Years 1–3
Estimated Cost:	\$100 k–\$250 k

Subtrack SC 3 (Tire-Pavement Noise) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 3 (Tire-Pavement Noise), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack SC 3 (Tire-Pavement Noise).

Problem Statement SC 3.1. Standardized Tire-Pavement Noise Measurement

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 3. Tire-Pavement Noise
Approximate Phasing:	Years 3–6
Estimated Cost:	$1 M–$2 M (including $100 k matching funds)

Several methods currently measure both vehicle and tire-pavement noise. Traditionally, traffic noise is measured using wayside measures such as statistical pass-by testing, which samples passing vehicles at the roadside and classifies their noise emission by the type of vehicle. Another wayside method, termed controlled pass by, uses a known (test) vehicle with known tire properties that passes a fixed microphone. This method allows a detailed assessment of noise generation, because many of the dependent variables are known or controlled. In recent years, an alternative classification of noise measurement called close proximity or near-field testing has become more common. In these methods, various microphones are mounted to a test vehicle near the tire-pavement contact patch. These methods seek to isolate the noise generated at the contact patch from other sources. However, since the pass-by and close proximity methods do not measure the same noise sources, no simple relationship between them is evident. Furthermore, each variant within these two testing categories results in a different measurement, making comparison between the various methods even more difficult. Because of these compatibility issues, as well as the impact of tire-pavement noise on policy in Europe and now in the United States, the research in this problem statement will develop standardized methods for measuring and comparing tire-pavement noise.

Tasks:

1. Identify and synthesize various accepted methods of measuring vehicle noise, particularly those that isolate tire-pavement noise.
2. Conduct a preliminary investigation to determine the best methods for quantifying tire-pavement noise. Confirm that measuring tire-pavement noise will advance the industry and meet the goals for track 4.
3. Identify decisionmaking criteria for a standard method selection and prioritize the available methods. Where applicable, recommend variations of existing test methods or combinations of test methods. If necessary, develop new methods that can be tested in the field.
4. Develop a final recommended method or combination of methods for measuring tire-pavement noise.
5. Develop standards and specifications to ensure that proper procedures are followed when the recommended methods are used.

Benefits:	Methods that advance the industry by allowing for a comparison of tire-pavement noise measurements made using different testing methods.
Products:	A standardized method or combination of methods for measuring tire-pavement noise.
Implementation:	The research in this problem statement will develop standardized methods for measuring tire-pavement noise.

Problem Statement SC 3.2. Standardized Vehicle Interior Noise Measurement

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 3. Tire-Pavement Noise
Approximate Phasing:	Years 5–8
Estimated Cost:	$250 k–$500 k (including $50 k matching funds)

Recent research has found that objectionable vehicle interior noise is identified with tonal quality (specific frequencies) more than total noise level. This objectionable tonal quality primarily results from spikes in sound pressures at discrete frequencies, commonly generated by repeating patterns in pavement texture, such as transverse tining or even low frequency chatter. To better understand these phenomena, standardized interior noise evaluation procedures are required. Previous research revealed that subjective noise ratings of subjects in test vehicles on different surface textures do not correspond with the objective total noise measurements taken outside the vehicle. Therefore, to further explore these gaps, the research in this problem statement will develop a standardized method for measuring vehicle interior noise.

Tasks:

1. Identify and analyze accepted and prospective methods of measuring vehicle interior noise.
2. Conduct a preliminary investigation to determine the best methods for measuring interior vehicle noise. Confirm that more sophisticated noise measurement techniques will advance the industry and meet the goals for track 4.
3. After comparing the various methods, recommend methods of measurement that include either an existing method or a combination of methods.
4. Develop standards and specifications to ensure proper procedures are followed for the measurement method.

Benefits:	A method that advances procedures for measuring vehicle interior noise, allowing improved decisions about the influence of tire-pavement noise on the traveling public.
Products:	A standardized method for measuring interior vehicle noise.
Implementation:	The results of this research will advance methods for measuring vehicle interior noise, allowing more informed decisions about the impact of vehicle interior noise on the traveling public.

Problem Statement SC 3.3. Tire-Pavement Noise Thresholds

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 3. Tire-Pavement Noise
Approximate Phasing:	Years 4–6
Estimated Cost:	$500 k–$1 M

Altering certain concrete pavement surface characteristics—for example, increasing macrotexture for improved friction or reduced splash and spray—can sometimes worsen tire-pavement noise. While safety is more important than driver comfort or reduced noise, noise thresholds should be a factor in pavement optimization, just as are friction thresholds. These noise thresholds should characterize tire-pavement noise levels and frequencies, scaling them to include a range of human responses, from mere annoyance to driver and abutter distraction. The research in this problem statement will define these threshold values so that more informed decisions can be made about the tradeoffs between tire-pavement noise and other pavement surface characteristics.

Tasks:

1. Identify pavements that have varying types of tire-pavement noise, including various noise levels and spectral content.
2. Synthesize the current knowledge in this area, drawing from existing work in psychoacoustics. If necessary, conduct validation surveys on various pavements, assessing the human response to the received noise.
3. From the results of this inquiry, identify threshold values that can base a more rational characterization of the human response to both tire-pavement noise level and frequency.

Benefits:	Identified thresholds that advance the concrete pavement industry by providing rational methods for designing and constructing concrete pavements with acceptable friction and tire-pavement noise characteristics.
Products:	A report defining tire-pavement noise thresholds that can be used to optimize concrete pavement surface characteristics.
Implementation:	The results of this research will be to identify tire-pavement noise thresholds that provide more rational methods to optimize concrete pavement surface characteristics.

Problem Statement SC 3.4. Behind-the-Paver Noise Sensing Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 3. Tire-Pavement Noise
Approximate Phasing:	Years 8–10
Estimated Cost:	$100 k–$250 k

The noise generated by tire-pavement contact is related to the surface texture and other concrete pavement surface properties, particularly on the wearing course. However, current technology only allows tire-pavement noise levels to be assessed after the pavement has hardened sufficiently to accommodate a test vehicle. If tire-pavement noise is a specification value, and if this value falls outside an acceptable level, costly methods could be required to mitigate the problem. However, if tire-pavement noise, pavement surface texture, and other properties (e.g., absorptivity) related to tire-pavement noise could be assessed during placement, improvements could be made in real time while the concrete is still plastic. The research in this problem statement will identify and tentatively develop effective and advanced behind-the-paver noise sensing equipment.

Tasks:

1. Identify available behind-the-paver noise/texture sensing equipment.
2. Analyze the equipment for accuracy, precision, and ease of use.
3. Identify the most effective equipment based on cost, technological maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
4. Develop standards and specifications for the proper use of the equipment for sensing pavement noise, texture, and other concrete properties related to noise.

Benefits:	Technology that serves as a key component in sensing concrete pavement noise and surface texture behind the paver.
Products:	Advanced and effective equipment to measure concrete pavement noise and related surface characteristics behind the paver; standards and specifications for using the equipment.
Implementation:	The research in this problem statement will be coordinated closely with problem statement ND 2.11 (Tire-Pavement Noise Sensing).

Problem Statement SC 3.5. Unified Tire-Pavement Noise Model that Includes Texture and Absorptivity

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 3. Tire-Pavement Noise
Approximate Phasing:	Years 2–5
Estimated Cost:	$500 k–$1 M

A relationship clearly exists between concrete pavement surface texture and the noise generated by the tire-pavement interface. Furthermore, various concrete pavement properties, including absorptivity, stiffness, and density, affect tire-pavement noise levels. Currently, information about the relationships between tire-pavement noise and physical pavement characteristics is empirical at best. However, models must contain numerous levels of complexity, because tire characteristics are equally as important and complex. The research in this problem statement will identify and/or develop improved models to predict the tire-pavement noise for a variety of concrete pavement surfaces. The unified model should consider various types of directional texturing as well as more random textures that may result from advancements in texturing technology.

Tasks:

1. Synthesize the current models that relate concrete pavement texture and other properties to tire-pavement noise generation.
2. Based on the models synthesized, assess whether additional models need to be developed; develop new models as needed.
3. Validate the models using controlled experiments with tire-pavement noise measurements or pavement structures with known textures and physical characteristics.
4. Document the models to allow them to be integrated readily into related work that optimizes pavement texture to minimize the potential for excessive tire-pavement noise.

Benefits:	Models that predict tire-pavement noise as a function of its relationship to texture, materials characteristics, and other pavement features; a rational approach to predicting tire-pavement noise.
Products:	A sophisticated model for predicting tire-pavement noise as a function of concrete pavement texture and other physical properties.
Implementation:	This research will develop a model that supplements numerous tasks that require a better understanding of the relationship between texture, materials characteristics, and tire-pavement noise. For example, concrete mix design procedures that attempt to produce low-noise pavements will require this model.

SUBTRACK SC 4. OTHER CONCRETE PAVEMENT SURFACE CHARACTERISTICS

This subtrack focuses on issues related to other surface characteristics with respect to concrete pavements. Table 20 provides an overview of this subtrack.

Table 20. Subtrack SC 4 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 4.0. Framework for Other Concrete Pavement Surface Characteristics (Subtrack SC 4)	\$100 k–\$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 4.1. Splash and Spray Assessment Equipment	\$1 M–\$2 M	Effective and advanced splash and spray assessment equipment with specifications for its use.	Equipment that assesses the relationship between macrotexture and splash and spray, improving safe driving conditions.
SC 4.2. Rolling Resistance Assessment Equipment	\$1 M–\$2 M	Advanced and effective rolling resistance assessment equipment with standards and specifications for its use.	Equipment that directly measures rolling resistance and methods to reduce this resistance, which increases user costs through increased fuel consumption and vehicle wear.
SC 4.3. Reflectivity/ Illuminance Assessment Equipment	\$1 M–\$2 M	Advanced and effective reflectivity/ illuminance assessment equipment.	Equipment that assesses concrete pavement reflectivity/illuminance to optimize the level of reflectivity/illuminance; improved ride safety during daylight hours.
SC 4.4. Tire and Vehicle Wear Assessment Equipment	\$1 M–\$2 M	Advanced and effective tire and vehicle wear assessment equipment.	Equipment that directly assesses tire and vehicle wear; a better understood relationship between texture and tire and vehicle wear.

Problem Statement SC 4.0. Framework for Other Concrete Pavement Surface Characteristics (Subtrack SC 4)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 4. Other Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 1–3
Estimated Cost:	$100 k–$250 k

Subtrack SC 4 (Other Concrete Pavement Surface Characteristics) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 4 (Other Concrete Pavement Surface Characteristics), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack SC 4 (Other Concrete Pavement Surface Characteristics).

Problem Statement SC 4.1. Splash and Spray Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 4. Other Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 2–5
Estimated Cost:	$1 M–$2 M (including $100 k matching funds)

Tires rolling on a pavement with standing water commonly produce splash and spray, which occurs when the vehicle tires on the pavement surface attract water and eject it as small droplets into the air. The airborne water then can reduce visibility, particularly for vehicles traveling next to or closely behind other vehicles. Research suggests that 10 percent of wet weather accidents are caused by poor visibility due to splash and spray. While macrotexture is a primary contributor to splash and spray, little is known about the quantitative relationship between macrotexture and splash and spray. The research in this problem statement will develop effective splash and spray assessment equipment. This equipment will allow the relationship between surface texture and splash and spray to be better understood. Furthermore, this test procedure may be used to measure the effectiveness of a given pavement in meeting reasonable splash and spray limits, thus increasing safety.

Tasks:

1. Identify existing equipment or new equipment as needed to assess splash and spray. Relate this task to the macrotexture research being conducted under SC 1.1 (High-Speed 3D Macrotexture Assessment Equipment).
2. Develop meaningful and quantifiable relationships between macrotexture and splash and spray, if applicable.
3. Develop guidelines and specifications on the proper use of the equipment and the proper interpretation of the relationships between macrotexture and splash and spray.

Benefits:	Equipment that assess the relationship between macrotexture and splash and spray, improving safe driving conditions.
Products:	Effective and advanced splash and spray assessment equipment with specifications for its use.
Implementation:	The technology developed in this problem statement will be a key component in assessing splash and spray and improving safety.

Problem Statement SC 4.2. Rolling Resistance Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 4. Other Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 3–6
Estimated Cost:	\$1 M–\$2 M (including \$100 k matching funds)

Megatexture and concrete pavement roughness characteristics contribute to rolling resistance. Excessive rolling resistance can cause vehicles to work harder and thus increase user costs through increased fuel consumption and vehicle wear. The research in this problem statement will develop effective rolling resistance assessment equipment, allowing the effects of rolling resistance to be measured directly. This equipment also will improve understanding of the relationship between this surface characteristic, texture, and other physical concrete pavement properties.

Tasks:

1. Identify existing or new concepts for rolling resistance assessment equipment.
2. Analyze the equipment for accuracy, precision, and ease of use.
3. Identify the most effective equipment based on cost, technological maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
4. Develop meaningful and quantifiable relationships between megatexture/roughness and rolling resistance, if applicable.
5. Develop guidelines and specifications for properly using the equipment and properly interpreting relationships.

Benefits:	Equipment that directly measures rolling resistance and methods to reduce this resistance, which increases user costs through increased fuel consumption and vehicle wear.
Products:	Advanced and effective rolling resistance assessment equipment with standards and specifications for its use.
Implementation:	The technology developed in this problem statement will be a key component in assessing rolling resistance.

Problem Statement SC 4.3. Reflectivity/Illuminance Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 4. Other Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 3–6
Estimated Cost:	\$1 M–\$2 M (including \$100 k matching funds)

Different concrete pavement materials and textures can affect reflectivity/illuminance characteristics. Some reflectivity/illuminance can be beneficial (e.g., reflection that aids nighttime driving), but too much can be distracting (e.g., sunlight reflected during daylight hours, particularly at dawn or dusk). The research in this problem statement will develop effective reflectivity/illuminance assessment equipment. This equipment will allow optimum materials and textures to be selected to provide the ideal level of reflectivity/illuminance.

Tasks:

1. Identify available reflectivity/illuminance assessment equipment
2. Analyze the equipment for accuracy, precision, and ease of use.
3. Identify the most effective equipment based on cost, technological maturity, and the results of the above analyses, improving this equipment or developing new equipment as needed.
4. Develop standards and specifications to ensure the proper equipment use.

Benefits:	Equipment that assesses concrete pavement reflectivity/illuminance, allowing the level of reflectivity/illuminance to be optimized; improved ride safety during daylight hours.
Products:	Advanced and effective reflectivity/illuminance assessment equipment.
Implementation:	The technology developed in this problem statement will be a key component in assessing concrete pavement reflectivity/illuminance.

Problem Statement SC 4.4. Tire and Vehicle Wear Assessment Equipment

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 4. Other Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 5–8
Estimated Cost:	$1 M–$2 M (including $100 k matching funds)

Tire and vehicle wear relate directly to user costs. Microtexture is a primary factor that contributes to tire wear, while megatexture and roughness contribute to rolling resistance, which contributes to vehicle wear. The research in this problem statement will develop effective tire and vehicle wear assessment equipment. This equipment will improve understanding of the relationship between texture and vehicle and tire wear.

Tasks:

1. Identify effective microtexture and megatexture/roughness assessment equipment from problem statements SC 1.2 (In Situ 3D Microtexture Assessment Equipment), SC 1.3 (High-Speed 3D Microtexture Assessment Equipment), and SC 4.2 (Rolling Resistance Assessment Equipment).
2. Identify, refine, or develop as necessary equipment for assessing tire and vehicle wear.
3. Develop meaningful and quantifiable relationships between texture and tire and vehicle wear, if applicable.
4. Develop guidelines and specifications on the proper equipment use and the proper interpretation of the relationships.

Benefits:	Equipment that directly assesses tire and vehicle wear; a better understood relationship between texture and tire and vehicle wear.
Products:	Advanced and effective tire and vehicle wear assessment equipment.
Implementation:	The technology developed in this problem statement will be a key component in assessing tire and vehicle wear.

SUBTRACK SC 5. INTEGRATION OF CONCRETE PAVEMENT SURFACE CHARACTERISTICS

This subtrack focuses integrating the various surface characteristics for concrete pavements. Table 21 provides an overview of this subtrack.

Table 21. Subtrack SC 5 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 5.0. Framework for Integration of Concrete Pavement Surface Characteristics (Subtrack SC 5)	\$100 k–\$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 5.1. Comprehensive Concrete Pavement Surface Characteristics Field Study	\$500 k–\$1 M	A structured database and numerous supporting reports and case studies that define optimum concrete pavement surface characteristics and the methods for achieving them.	Concrete pavement surface characteristics guidance that supplements research in this and other tracks; improved understanding of optimum concrete pavement surface characteristics.
SC 5.2. Time Stability Evaluations of Concrete Pavement Surface Characteristics	\$500 k–\$1 M	Reports defining effective surfacing methods that provide durable surface characteristics.	Guidance that documents the longevity and durability of various concrete pavement surface characteristics; surfacing methods that result in more durable surface characteristics.
SC 5.3. Unified Model for Concrete Pavement Texture, Friction, Noise, and Smoothness	\$500 k–\$1 M	A model that unifies texture, friction, noise, smoothness, and other related variables.	Models that consider concrete pavement texture, friction, noise, smoothness, and other related variables to define optimal texture.
SC 5.4. PCC Pavement Mix Design System Integration Stage 4: Functionally Based Mix Design	\$500 k–\$1 M	A mix design system that accounts for the functional demands of the pavement surface layer.	Improved mix design techniques that will rationally meet pavement functional requirements, such as noise, ride quality, and texture.
SC 5.5. Relating Pavement Surface Characteristics to Vehicle Accidents	\$1 M–\$2 M	Reports detailing a methodical evaluation of vehicle accident risks as a function of the types and magnitudes of pavement surface characteristics.	Improved understanding of the relationship between pavement surface characteristics and vehicle accidents; improved methods for designing and constructing concrete pavements to minimize accident rates.

Problem Statement SC 5.0. Framework for Integration of Concrete Pavement Surface Characteristics (Subtrack SC 5)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 5. Integration of Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 1–3
Estimated Cost:	$100 k–$250 k

Subtrack SC 5 (Integration of Concrete Pavement Surface Characteristics) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 5 (Integration of Concrete Pavement Surface Characteristics), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the remaining problem statements in subtrack SC 5 (Integration of Concrete Pavement Surface Characteristics).

Problem Statement SC 5.1. Comprehensive Concrete Pavement Surface Characteristics Field Study

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 5. Integration of Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 2–3
Estimated Cost:	$500 k–$1 M (including $350 k matching funds)

Researching designs, construction records, and past performance reports often is not enough to understand the advantages or disadvantages of certain concrete surface pavement characteristics. Therefore, performing a field study is necessary. The research in this problem statement will perform a comprehensive field study of pavement surface characteristics to define the surface characteristics that maximize friction and smoothness while minimizing noise. Similarly, additional characteristics may be investigated as needed.

Tasks:

1. Identify the numerous variables to be included in the field study through a thorough synthesis and outreach effort. The controlled variables should be selected based on their known or anticipated sensitivity to the various surface characteristics being investigated. Develop a formal experimental plan for the field study.
2. Perform the field study or studies using the experimental plan. Measuring the surface characteristics should employ the latest techniques and technologies available. If standardized equipment has not been identified, numerous measurement devices should be included.
3. Reduce and analyze the data from the field study to define the variables affecting the measured characteristics and determine how the characteristics are affected. Shortcomings in the study also should be identified so that additional field studies address them.
4. Develop surface characteristics guidance that feeds into other tasks, such as problem statement SC 2.4 (Design and Construction Guidelines to Improve Concrete Pavement Smoothness), and can be used immediately to improve current practices.

Benefits:	Concrete pavement surface characteristics guidance that supplements research in this and other tracks; improved understanding of optimum concrete pavement surface characteristics.
Products:	A structured database and numerous supporting reports and case studies that define optimum concrete pavement surface characteristics and the methods for achieving them.
Implementation:	The data, reports, and case studies produced under this problem statement will advance the concrete paving industry toward the goal of achieving optimum concrete pavement surface characteristics.

Problem Statement SC 5.2. Time Stability Evaluations of Concrete Pavement Surface Characteristics

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 5. Integration of Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 4–10
Estimated Cost:	$500 k–$1 M (including $75 k matching funds)

Selecting texturing characteristics that maximize surface friction and smoothness while minimizing noise is undeniably important for optimizing concrete pavement performance. However, the longevity of these characteristics and the durability of the pavement itself also must be considered. The research in this problem statement will evaluate the time stability of certain pavement surface characteristics and the impacts that various surfacing methods might have on durability.

Tasks:

1. Identify existing and newly constructed pavements that possess a certain range of materials and surface characteristics. The pavements selected should include any constructed as part of the research conducted under SC 5.1 (Comprehensive Concrete Pavement Surface Characteristics Field Study). To the greatest extent possible, the selected pavements should cover a broad spectrum of climatic conditions and traffic levels.
2. Monitor the selected pavements over time, using carefully selected and thoroughly documented evaluation methods. The research minimally should evaluate measures of friction, smoothness, and tire-pavement noise. Additional surface characteristics should be included as necessary.
3. Periodically assess and publish findings and related guidance on the longevity of the studied surface characteristics, including pavement durability and performance.

Benefits:	Guidance that documents the longevity and durability of various concrete pavement surface characteristics; surfacing methods that result in more durable surface characteristics.
Products:	Reports defining effective surfacing methods that provide durable surface characteristics.
Implementation:	The reports written in this problem statement will advance the industry toward developing improved methods for designing and constructing more durable concrete pavement surfaces. This research will be coordinated closely with the experiments conducted under problem statement SC 5.1 (Comprehensive Concrete Pavement Surface Characteristics Field Study).

Problem Statement SC 5.3. Unified Model for Concrete Pavement Texture, Friction, Noise, and Smoothness

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 5. Integration of Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 5–9
Estimated Cost:	$500 k–$1 M (including $75 k matching funds)

Concrete pavement texture, friction, noise, and smoothness are all related and can therefore be related through modeling. Empirical evidence shows that certain types of texture that provide good friction will increase noise and decrease smoothness. Because ideal, as-built texture provides good friction while minimizing noise and maximizing smoothness, a more thorough understanding of the relationships between texture, friction, noise, and smoothness is necessary. The research in this problem statement will develop a comprehensive model that integrates texture, friction, noise, and smoothness to define optimal texture. This model should consider numerous other variables, including pavement materials properties and tire properties.

Tasks:

1. Synthesize and develop models of the relationships between texture, friction, noise, smoothness, and other important variables.
2. Evaluate these models using existing data sets and identify the need for additional data.
3. Release interim versions of the unified model as they become available so they can be used in other related research. The models should be developed so that peer review is accepted and integrated throughout the process.

Benefits:	Models that consider concrete pavement texture, friction, noise, smoothness, and other related variables to define optimal texture.
Products:	A model that unifies texture, friction, noise, smoothness, and other related variables.
Implementation:	This research will develop a model that will allow the industry to relate the complex nature of concrete pavement texture to the various pavement surface characteristics.

Problem Statement SC 5.4. PCC Pavement Mix Design System Integration Stage 4: Functionally Based Mix Design

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 5. Integration of Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 8–10
Estimated Cost:	$500 k–$1 M (including $500 k other funds)

Concrete pavement and materials engineering decisions often are driven by functional requirements established at the highest levels. These requirements commonly respond to a perceived public need, such as driver and abutter demands for quieter, smoother, and safer pavements. While concrete pavements can meet these functional demands, pavements must be designed appropriately to do so. The research in this problem statement will develop a concrete mix design system that will evaluate the effects of concrete materials and mixture on pavement functional requirements (i.e., noise, ride quality, and texture). With a better understanding of the relationships between concrete materials and mixtures and pavement functional requirements, improved mix design techniques can be developed to meet these functional requirements more rationally. These mix design procedures will allow innovative solutions such as two-lift pavements to be designed optimally for a given set of functional demands.

Tasks:

1. Assemble the requisite mix design models for the system.
2. Identify the requisite laboratory mix design test procedures and ensure standardized reporting for input to the mix design system.
3. Develop a beta version of the system and initiate peer review.
4. Develop a final version of the system and prepare it for training and implementation.

Benefits:	Improved mix design techniques that will rationally meet pavement functional requirements, such as noise, ride quality, and texture.
Products:	A mix design system that accounts for the functional demands of the pavement surface layer.
Implementation:	The research in this problem statement will develop a mix design system that sufficiently addresses the functional demands of the user. This research will be coordinated closely with problem statement MD 1.4 (PCC Pavement Mix Design System Integration Stage 4: Functionally Based Mix Design).

Problem Statement SC 5.5. Relating Pavement Surface Characteristics to Vehicle Accidents

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 5. Integration of Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 3–7
Estimated Cost:	\$1 M–\$2 M

Because safety is important, the highway community must design and build roads that minimize the acceptable risks of vehicular accidents. Pavement surface characteristics, including texture, friction, splash and spray, and illuminance and reflectivity, can impact accident potential. However, little is known about the relationship between pavement surface characteristics and the increased accident rate. Because numerous variables impact the overall accident rate, quantifying the accident risks from any single factor is difficult. Compounding this difficulty, moreover, are the potential liability issues involved with studies of this nature. This research, therefore, must reasonably ensure that its results will not damage the highway industry. The research in this problem statement should methodically evaluate numerous existing concrete pavements, assessing the relevant pavement surface characteristics and collecting accident rate statistics categorized by the likely contributors to the accidents.

Tasks:

1. Investigate the exposure to liability that the results of the research might incur, and take measures to formulate and execute the research so that this exposure is mitigated.
2. Identify the pavement surface characteristics most likely to contribute to vehicle accidents, and prioritize these characteristics for subsequent consideration in this research.
3. Develop an experimental plan that includes evaluating concrete pavements nationwide, collecting data on pavement surface characteristics and accident rates. The experimental plan must be statistically sound so the results are not biased and enough data is collected to make reliable conclusions.
4. Execute the experimental plan and report the findings.

Benefits:	Improved understanding of the relationship between pavement surface characteristics and vehicle accidents; improved methods for designing and constructing concrete pavements to minimize accident rates.
Products:	Reports detailing a methodical evaluation of vehicle accident risks as a function of the types and magnitudes of pavement surface characteristics.
Implementation:	The results of this research will help prioritize the measures needed to improve design and construction practices. Furthermore, optimizing concrete pavement surfaces requires that the risks of accidents derived in this optimization effort be understood.

SUBTRACK SC 6. EVALUATION OF PRODUCTS FOR CONCRETE PAVEMENT SURFACE CHARACTERISTICS

This subtrack includes an evaluation of various concrete paving solutions in improving surface characteristics. Table 22 provides an overview of this subtrack.

Table 22. Subtrack SC 6 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 6.0. Framework for Evaluation of Products for Concrete Pavement Surface Characteristics (Subtrack SC 6)	\$100 k–\$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 6.1. Porous Concrete and Related Issues	\$1 M–\$2 M	Guidelines and specifications for the design and construction of porous concrete surfaces.	Effective methods that will lead to the design, construction, and maintenance of high-quality, porous concrete pavement surfaces.
SC 6.2. Exposed Aggregate in Two-Course Paving	\$250 k–\$500 k	Guidelines and specifications for designing and constructing exposed aggregate concrete pavement surfaces.	Effective methods for designing and constructing exposed aggregate concrete pavement surfaces; exposed aggregate concrete pavement surfaces with low noise, excellent high-speed skidding resistance, good surface durability, and low splash and spray.
SC 6.3. Engineered/ Optimized Wet Concrete Texturing	\$1 M–\$2 M	Guidelines and specifications for designing and constructing conventionally textured concrete pavement surfaces.	Optimized conventional methods for texturing concrete pavement surfaces, maximizing surface friction while minimizing tire-pavement noise.
SC 6.4. Engineered/ Optimized Hardened Concrete Grinding and Grooving	\$1 M–\$2 M	Guidelines and specifications for designing, constructing, and grinding concrete pavement surfaces.	Effective grinding and grooving methods that maximize surface friction while minimizing tire-pavement noise, improving macrotexture and microtexture.
SC 6.5. Precast Pavement Surfaces	\$250 k–\$500 k	Guidelines and specifications for designing and constructing precast concrete pavement solutions.	Methods for designing and constructing precast concrete pavement surfaces with optimum surface characteristics; optimized surface characteristics that are constructed as designed, with minimized variations due to construction conditions.

Problem Statement SC 6.0. Framework for Evaluation of Products for Concrete Pavement Surface Characteristics (Subtrack SC 6)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 1–3
Estimated Cost:	\$100 k–\$250 k

Subtrack SC 6 (Evaluation of Products for Concrete Pavement Surface Characteristics) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 6 (Evaluation of Products for Concrete Pavement Surface Characteristics), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack SC 6 (Evaluation of Products for Concrete Pavement Surface Characteristics).

Problem Statement SC 6.1. Porous Concrete and Related Issues

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 2–6
Estimated Cost:	$1 M–$2 M (including $250 k matching funds)

Porous concrete pavement has demonstrated an ability to provide surface characteristics similar to those associated with open-graded (porous) asphalt pavements. However, the porous concrete pavement only performs well if the surface is well maintained. As with porous asphalt surfaces, the porous concrete pavement surface must be cleaned regularly to prevent debris from clogging the pores that give the surface its beneficial drainage and acoustic properties. Additionally, initial experiences with porous concrete pavement in Belgium showed poor durability in freezing weather; however, these mixtures since have been made more durable by adding polymers and other cement contents. The research in this problem statement will further develop effective methods for designing and constructing porous concrete surfaces.

Tasks:

1. Identify cases in which porous concrete was used and study how it performed in terms of tire-pavement noise, durability, and other engineering properties.
2. Assess how the porous concrete pavement sections studied were designed and built, identifying relationships between design, construction, and performance.
3. Design and build test sections based on the results of previous studies. Thoroughly evaluate the initial and long-term material, structural, and acoustic performance of the test pavements.
4. Change the design and construction practices as necessary.
5. Develop final guidelines and specifications to ensure proper design and construction of porous concrete pavement surfaces.

Benefits:	Effective methods that will lead to the design, construction, and maintenance of high-quality, porous concrete pavement surfaces.
Products:	Guidelines and specifications for the design and construction of porous concrete surfaces.
Implementation:	The guidelines and specifications developed in this problem statement will improve design and construction of porous concrete pavement surfaces.

Problem Statement SC 6.2. Exposed Aggregate in Two-Course Paving

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 5–9
Estimated Cost:	$250 k–$500 k (including $100 k matching funds)

Though widely used in European countries, the exposed aggregate technique has not been used widely in the United States. One reason for this is that an experimental U.S. project on Interstate (I)–75 in Detroit, MI, did not show the improved surface friction and tire-pavement noise that had been expected. However, the European experience with the exposed aggregate technique illustrates that, when properly designed and constructed, exposed aggregate surfaces perform very well. Characteristics improved in exposed aggregate pavements include low noise, excellent high-speed skidding resistance, good surface durability, and low splash and spray. The research in this problem statement will further develop effective methods for designing and constructing exposed aggregate concrete pavement surfaces.

Tasks:

1. Identify cases where exposed aggregate surfaces have been used and study their performance in terms of tire-pavement noise, durability, and other engineering properties.
2. Assess the design and construction methods for these cases, identifying relationships between these design and construction and performance.
3. Design and build test sections based on the results of previous studies. Thoroughly evaluate the initial and long-term material, structural, and acoustic performance.
4. Change design and construction practices as necessary.
5. Develop final guidelines and specifications to ensure proper design and construction of exposed aggregate concrete pavement surfaces.

Benefits:	Effective methods for designing and constructing exposed aggregate concrete pavement surfaces; exposed aggregate concrete pavement surfaces with low noise, excellent high-speed skidding resistance, good surface durability, and low splash and spray.
Products:	Guidelines and specifications for designing and constructing exposed aggregate concrete pavement surfaces.
Implementation:	The guidelines and specifications developed in this problem statement will improve the design and construction of exposed aggregate concrete pavement surfaces. This research will be coordinated closely with problem statement EA 2.4 (Two-Course Concrete Paving).

Problem Statement SC 6.3. Engineered/Optimized Wet Concrete Texturing

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 2–6
Estimated Cost:	$1 M–$2 M

The importance of concrete pavement surface texture characteristics for roadway safety has been recognized since the late 1940s, when increases in traffic volumes and vehicle speeds resulted in increased wet weather accidents and fatalities. Often, appropriate microtexture is sufficient to provide adequate stopping on a PCC pavement when vehicles are traveling slower than 80 kilometers per hour (km/h) (50 miles per hour (mi/h)). However, when higher vehicle speeds are expected, improved microtexture and macrotexture is necessary to provide adequate wet-pavement friction. While increasing macrotexture reduces splash and spray, rougher macrotexture also increases tire-pavement noise. Similarly, increasing microtexture increases tire wear, although often insignificantly. The research in this problem statement will refine the conventional texturing methods frequently used today, including tining and drag methods used on fresh concrete pavement surfaces. These texturing methods will be engineered to maximize surface friction and minimize tire-pavement noise.

Tasks:

1. Identify cases that have evaluated numerous conventional texturing methods side by side with minimal variation in other parameters. Study the ways these various textures performed in terms of tire-pavement noise, durability, and other engineering properties.
2. Assess the design and construction for the sections studied, identifying relationships between design and construction and performance.
3. Design and build additional test sections based on the results of previous studies. Thoroughly evaluate the initial and long-term material, structural, and acoustic performance.
4. Change design and construction practices as necessary.
5. Develop final guidelines and specifications to ensure proper design and construction of conventionally textured concrete pavement surfaces.

Benefits:	Optimized conventional methods for texturing concrete pavement surfaces, maximizing surface friction while minimizing tire-pavement noise.
Products:	Guidelines and specifications for designing and constructing conventionally textured concrete pavement surfaces.
Implementation:	The guidelines and specifications developed in this problem statement will improve the design and construction of conventionally textured concrete pavement surfaces.

Problem Statement SC 6.4. Engineered/Optimized Hardened Concrete Grinding and Grooving

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 2–6
Estimated Cost:	\$1 M–\$2 M (including \$200 k matching funds)

Grinding both newly placed and existing concrete pavements effectively improves surface friction and smoothness while decreasing tire-pavement noise. Grinding improves pavement frictional characteristics by exposing microtexture and creating macrotexture. Additionally, grinding increases lateral control for vehicles, especially on transitions and superelevated curve sections. The research in this problem statement will develop effective grinding and grooving methods that will maximize surface friction and minimize tire-pavement noise.

Tasks:

1. Identify cases that evaluated numerous grinding or grooving methods side by side with minimal variation in other parameters. Study ways in which these various textures performed in terms of tire-pavement noise, durability, and other engineering properties.
2. Assess the design, construction, and subsequent texturing for these test sections, identifying relationships between design, construction, texturing, and performance.
3. Design, build, and texture additional test sections based on the results of the previous studies. Thoroughly evaluate the initial and long-term material, structural, and acoustic performance.
4. Change the design, construction, or grinding practices as necessary.
5. Develop final guidelines and specifications to ensure proper design, construction, and grinding of concrete pavement surfaces.

Benefits:	Effective grinding and grooving methods that maximize surface friction while minimizing tire-pavement noise, improving macrotexture and microtexture.
Products:	Guidelines and specifications for designing, constructing, and grinding concrete pavement surfaces.
Implementation:	The guidelines and specifications developed in this problem statement will improve the design, construction, and grinding of concrete pavement surfaces.

Problem Statement SC 6.5. Precast Pavement Surfaces

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 6. Evaluation of Products for Concrete Pavement Surface Characteristics
Approximate Phasing:	Years 6–10
Estimated Cost:	$250 k–$500 k (including $50 k matching funds)

Concrete pavements designed with optimized surface characteristics may not be constructed as designed due to many factors, including contractor inexperience or environmental conditions during construction. Using precast concrete pavement surfaces will minimize these construction variables because construction processes can be more controlled. The research in this problem statement will develop guidelines and specifications for designing and constructing precast concrete pavement surfaces with optimum surface characteristics. Precast surfaces with innovative features, such as Helmholtz resonators, have already been implemented in Europe; these precast surface technologies also should be attempted in the United States.

Tasks:

1. Identify cases in which precast concrete pavements have been used to mitigate noise and study these pavements' performance in terms of tire-pavement noise, durability, and other engineering properties.
2. Assess the design and construction of these test sections, identifying relationships between design and construction and pavement performance.
3. Design and build test sections based on the results of previous studies. Thoroughly evaluate the initial and long-term material, structural, and acoustic performance.
4. Change design and construction practices as necessary.
5. Develop final guidelines and specifications to ensure proper design and construction of precast concrete pavements.

Benefits:	Methods for designing and constructing precast concrete pavement surfaces with optimum surface characteristics; optimized surface characteristics that are constructed as designed, with minimized variations due to construction conditions.
Products:	Guidelines and specifications for designing and constructing precast concrete pavement solutions.
Implementation:	The guidelines and specifications developed in this problem statement will improve the design and construction of precast concrete pavements. This research will be coordinated closely with problem statement RC 2.5 (Precast Quiet Pavement Surfaces).

SUBTRACK SC 7. CONCRETE PAVEMENT SURFACE CHARACTERISTICS IMPLEMENTATION

This subtrack includes implementation activities related to concrete pavement surface characteristics. Table 23 provides an overview of this subtrack.

Table 23. Subtrack SC 7 overview.

Problem Statement	Estimated Cost	Products	Benefits
SC 7.0. Framework for Concrete Pavement Surface Characteristics Implementation (Subtrack SC 7)	$100 k–$250 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
SC 7.1. Workshops on Products to Improve Concrete Pavement Surface Characteristics	$1 M–$2 M	Workshops and conferences on products for improving concrete pavement surface characteristics.	Technology transfer opportunities for products that improve concrete pavement surface characteristics.
SC 7.2. Workshops on Measurement of Concrete Pavement Surface Characteristics	$1 M–$2 M	Workshops and conferences on methods and equipment for measuring concrete pavement surface characteristics.	Technology transfer opportunities for methods and equipment that measure concrete pavement surface characteristics.
SC 7.3. Web-Based Training for Implementation of Research Products for Concrete Pavement Surface Characteristics	$500 k–$1 M	A Web site that hosts Web-based modules that train contractors, designers, and owner-agencies in software and equipment on concrete pavement surface characteristics.	Web-based training modules that allow contractors, designers, and owner-agencies to access recent research on concrete pavement surface characteristics; technology transfer accessible from any computer with Internet access.

Problem Statement SC 7.0. Framework for Concrete Pavement Surface Characteristics Implementation (Subtrack SC 7)

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 7. Concrete Pavement Surface Characteristics Implementation
Approximate Phasing:	Years 1–3
Estimated Cost:	$100 k–$250 k

Subtrack SC 7 (Concrete Pavement Surface Characteristics Implementation) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack SC 7 (Concrete Pavement Surface Characteristics Implementation), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack SC 7 (Concrete Pavement Surface Characteristics Implementation).

Problem Statement SC 7.1. Workshops on Products to Improve Concrete Pavement Surface Characteristics

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 7. Concrete Pavement Surface Characteristics Implementation
Approximate Phasing:	Years 4–10
Estimated Cost:	$1 M–$2 M

While new products for improving concrete pavement surface characteristics constantly are being developed, transportation agencies often are slow to adopt them because they are unfamiliar with the new technologies and lack research resources. Workshops provide an ideal environment for familiarizing and training agencies in new products for improving concrete pavement surface characteristics. The workshops developed will provide technology transfer opportunities for products that improve concrete pavement surface characteristics.

Tasks:

1. Identify States and industry representatives willing to host workshops and conferences devoted to products for improving concrete pavement surface characteristics.
2. Assemble pertinent information on the new concrete pavement surface characteristics products to be discussed at the workshops.
3. Conduct workshops and conferences, presenting information on these products and providing hands-on training.

Benefits:	Technology transfer opportunities for products that improve concrete pavement surface characteristics.
Products:	Workshops and conferences on products for improving concrete pavement surface characteristics.
Implementation:	This problem statement will result in numerous workshops and conferences on products for improving concrete pavement surface characteristics at various venues throughout the United States, advancing concrete pavement surface design, construction, and evaluation.

Problem Statement SC 7.2. Workshops on Measurement of Concrete Pavement Surface Characteristics

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 7. Concrete Pavement Surface Characteristics Implementation
Approximate Phasing:	Years 2–10
Estimated Cost:	$1 M–$2 M

While new methods and equipment for measuring concrete pavement surface characteristics constantly are being developed, transportation agencies are often slow to adopt them because they are unfamiliar with these new technologies and lack research resources. Workshops provide an ideal environment for familiarizing and training agencies in new methods and equipment for measuring concrete pavement surface characteristics. The workshops developed will provide technology transfer of methods and equipment for measuring concrete pavement surface characteristics.

Tasks:

1. Identify States or industry representatives willing to host workshops and conferences on methods and equipment for measuring concrete pavement surface characteristics.
2. Assemble pertinent information on these measurement techniques and equipment.
3. Conduct workshops and conferences, presenting information and hands-on training for these measurement methods and equipment.

Benefits:	Technology transfer opportunities for methods and equipment that measure concrete pavement surface characteristics.
Products:	Workshops and conferences on methods and equipment for measuring concrete pavement surface characteristics.
Implementation:	This problem statement will result in numerous workshops and conferences on methods and equipment for measuring concrete pavement surface characteristics, advancing concrete pavement surface design, construction, and evaluation.

Problem Statement SC 7.3. Web-Based Training for Implementing Research Products for Concrete Pavement Surface Characteristics

Track:	4. Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements (SC)
Subtrack:	SC 7. Concrete Pavement Surface Characteristics Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	\$500 k–\$1 M

Although every year many new research products and technologies are developed and ready for implementation, transportation agencies often implement and use the new research inadequately. Workshops offer contractors and owner-agencies the opportunity to learn about new research products and technologies, but often agencies cannot afford to send employees to workshops or may be restricted from traveling to a workshop outside the home State. Fortunately, with Web-based training, contractors, designers, and owner-agencies can explore new research products and technologies from any computer with Internet access. On-demand Web-based training can include case studies, online software applications, documentation, and other resources to make recent research on concrete pavement surface characteristics accessible to the concrete paving community.

Tasks:

1. Compile information on new equipment, procedures, and applicable software related to concrete pavement surface characteristics, including thorough documentation, case studies, downloadable software applications, photos, and video, as needed.
2. Develop Web-based training modules that train contractors, designers, and owner-agencies on the concrete pavement surface characteristics software and equipment.
3. Develop a Web site allowing contractors, designers, and owner-agencies to access the training modules. Maintain the Web site with updates on new research products or refinements to existing products.

Benefits:	Web-based training modules that allow contractors, designers, and owner-agencies to access recent research on concrete pavement surface characteristics; technology transfer accessible from any computer with Internet access.
Products:	A Web site that hosts Web-based modules that train contractors, designers, and owner-agencies in software and equipment on concrete pavement surface characteristics.
Implementation:	The Web-based training modules developed in this problem statement will allow widely accessible technology transfer to implement new research products for concrete pavement surface characteristics.

Track 5. Concrete Pavement Equipment Automation and Advancements (EA)

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TRACK 5 (EA) OVERVIEW

The problem statements in this track propose process improvements and equipment developments for high-speed, high-quality concrete paving equipment. Research on technologies like those listed below are needed to meet the concrete paving industry's projected needs and the traveling public's expectations for highway performance in the future:

- Next generation of concrete batching equipment.
- Next generation of concrete placement equipment that addresses new construction processes.
- Behind-the-paver equipment to improve quality, speed, and cost-effectiveness.
- Mechanized ways to place and control subdrains and other foundation elements.
- Next generation of equipment that will integrate the removal/replacement of the slab in one-pass construction.
- Improved repair processes that decrease the time of operations and provide the workforce and traveling public with less exposure.
- Methods for evaluating the new equipment on actual constructions projects.

Efforts in the area of equipment automation and advancements will require collaborative partnerships between equipment manufacturers, contractors, and State highway agencies. After equipment concepts have been established, it is hoped that contractors and industry will be willing to invest in developing new equipment. Involving contractors and industry from the start is essential for ensuring the equipment is practical for actual implementation. This private funding will also help introduce the new equipment into everyday practice much faster than if development and implementation costs were solely carried by the government.

Stringless, global positioning system (GPS) control of slipform paving equipment is just one example of many pioneering technologies that, if further developed and tested, could increase efficiency, lower costs, and increase performance for the concrete paving industry.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, then follow.

Track Goal

Concrete paving process improvements and equipment advancements will expedite and automate PCC pavement rehabilitation and construction, resulting in high-quality concrete pavements, reduced waste, and safer working environments.

Track Objectives

1. Develop batching equipment that will produce better quality concrete mixes by optimizing the materials used and allowing rapid adjustment of mix proportions.
2. Improve paving techniques and equipment to produce higher quality concrete pavements, while optimizing material use and reducing construction time and processes.
3. Improve techniques for curing, texturing, and jointing concrete pavements, while allowing pavements to be opened to traffic more quickly.
4. Improve equipment and techniques for expedited subbase stabilization and subdrain installation.

5. Develop equipment for rapid in place reconstruction of concrete pavements using existing/recycled materials.
6. Improve and automate techniques and equipment for rapid CPR.
7. Introduce contractors and owner-agencies to new advanced equipment and help them purchase such equipment.

Research Gaps

- Lack of formal partnering that justifies equipment development economics.
- Lack of framework and justification for automation technology.
- Lack of incentives to develop innovative and durable equipment.
- Lack of automated material/concrete property characterization.
- Lack of knowledge about advancing higher order use of recycled concrete materials.
- Lack of a continuing working relationship among equipment manufacturers, contractors, and State highway agencies.

Research Challenges

- Develop advanced automated equipment that contractors and owner-agencies can afford to invest in and bring the equipment industry and the State highway agencies together to work strategically in a cost-sharing atmosphere.
- Develop equipment that will automate construction processes but still allow human intervention to make necessary adjustments and to assure that the workforce is trained effectively.
- Develop equipment and techniques that are practical to use and durable under construction conditions and establish performance specifications that allow the use of innovative equipment.
- Identify the effect of material properties (e.g., aggregate shape and texture) and concrete properties (e.g., rheology) on pavement performance and determine how these properties can be identified using automated equipment.
- Determine the usability of recycled materials in light of long-term pavement performance, learn how to properly crush and grade the recycled material, and find innovative uses for the fines.
- Establish long-term relationships that jointly define the potential equipment advancement market and determine ways to breakdown evaluation processes at State borders.

Research Track 5 (EA) Phasing

The horizontal bar chart in figure 5 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

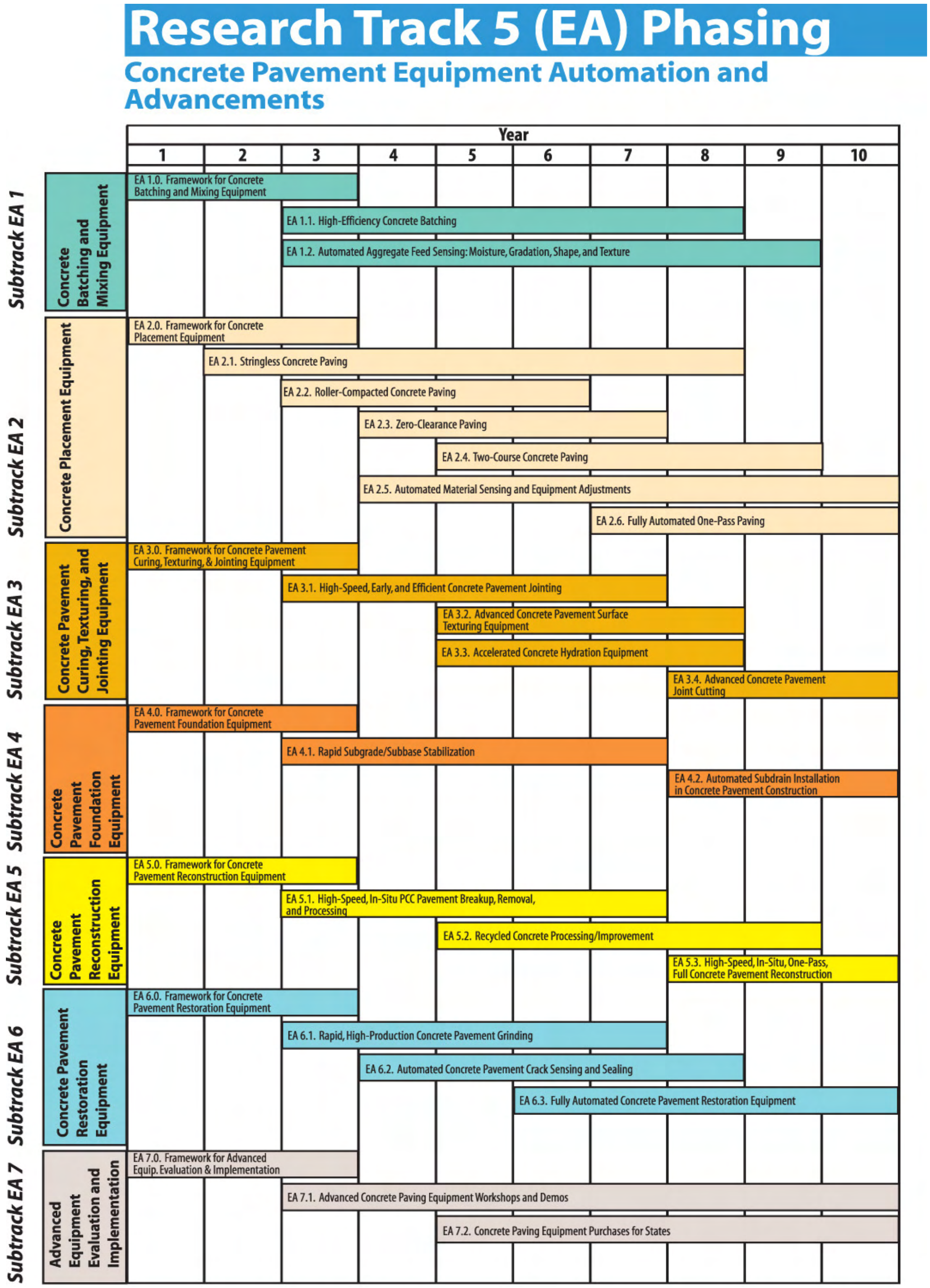

Figure 5. Track 5 (EA) subtrack and problem statement phasing chart.

Research Track 5 (EA) Estimated Costs

Table 24 shows the estimated costs for this research track.

Table 24. Research track 5 (EA) estimated costs.

Problem Statement	Estimated Cost
Subtrack EA 1. Concrete Batching and Mixing Equipment	
EA 1.0. Framework for Concrete Batching and Mixing Equipment (Subtrack EA 1)	$150 k
EA 1.1. High-Efficiency Concrete Batching	$250 k–$500 k
EA 1.2. Automated Aggregate Feed Sensing: Moisture, Gradation, Shape, and Texture	$500 k–$1 M
Subtrack EA 2. Concrete Placement Equipment	
EA 2.0. Framework for Concrete Placement Equipment (Subtrack EA 2)	$200 k
EA 2.1. Stringless Concrete Paving	$1 M-$2 M
EA 2.2. Roller-Compacted Concrete Paving	$250 k–$500 k
EA 2.3. Zero-Clearance Paving	$500 k–$1 M
EA 2.4. Two-Course Concrete Paving	$1 M–$2 M
EA 2.5. Automated Material Sensing and Equipment Adjustments	$2 M–$5 M
EA 2.6. Fully Automated One-Pass Paving	$2 M–$5 M
Subtrack EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment	
EA 3.0. Framework for Concrete Pavement Curing, Texturing, and Jointing Equipment (Subtrack EA 3)	$150 k
EA 3.1. High-Speed, Early, and Efficient Concrete Pavement Jointing	$1 M–$2 M
EA 3.2. Advanced Concrete Pavement Surface Texturing Equipment	$1 M–$2 M
EA 3.3. Accelerated Concrete Hydration Equipment	$1 M–$2 M
EA 3.4. Advanced Concrete Pavement Joint Forming	$500 k–$1 M
Subtrack EA 4. Concrete Pavement Foundation Equipment	
EA 4.0. Framework for Concrete Pavement Foundation Equipment (Subtrack EA 4)	$150 k
EA 4.1. Rapid Subgrade/Subbase Stabilization	$1 M–$2 M
EA 4.2. Automated Subdrain Installation in Concrete Pavement Construction	$1 M–$2 M
Subtrack EA 5. Concrete Pavement Reconstruction Equipment	
EA 5.0. Framework for Concrete Pavement Reconstruction Equipment (Subtrack EA 5)	$200 k
EA 5.1. High-Speed, In Situ PCC Pavement Breakup, Removal, and Processing	$2 M–$5 M
EA 5.2. Recycled Concrete Processing/Improvement	$1 M–$2 M
EA 5.3. High-Speed, In Situ, One-Pass, Full Concrete Pavement Reconstruction	$2 M–$5 M
Subtrack EA 6. Concrete Pavement Restoration Equipment	
EA 6.0. Framework for Concrete Pavement Restoration Equipment (Subtrack EA 6)	$150 k
EA 6.1. Rapid, High-Production Concrete Pavement Grinding	$1 M–$2 M
EA 6.2. Automated Concrete Pavement Crack Sensing and Sealing	$500 k–$1 M
EA 6.3. Fully Automated Concrete Pavement Restoration Equipment	$1 M–$2 M
Subtrack EA 7. Advanced Equipment Evaluation and Implementation	
EA 7.0. Framework for Advanced Equipment Evaluation and Implementation (Subtrack EA 7)	$150 k
EA 7.1. Advanced Concrete Paving Equipment Workshops and Demonstrations	$2 M–$5 M
EA 7.2. Concrete Paving Equipment Purchases for States	$2 M–$5 M
Track 5 (EA)	
Total	$25.65 M–$56.15 M

Track Organization: Subtracks and Problem Statements

Track 5 (EA) problem statements are grouped into seven subtracks:

- Subtrack EA 1. Concrete Batching and Mixing Equipment.
- Subtrack EA 2. Concrete Placement Equipment.
- Subtrack EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment.
- Subtrack EA 4. Concrete Pavement Foundation Equipment.
- Subtrack EA 5. Concrete Pavement Reconstruction Equipment.
- Subtrack EA 6. Concrete Pavement Restoration Equipment.
- Subtrack EA 7. Advanced Equipment Evaluation and Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK EA 1. CONCRETE BATCHING AND MIXING EQUIPMENT

This subtrack focuses on the batch plant operation, looking for joint ventures with industry to design the next generation of batching equipment. Table 25 provides an overview of this subtrack.

Table 25. Subtrack EA 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 1.0. Framework for Concrete Batching and Mixing Equipment (Subtrack EA 1)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 1.1. High-Efficiency Concrete Batching	$250 k–$500 k	More efficient batching techniques and equipment.	More efficient batching techniques and equipment that use materials better, produce higher quality concrete mixes, and allow for automatic adjustments to concrete mixes.
EA 1.2. Automated Aggregate Feed Sensing: Moisture, Gradation, Shape, and Texture	$500 k–$1 M	Automated, high-speed aggregate property classification techniques and equipment.	Automated aggregate classification, allowing concrete mixes to be fine-tuned automatically based on the aggregate properties and allowing immediate approval or rejection of a given material, resulting in higher quality concrete mixes.

Problem Statement EA 1.0. Framework for Concrete Batching and Mixing Equipment (Subtrack EA 1)

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 1. Concrete Batching and Mixing Equipment
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack EA 1 (Concrete Batching and Mixing Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 1 (Concrete Batching and Mixing Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 1 (Concrete Batching and Mixing Equipment).

Problem Statement EA 1.1. High-Efficiency Concrete Batching

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 1. Concrete Batching and Mixing Equipment
Approximate Phasing:	Years 3–8
Estimated Cost:	$250 k–$500 k

Concrete pavement mixes are evolving continually, becoming more complex as new admixtures are added to produce a better product. More complex mixes require greater attention to mix batching to ensure that proper equipment is being used and that the mixer is charged with the right proportion of each material at the proper time. For example, with newer, more complex mixes, the rheological mix properties must meet the specified requirements for the particular application (slipform paving, fixed-form paving), because rheological properties can affect significantly the efficiency of the paving operation and the quality of the finished product. More efficient batching processes that also can be adjusted automatically are needed. For example, a passing cold front during a paving operation may prompt the contractor to reduce the amount of fly ash in the mix to account for the changing climatic conditions. New, efficient batching processes will allow this type of adjustment without delaying delivery of the fresh concrete. In addition, alternative batching techniques, such as on-grade ultrasonic concrete mixers that mix the concrete at the paving operation rather than at a central batch plant to improve paving efficiency, need to be examined.

Tasks:

1. Identify the most commonly used batching operations for concrete paving projects.
2. Identify current batching operation limitations based on contractor and owner-agency experience.
3. Work with contractors and industry (batch plant manufacturers, paving machine manufacturers) to modify or develop existing or new batching equipment that will permit automatic adjustments.
4. Identify alternative batching techniques (such as on-grade ultrasonic mixers) that could improve paving efficiency and quality.
5. Recommend new batching equipment or modifications to existing equipment as well as alternative batching techniques.

Benefits:	More efficient batching techniques and equipment that use materials better, produce higher quality concrete mixes, and allow for automatic adjustments to concrete mixes.
Products:	More efficient batching techniques and equipment.
Implementation:	This research will recommend new batching equipment or modifications to existing equipment as well as alternative batching techniques.

Problem Statement EA 1.2. Automated Aggregate Feed Sensing: Moisture, Gradation, Shape, and Texture

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 1. Concrete Batching and Mixing Equipment
Approximate Phasing:	Years 3–9
Estimated Cost:	\$500 k–\$1 M

Aggregate properties, such as shape, texture, moisture content, and gradation, significantly influence the packing and bonding characteristics of coarse aggregates as well as the rheological properties of concrete mixes. For example, elongated and flaky aggregates do not pack together in a concrete mix as well as rounded aggregates. Smooth, rounded aggregates do not bond as strongly as crushed aggregates with jagged, fractured faces. Well-graded aggregates tend to produce more workable mixes with better durability. Aggregates with a higher moisture content than predicted produce a mix with a lower water-cement ratio, which can weaken hardened concrete and reduce its durability.

These examples suggest that better understanding the aggregate properties is important for paving operations and pavement performance. Digital imaging processing techniques have been developed for aggregate sample scanning and shape and texture analysis. However, current technology is time-consuming and expensive, and the equipment may not be suited for use at a batch plant or quarry. Therefore, research that improves imaging equipment efficiency or develops new technology is needed so that a large sample of aggregate can be scanned and analyzed quickly. Sieve analyses and moisture content measurements accurately depict aggregate gradation and moisture content, respectively, but both can be time-consuming and represent a small sample of the aggregate used for a given project. Techniques that can quickly determine the gradation and moisture content of a much larger aggregate sample could benefit concrete paving projects. New technologies such as these will help contractors and owner-agencies quickly determine the suitability of a given aggregate. The aggregate then can be either rejected or reprocessed (i.e., crushed) or the pay factor adjusted before the aggregate is used in a concrete mix.

Tasks:

1. Identify aggregate properties (shape, texture, moisture content, gradation) that affect concrete mix properties and pavement performance.
2. Identify existing techniques for determining aggregate shape, texture, gradation, and moisture content and the advantages and disadvantages of each.
3. Modify or develop new or existing equipment to scan large aggregate samples rapidly.
4. Conduct field trials or case studies with existing (modified) or new equipment.

Benefits:	Automated aggregate classification, allowing concrete mixes to be automatically fine-tuned based on the aggregate properties and allowing immediate approval or rejection of a given material, resulting in higher quality concrete mixes.
Products:	Automated, high-speed aggregate property classification techniques and equipment.
Implementation:	This research will result in new equipment for faster classification of aggregate properties in the field.

SUBTRACK EA 2. CONCRETE PLACEMENT EQUIPMENT

This subtrack focuses on the placement equipment, looking for joint ventures with industry to design the next generation of batching equipment. It also addresses new construction processes that depend on equipment. Table 26 provides an overview of this subtrack.

Table 26. Subtrack EA 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 2.0. Framework for Concrete Placement Equipment (Subtrack EA 2)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 2.1. Stringless Concrete Paving	$1 M-$2 M	Stringless concrete paving technology and equipment.	Stringless paving technology that will eliminate common pavement smoothness issues, such as chord effects, sag effects, and random survey effects, and improve paving efficiency.
EA 2.2. Roller-Compacted Concrete Paving	$250 k–$500 k	Guidelines and recommendations for using roller-compacted concrete (RCC) in highway pavements.	Guidelines and recommendations that can help construct durable, high-strength RCC pavements, possibly beginning with pilot projects and eventually progressing toward urban highway pavements.
EA 2.3. Zero-Clearance Paving	$500 k–$1 M	Advancements in zero- or minimum-clearance paving equipment.	Zero- or minimum-clearance paving machines that will enhance the flexibility of PCC paving, permitting slipform paving next to fixed barriers and eliminating the need for widening the paver tracks.
EA 2.4. Two-Course Concrete Paving	$1 M–$2 M	Guidelines and recommendations for two-course paving construction procedures.	Guidelines and recommendations that can be used for constructing two-course concrete pavements, beginning with pilot projects and progressing to urban highway pavements.
EA 2.5. Automated Material Sensing and Equipment Adjustments	$2 M–$5 M	Fully automated, material sensing concrete paving equipment.	Material sensing paving equipment that will detect changes in concrete rheological properties as it is fed into the paver and automatically adjust paver speed, vibration, and extrusion pressure, resulting in better quality concrete pavement.
EA 2.6. Fully Automated One-Pass Paving	$2 M–$5 M	One-pass concrete paving equipment.	One-pass paving equipment that will perform all processes in a single pass, including concrete placement, finishing, texturing, curing, and jointing, making adjustments automatically and resulting in a very efficient paving operation.

Problem Statement EA 2.0. Framework for Concrete Placement Equipment (Subtrack EA 2)

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 2. Concrete Placement Equipment
Approximate Phasing: Years 1–3
Estimated Cost: $200 k

Subtrack EA 2 (Concrete Placement Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 2 (Concrete Placement Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.
Products: A validated, sequenced, and detailed research framework for this subtrack.
Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 2 (Concrete Placement Equipment).

Problem Statement EA 2.1. Stringless Concrete Paving

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 2. Concrete Placement Equipment
Approximate Phasing: Years 2–8
Estimated Cost: $1 M–$2 M

Modern concrete paving construction conventionally uses physical guidance systems, such as stringlines, for the slipform pavers. However, several drawbacks of using the stringline system may mar the finished pavement surface (e.g., the chord effect, sag effect, and random survey effect). Although the adverse impacts of the stringline system may be mitigated with stringline length optimization techniques, another solution uses stringless technologies. Stringless paving is not a new idea—it often is used to construct asphalt pavement, and various stringless paving technologies have been developed, tested, and improved in the past decade. However, stringless paving is still a fairly new technology, and only limited slipform pavers have been used in experiments with stringless technologies. Developing stringless paving technologies commonly begins with collecting survey data and building a database, such as the Geographic Information System (GIS). Computer-aided design and modeling for the pavement system follows. A noncontact guidance system then ties the paving surface to the 3D GIS and guides the movements of all paving equipment during construction. Noncontact sensors can be either GPS- or laser-based. Stringless paving research shows that laser-based sensors are more accurate, with a vertical deviation of 10 millimeters (mm) (0.4 inch). To achieve stringless paving successfully, the survey data and onsite guidance system must update the equipment's position quickly. A good system deviation may be 2.5 mm (0.1 inch) vertically and 5.1 mm (0.2 inch) horizontally. Despite the limited success mentioned above, achieving the target vertical control deviation when paving through horizontal/vertical curves and superelevated sections is difficult.

This research will explore better guidance systems to improve stringless concrete paving technologies, even for paving at horizontal/vertical curves and superelevation. The TRIZ system, an algorithm known for systematic innovation and technical creativity, is recommended to achieve the research goals. This research also will demonstrate the system for future concrete technology innovation.

Tasks:

1. Identify existing stringless paving technology for PCC pavements.
2. Identify advantages and disadvantages of existing technology and places for improvement.
3. Work with owner-agencies and industry representatives to modify existing equipment or develop new equipment for stringless paving.
4. Conduct field trials of the improved technology and recommend further refinement.

Benefits: Stringless paving technology that will eliminate common pavement smoothness issues, such as chord effects, sag effects, and random survey effects, and improve paving efficiency.

Products: Stringless concrete paving technology and equipment.

Implementation: This work will develop stringless concrete paving equipment.

Problem Statement EA 2.2. Roller-Compacted Concrete Paving

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 2. Concrete Placement Equipment
Approximate Phasing:	Years 3–6
Estimated Cost:	$250 k–$500 k

RCC has been used in concrete pavements for many years, primarily in industrial areas such as shipping yards, in which heavy wheel loads are common and pavement smoothness is not a concern. RCC has proven to be a very durable, high-strength paving material for these applications, and placement techniques now use common equipment similar to HMA paving machines. RCC pavement's poor smoothness characteristics have made contractors reluctant to use RCC for highway pavement applications. However, recent advancements in diamond grinding technology and improvements to slipform paving equipment indicate that RCC should be examined more thoroughly for highway pavement applications. Improved durability, reduced permeability, and reduced slab thickness make RCC an appealing alternative for highway pavement applications. This research will explore the feasibility of using RCC for highway facilities in light of new advancements in pavement technology.

Tasks:

1. Identify projects that have used RCC pavement, documenting design details, materials, construction procedures, and problems with the materials or construction.
2. Identify potential issues associated with using RCC for highway pavements.
3. Identify potential solutions that make RCC viable for highway pavements.
4. Work with owner-agencies to develop RCC pavement pilot projects.
5. Develop guidelines and recommendations for using RCC in highway pavements.

Benefits:	Guidelines and recommendations that can help construct durable, high-strength RCC pavements, possibly beginning with pilot projects and eventually progressing toward urban highway pavements.
Products:	Guidelines and recommendations for using RCC in highway pavements.
Implementation:	This research will result in guidelines and recommendations for using RCC in highway pavements.

Problem Statement EA 2.3. Zero-Clearance Paving

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 2. Concrete Placement Equipment
Approximate Phasing: Years 4–7
Estimated Cost: $500 k–$1 M

Zero-clearance (or minimum-clearance) pavers often are required next to fixed objects, such as median barriers or guardrails. Although most HMA pavers are zero-clearance pavers, the size and weight of PCC slipform pavers make zero (or minimum) clearance very difficult. However, because such paving equipment always will be needed, this technology must be developed further. This research will examine the requirements for zero-clearance pavers, the current technology, and refinements to existing technology or new developments needed for zero-clearance paving applications.

Tasks:

1. Identify available zero- or minimum-clearance paving equipment and its limitations.
2. Identify contractor and owner-agency requirements for zero-clearance paving.
3. Work with contractors and industry representatives to modify existing equipment or develop new equipment for zero-clearance paving.
4. Work with owner-agencies and contractors to conduct case studies or pilot projects to evaluate any new or refined zero-clearance pavers.

Benefits: Zero- or minimum-clearance paving machines that will enhance the flexibility of PCC paving, permitting slipform paving next to fixed barriers and eliminating the need for wider paver tracks.

Products: Advancements in zero- or minimum-clearance paving equipment.

Implementation: This work will result in new or modified equipment for zero-clearance paving.

Problem Statement EA 2.4. Two-Course Concrete Paving

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 2. Concrete Placement Equipment
Approximate Phasing:	Years 5–9
Estimated Cost:	$1 M–$2 M

Two-course concrete pavements can reduce construction costs while providing a pavement performance equal to or greater than that of conventional concrete pavement. Recent advances in ultrathin whitetopping (UTW) have shown that a durable, high-strength concrete surface has advantages in high-stress areas. Some sections of two-course pavement have been constructed in the United States, but these sections have not been analyzed (or the results have not been distributed to a large audience of pavement specifiers). For example, a 1993 European demonstration in Michigan was a two-course construction pavement. However, followup studies have not been conducted to determine project performance. Also, RCC for the lower course of a two-course system has not been researched.

Tasks:

1. Identify two-course pavements that have been constructed in the United States and abroad, documenting materials, construction techniques, and performance.
2. Identify advantages and disadvantages of the various two-course paving techniques.
3. Identify needs or applications for two-course paving from owner-agencies.
4. Develop recommendations for two-course paving materials and construction procedures.
5. Work with owner-agencies to develop case studies or pilot projects that use two-course paving techniques.

Benefits:	Guidelines and recommendations that can be used for constructing two-course concrete pavements, beginning with pilot projects and progressing to urban highway pavements.
Products:	Guidelines and recommendations for two-course concrete paving construction procedures.
Implementation:	This research will recommend two-course concrete paving materials and construction procedures.

Problem Statement EA 2.5. Automated Material Sensing and Equipment Adjustments

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 2. Concrete Placement Equipment
Approximate Phasing: Years 4–10
Estimated Cost: $2 M–$5 M

Rheological concrete properties greatly affect slipform paving operations. slipform paving machines extrude concrete, making it necessary to fluidize the material while forcing it through the mold (pan). Variations in concrete properties, such as workability, can alter the extrusion effectiveness and vary pavement shape and smoothness results. These variations also affect the timing of finishing, surface texturing, and curing. To maintain consistent extrusion pressures and improve slipforming results, it is necessary to identify concrete's rheological properties and use this information as feedback for the slipform paving machine. The speed, vibration, and extrusion pressure of the paving machine and the timing of other operations then can be adjusted for the varying concrete mix properties. The more automated this process is, the less human error will be a factor, and the more quickly adjustments can be made. First, research must determine the optimal operating ranges for paving machines and the timing of paving operations for concrete mixes with varying rheological properties. This information then can be used to program paving trains to adjust speed and timing automatically based on concrete properties. In addition, techniques for automatically measuring or detecting concrete rheological properties need to be developed. These techniques will allow for a fully automated paving process that will check concrete properties continuously and adjust the operation as necessary.

Tasks:

1. Identify concrete mix properties that affect slipform paving operations.
2. Determine optimal operating ranges (speed, vibration, extrusion pressure, timing of finishing, texturing, and curing) for common slipform pavers based on varying concrete rheological properties.
3. Develop semiautomated or fully automated techniques for measuring the rheological properties of fresh concrete deposited in front of the paver.
4. Work with industry representatives and paving contractors to modify paving equipment to adjust the operation automatically based on concrete properties.
5. Work with industry representatives and owner-agencies to conduct pilot projects or field trials using the automated equipment.

Benefits: Material sensing paving equipment that will detect changes in concrete rheological properties as it is fed into the paver and make automatic adjustments to paver speed, vibration, and extrusion pressure, resulting in better quality concrete pavement.

Products: Fully automated, material sensing concrete paving equipment.

Implementation: This work will fully automate paving equipment that can measure concrete properties and adjust the paving operations based on those properties.

Problem Statement EA 2.6. Fully Automated One-Pass Paving

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 2. Concrete Placement Equipment
Approximate Phasing:	Years 7–10
Estimated Cost:	\$2 M–\$5 M

Several components constitute a typical paving operation, including concrete placement, finishing, texturing (turf drag or tining), curing, and joint sawcutting. These processes usually are separate from each other, often slowing the paving operation and preventing the pavement from being opened to traffic quickly. Incorporating these numerous, independent paving activities into a single automated one-pass process should be explored further. To meet fast-track criteria, dowels and tie bars could be vibrated in, the joint grooves could be formed into the fresh concrete, and the surface texturing and curing would follow immediately. No subsequent operations behind the slipform operation would be required.

Tasks:

1. Identify existing automated processes for slipform paving operations (automatic dowel bar/tie bar inserters, automatic finishers, etc.).
2. Develop new techniques for other automated slipform paving processes (such as joint forming).
3. Work with slipform industry representatives and contractors to integrate all processes into an automated one-pass operation.
4. Work with contractors and owner-agencies to conduct pilot projects using one-pass slipform equipment.

Benefits:	One-pass paving equipment that will perform all processes in a single pass, including concrete placement, finishing, texturing, curing, and jointing, making adjustments automatically and resulting in a very efficient paving operation.
Products:	One-pass concrete paving equipment.
Implementation:	This work will result in automated one-pass concrete paving equipment.

SUBTRACK EA 3. CONCRETE PAVEMENT CURING, TEXTURING, AND JOINTING EQUIPMENT

This subtrack focuses on the key behind-the-paver equipment. It aims to advance the state of the art beyond labor-intensive operations to improve quality, speed, and cost-effectiveness. Table 27 provides an overview of this subtrack.

Table 27. Subtrack EA 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 3.0. Framework for Concrete Pavement Curing, Texturing, and Jointing Equipment (Subtrack EA 3)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 3.1. High-Speed, Early, and Efficient Concrete Pavement Jointing	$1 M–$2 M	High-speed jointing equipment for early-age concrete and/or best practice recommendations for sawcutting.	New techniques and equipment for early jointing and recommendations for sawcutting to ensure that joints are cut cleanly at the earliest possible time; improved joints that result in better pavement performance.
EA 3.2. Advanced Concrete Pavement Surface Texturing Equipment	$1 M–$2 M	New equipment for surface texturing.	New surface texturing equipment and techniques that will meet consistent skid resistance, tire-pavement noise, and rideability requirements without compromising the pavement surface integrity.
EA 3.3. Accelerated Concrete Hydration Equipment	$1 M–$2 M	Equipment for accelerating the hydration of PCC pavements.	Accelerated hydration techniques that allow joints to be cut sooner and permit earlier opening to traffic without using exotic, fast-setting mixes.
EA 3.4. Advanced Concrete Pavement Joint Forming	$500 k–$1 M	New equipment or techniques for forming joints.	New techniques and equipment for forming joints that will improve joint quality and allow for earlier jointing, resulting in better joint control and performance.

Problem Statement EA 3.0. Framework for Concrete Pavement Curing, Texturing, and Jointing Equipment (Subtrack EA 3)

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack EA 3 (Concrete Pavement Curing, Texturing, and Jointing Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 3 (Concrete Pavement Curing, Texturing, and Jointing Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 3 (Concrete Pavement Curing, Texturing, and Jointing Equipment).

Problem Statement EA 3.1. High-Speed, Early, and Efficient Concrete Pavement Jointing

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment
Approximate Phasing:	Years 3–7
Estimated Cost:	\$1 M–\$2 M

Joints can affect PCC structural and functional pavement performance significantly, making jointing a critical process in pavement construction. While many techniques can be used, such as inserts and hand grooving, sawcutting has been the predominant technique due to the end product's high quality and relatively low cost. However, sawcutting requires special considerations. From a construction standpoint, sawcutting joints as quickly as possible opens the pavement to traffic more quickly. However, sawcutting the joints too soon causes raveling distress along the joint, while uncontrolled cracking may develop if joints are cut too late. Also, sawcut depth is usually specified as one-third or one-fourth of the pavement depth to ensure that cracks form at predetermined locations, but this depends on the maximum aggregate size used, among other factors. Previous efforts have developed guidelines to determine the sawcutting window and optimum depth, but no standard procedures or guidelines have been adopted. Additionally, new jointing techniques/technologies must be considered if the construction windows are to be narrowed further. Research that fully examines and documents sawcutting and alternative high-speed jointing techniques is needed to prevent delays in opening the pavement to traffic.

Tasks:

1. Identify previously used, early-age jointing techniques, documenting advantages and disadvantages of the different techniques.
2. Identify pavement sections that have used each of the jointing techniques and document joint performance.
3. Work with industry and contractors to modify existing early-age jointing techniques or develop new ones.
4. Develop recommendations and/or best practice guidelines for high-speed, early-age jointing techniques.
5. Work with owner-agencies and contractors to evaluate new jointing techniques on pilot projects.

Benefits:	New techniques and equipment for early jointing and recommendations for sawcutting to ensure that joints are cut cleanly at the earliest possible time; improved joints that result in better pavement performance.
Products:	High-speed jointing equipment for early-age concrete and/or best practice recommendations for sawcutting.
Implementation:	This work will recommend best practice guidelines for high-speed, early-age jointing techniques.

Problem Statement EA 3.2. Advanced Concrete Pavement Surface Texturing Equipment

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment
Approximate Phasing:	Years 5–8
Estimated Cost:	$1 M–$2 M

Surface texture is a critical aspect of concrete pavements, affecting safety, tire-pavement noise, and rideability. Surface texture provides skid resistance—particularly important in wet driving conditions—and can even channel water away from the pavement-tire interface, in the case of tining. However, surface texture also increases tire-pavement noise and degrades rideability if not properly constructed. Unfortunately, some of the best surface textures for providing skid resistance also can be the noisiest and the most difficult to construct properly.

This research will investigate new surface texturing equipment and techniques that provide the desired balance of skid resistance, low noise levels, and rideability. Texturing equipment should provide a consistent surface texture soon after finishing the pavement surface. Also, surface texturing techniques should not compromise the concrete surface integrity.

Tasks:

1. Identify commonly used surface texturing techniques and equipment and their limitations.
2. Identify new, documented surface texturing techniques and equipment to improve skid resistance, reduce tire-pavement noise, and improve rideability.
3. Determine typical characteristics (skid resistance, tire-pavement noise, rideability) documented for each technique.
4. Work with contractors and industry to develop and/or apply new surface texturing equipment and techniques.
5. Develop recommendations for new use of surface texturing techniques and equipment.
6. Work with owner-agencies and contractors to evaluate new techniques and equipment using pilot projects.

Benefits:	New surface texturing equipment and techniques that will meet consistent skid resistance, tire-pavement noise, and rideability requirements without compromising the pavement surface integrity.
Products:	New equipment for surface texturing.
Implementation:	This work will result in surface texturing equipment and/or techniques and recommendations for their use.

Problem Statement EA 3.3. Accelerated Concrete Hydration Equipment

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment
Approximate Phasing:	Years 5–8
Estimated Cost:	\$1 M–\$2 M

Accelerating PCC hydration will allow the material to reach its required strength faster. For PCC pavements, accelerating the hydration process will help the pavement to be finished, textured, jointed, and cured more quickly, allowing it to open to traffic earlier. Techniques for accelerating hydration should be explored further so they can be applied to fast-track PCC paving operations. Microwave-induced setting is one such technique that instantly heats the concrete internally to initiate the setting, allowing finishing, jointing, texturing, and curing to be completed in the trailing forms and eliminating the need to return for joint sawing. Induction heating, which heats steel fibers in the concrete mixture with an externally applied electric current, is another technique that can accelerate setting.

Tasks:

1. Identify accelerated hydration techniques and equipment that could be applied to concrete pavement construction.
2. Determine the advantages and disadvantages of each technique, analyzing the cost versus benefit and investigating the effects of accelerated hydration on PCC pavement performance.
3. Work with contractors and industry representatives to develop techniques/equipment for accelerated hydration.
4. Work with owner-agencies and contractors to develop pilot studies for implementing accelerated hydration on PCC pavement projects.

Benefits:	Accelerated hydration techniques that allow joints to be cut sooner and permit earlier opening to traffic without using exotic, fast-setting mixes.
Products:	Equipment for accelerating the hydration of PCC pavements.
Implementation:	This work will result in accelerated hydration techniques/equipment for PCC pavement construction.

Problem Statement EA 3.4. Advanced Concrete Pavement Joint Forming

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 3. Concrete Pavement Curing, Texturing, and Jointing Equipment
Approximate Phasing: Years 8–10
Estimated Cost: $500 k–$1 M

Sawcutting long has been the preferred method for forming contraction joints in PCC pavements. Lightweight, early-entry saws have been developed; these allow the contractor to sawcut joints much earlier than did previous saws However, because concrete saws are rotary, raveling and spalling often can result, even if the concrete has hardened sufficiently. Sawcutting is also time-consuming and can give variable results, depending on the saw operator.

This research will investigate advanced joint cutting techniques. Laser cutting, water jets, or other high-energy techniques may provide much better results under a more controlled process. Low-tech solutions such as the bobsled also might be refined in this research. New techniques should provide better, more consistent results for early-age joint cutting. Ideally, new techniques will permit joint cutting immediately after surface texturing, allowing a one-pass paving process.

Tasks:

1. Identify techniques and equipment that could be used for early-age concrete joint forming.
2. Evaluate new techniques/equipment for their applicability to concrete pavement jointing, including speed, cutting consistency, and cost.
3. Work with industry and contractors to apply new jointing techniques and equipment to paving operations.
4. Work with contractors and owner-agencies to develop pilot projects that use the new jointing techniques and equipment.

Benefits: New techniques and equipment for forming joints that will improve joint quality and allow for earlier jointing, resulting in better joint control and performance.

Products: New equipment or techniques for forming joints.

Implementation: This work will result in new techniques and/or equipment for forming joints that are suitable for early-age concrete pavement.

SUBTRACK EA 4. CONCRETE PAVEMENT FOUNDATION EQUIPMENT

This subtrack focuses on ways to place and control the foundation elements, including ways to mechanize the placement of subdrains. Table 28 provides an overview of this subtrack.

Table 28. Subtrack EA 4 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 4.0. Framework for Concrete Pavement Foundation Equipment (Subtrack EA 4)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 4.1. Rapid Subgrade/Subbase Stabilization	$1 M–$2 M	New techniques and equipment for rapid subgrade/subbase stabilization.	Rapid subgrade/subbase stabilization that will allow subgrade/subbase support to be repaired and restored before placing new pavement in a short construction window.
EA 4.2. Automated Subdrain Installation in Concrete Pavement Construction	$1 M–$2 M	New techniques and equipment for automated subdrain installation.	Automated subdrain installation that permits the process to be completed in a single pass immediately in front of the paver, thus expediting construction.

Problem Statement EA 4.0. Framework for Concrete Pavement Foundation Equipment (Subtrack EA 4)

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 4. Concrete Pavement Foundation Equipment
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack EA 4 (Concrete Pavement Foundation Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 4 (Concrete Pavement Foundation Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 4 (Concrete Pavement Foundation Equipment).

Problem Statement EA 4.1. Rapid Subgrade/Subbase Stabilization

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 4. Concrete Pavement Foundation Equipment
Approximate Phasing:	Years 3–7
Estimated Cost:	$1 M–$2 M

One of the problems with fast-track paving (i.e., overnight construction using fast-setting/high-early strength or precast concrete) is stabilizing the existing base material. The pavements being replaced often have deteriorated due to problems with the base material, such as pumping or swelling, resulting in voids beneath the pavement. Using conventional paving techniques, the base material can be replaced or treated (cement/lime/asphalt stabilization) to mitigate these problems. Unfortunately, most existing stabilization techniques cannot be completed in a short (e.g., overnight) construction window because many materials currently used for stabilization cannot be used for overnight stabilization processes. Therefore, research should develop rapid base stabilization and restoration techniques that can be completed within short construction windows. This may require new equipment for rapid stabilization or even new materials. The techniques developed should be able to be incorporated into a one pass pavement removal and replacement operation that uses high-early strength or precast concrete.

Tasks:

1. Identify existing stabilization materials and techniques.
2. Evaluate existing stabilization materials and techniques for their applicability to rapid stabilization (i.e., overnight and one-pass operations).
3. Work with contractors and industry representatives to modify or develop new equipment and materials for rapid stabilization.
4. Work with contractors and owner-agencies to develop pilot studies that use rapid stabilization techniques and materials.

Benefits:	Rapid subgrade/subbase stabilization that will allow subgrade/subbase support to be repaired and restored before placing new pavement in a short construction window.
Products:	New techniques and equipment for rapid subgrade/subbase stabilization.
Implementation:	This research will result in new techniques, equipment and/or materials for rapid stabilization.

Problem Statement EA 4.2. Automated Subdrain Installation in Concrete Pavement Construction

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 4. Concrete Pavement Foundation Equipment
Approximate Phasing:	Years 8–10
Estimated Cost:	\$1 M–\$2 M

While certain regions of the United States require pavement subdrains, installing these subdrains is often costly and time-consuming. Research is needed to explore ways to install subdrains quickly and efficiently during the paving operation. Ideally, automated installation equipment would install the subdrains immediately in front of the paving operation, eliminating the need for two separate construction processes and additional construction time. Subdrain installation would thus be a one-pass operation that includes excavation, drain installation, and backfilling.

Tasks:

1. Identify typical subdrain specifications required by owner-agencies and viable new subdrain specifications.
2. Work with contractors and industry representatives to develop automated subdrain installation equipment that could be completed in one pass in front of the paving operation.
3. Work with owner-agencies and contractors to develop pilot projects that demonstrate automated subdrain installation.

Benefits:	Automated subdrain installation that permits the process to be completed in a single pass immediately in front of the paver, thus expediting construction.
Products:	New techniques and equipment for automated subdrain installation.
Implementation:	This work will result in new techniques and/or equipment for rapid automated subdrain installation in concrete pavement construction.

SUBTRACK EA 5. CONCRETE PAVEMENT RECONSTRUCTION EQUIPMENT

This subtrack focuses on the next generation of equipment that will integrate the removal/ replacement of the slab in one-pass construction. Table 29 provides an overview of this subtrack.

Table 29. Subtrack EA 5 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 5.0. Framework for Concrete Pavement Reconstruction Equipment (Subtrack EA 5)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 5.1. High-Speed, In Situ PCC Pavement Breakup, Removal, and Processing	$2 M–$5 M	Equipment for high-speed, one-pass, in situ breaking up, removing, and processing PCC pavement.	Equipment that will permit old concrete pavement to be broken up, removed, and processed in place, allowing the concrete material to be recycled into base material or new concrete and significantly reducing or even eliminating waste material.
EA 5.2. Recycled Concrete Processing/ Improvement	$1 M–$2 M	Equipment and recommendations for separating crushed concrete into usable materials.	Equipment that will separate crushed concrete properly into materials that can be used for new concrete, minimizing or eliminating waste from reconstructed concrete pavements.
EA 5.3. High-Speed, In Situ, One-Pass, Full Concrete Pavement Reconstruction	$2 M–$5 M	New equipment for one-pass pavement reconstruction.	Equipment that permits one-pass concrete pavement reconstruction, including breaking up, removing, and processing the old pavement, and placing the new pavement using recycled materials from the old pavement; expedited pavement reconstruction with no waste generated.

Problem Statement EA 5.0. Framework for Concrete Pavement Reconstruction Equipment (Subtrack EA 5)

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 5. Concrete Pavement Reconstruction Equipment
Approximate Phasing: Years 1–3
Estimated Cost: $200 k

Subtrack EA 5 (Concrete Pavement Reconstruction Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 5 (Concrete Pavement Reconstruction Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.

Products: A validated, sequenced, and detailed research framework for this subtrack.

Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 5 (Concrete Pavement Reconstruction Equipment).

Problem Statement EA 5.1. High-Speed, In Situ PCC Pavement Breakup, Removal, and Processing

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 5. Concrete Pavement Reconstruction Equipment
Approximate Phasing:	Years 3–7
Estimated Cost:	$2 M–$5 M

With the current aging infrastructure, many concrete pavements require complete replacement rather than minor rehabilitation. Unfortunately, many of these pavements are located in urban areas that permit only short construction windows for removing and replacing the pavement. Removing the existing pavement can be the most time-consuming aspect of this process. Research should investigate the high-speed breakup, removal, and processing of the old pavement material. Ideally, a one-pass operation would breakup the pavement, remove it, and crush it into manageably sized material that can then be reused as base material or concrete aggregate. Breaking up and removing old material should not damage the underlying base material or compromise its integrity. Nonimpact methods, such as lasers, should be investigated as possible techniques for breaking up the old concrete. Breakup and processing also should consider concrete pavements with and without asphalt overlays and determine how to separate the two materials.

Tasks:

1. Identify techniques for breaking up existing concrete pavements with or without asphalt overlays, including such new nonimpact technologies as lasers.
2. Identify techniques for removing and processing the material in situ, including techniques for separating asphalt overlay material from PCC material.
3. Work with industry representatives and contractors to develop new techniques and equipment for high-speed breaking up, removing, and processing old pavements.
4. Work with owner-agencies to develop pilot studies that use new breakup and removal processes.

Benefits:	Equipment that will permit old concrete pavement to be broken up, removed, and processed in place, allowing the concrete material to be recycled into base material or new concrete and significantly reducing or even eliminating waste material.
Products:	Equipment for high-speed, one-pass, in situ breaking up, removing, and processing PCC pavement.
Implementation:	This work will result in new equipment for high-speed breakup, removal, and processing of concrete pavement with or without asphalt overlays.

Problem Statement EA 5.2. Recycled Concrete Processing/Improvement

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 5. Concrete Pavement Reconstruction Equipment
Approximate Phasing:	Years 5–9
Estimated Cost:	\$1 M–\$2 M

Reconstructing concrete pavements produces large stockpiles of old concrete material that can be reused in some form for new construction. Several studies have examined sophisticated methods to separate concrete into components that can be used as aggregates and cement precursors. One method heats concrete to between 650 and 700 °C (1,202 and 1,292 °F) in an electrical furnace. Another promising technology called Franka-Stein treats concrete in a powerful electric arc using electrodynamic fragmentation, which separates the electrically weak material boundaries prevalent in concrete. In addition to producing clean aggregate, the Franka-Stein process separates cementitious material that can replace natural raw material in cement production. Research is needed to investigate these recycling methods further to determine their cost-effectiveness, considering the energy consumption of the separation process.

Tasks:

1. Identify existing processes for separating recycled concrete, including Franka-Stein and others.
2. Evaluate the effectiveness of the separation processes and the suitability of the resulting material for reuse in new concrete pavement.
3. Evaluate the cost versus benefit of different recycling processes, considering the energy consumption of the separation process.
4. Work with contractors and industry representatives to develop new equipment or modify and adapt existing equipment for rapid recycling of concrete pavement.

Benefits:	Equipment that will separate crushed concrete properly into materials that can be used for new concrete, minimizing or eliminating waste from reconstructed concrete pavements.
Products:	Equipment and recommendations for separating crushed concrete into usable materials.
Implementation:	This work will result in equipment for recycling and processing concrete pavement and recommendations for using recycled materials in new concrete.

Problem Statement EA 5.3. High-Speed, In Situ, One-Pass, Full Concrete Pavement Reconstruction

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 5. Concrete Pavement Reconstruction Equipment
Approximate Phasing:	Years 8–10
Estimated Cost:	$2 M–$5 M

The traveling public expects and demands fewer delays, often making user costs the highest expense for a major reconstruction project. For major reconstruction efforts, traffic control barrels are positioned to alter traffic flow around the work site for weeks or months, straining public travel through the area. Therefore, agencies often delay necessary highway reconstruction or choose less disruptive repairs to avoid traffic interruptions. These decisions eventually strain the State's pavement network, since the majority of the network has a short expected life. In addition, material is removed and hauled offsite during reconstruction—this is a labor-intensive process that often increases the cost and extends the length of reconstruction projects. However, improved equipment capable of removing, recycling, mixing and placing concrete pavement using a single, continuous operation would ease reconstruction.

The process would require a marriage of mobile crushing and screening with a mixer and slipform paver. This research will conceptualize and build efficient and effective methods and/or processes that will permit recycling, mixing, and placing of existing concrete pavement using a single continuous operation. A recent initiative in Europe advanced the linear quarry, in which materials generated by the reclamation of the existing pavement structure would be reprocessed into the new structure along the same alignment. While this concept has been limited to HMA pavements, this research will explore the same concept for concrete pavements. The feasibility of crushing, collecting, sizing, batching, and placing concrete pavements within the right of way should be studied. If the feasibility study returns positive results, additional provisions should be made to test this concept in the field.

Tasks:

1. Identify existing linear quarry technology for in situ material processing and recycling.
2. Identify existing equipment for in situ PCC materials removal and processing.
3. Determine the viability of using reprocessed concrete materials for new pavement.
4. Complete a feasibility study that incorporates breaking up, removing, crushing, sizing, batching, and placing new concrete in a single operation within the right-of-way.
5. Conceptualize and develop high-speed one-pass, in situ reconstruction equipment.

Benefits:	Equipment that permits one-pass concrete pavement reconstruction, including breaking up, removing, and processing the old pavement, and placing the new pavement using recycled materials from the old pavement; expedited pavement reconstruction with no waste generated.
Products:	New equipment for one-pass concrete pavement reconstruction.
Implementation:	This work will assess the feasibility of high-speed, one-pass, in situ reconstruction equipment, and possibly develop such equipment.

SUBTRACK EA 6. CONCRETE PAVEMENT RESTORATION EQUIPMENT

This subtrack focuses on the repair processes, aiming to speed the operations and provide the workforce and traveling public with less exposure to the process. Table 30 provides an overview of this subtrack.

Table 30. Subtrack EA 6 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 6.0. Framework for Concrete Pavement Restoration Equipment (Subtrack EA 6)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 6.1. Rapid, High-Production Concrete Pavement Grinding	$1 M–$2 M	More efficient, high-production grinding equipment.	High-production grinding equipment that will permit faster, more efficient concrete pavement grinding, reducing construction time and ground surface variability by grinding a wider section of pavement with a single pass.
EA 6.2. Automated Concrete Pavement Crack Sensing and Sealing	$500 k–$1 M	Automated crack sensing and crack sealing equipment/vehicle.	Automated concrete pavement crack sensing and crack sealing equipment that requires less labor, minimal traffic control, and provides a safer working environment for crack sealing.
EA 6.3. Fully Automated Concrete Pavement Restoration Equipment	$1 M–$2 M	Fully automated one-pass DBRs and patching equipment.	Fully automated DBR and patching equipment that will expedite these CPR processes, requiring less labor and lowering costs.

Problem Statement EA 6.0. Framework for Concrete Pavement Restoration Equipment (Subtrack EA 6)

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 6. Concrete Pavement Restoration Equipment
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack EA 6 (Concrete Pavement Restoration Equipment) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 6 (Concrete Pavement Restoration Equipment), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 6 (Concrete Pavement Restoration Equipment).

Problem Statement EA 6.1. Rapid, High-Production Concrete Pavement Grinding

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 6. Concrete Pavement Restoration Equipment
Approximate Phasing:	Years 3–7
Estimated Cost:	$1 M–$2 M

Diamond grinding technology has reached the point where meeting the most stringent ride quality specifications is not difficult for an experienced operator. Unfortunately, the process is still very slow, and each pass generally is limited to a 0.91- to 1.2-m (3- to 4-ft) width. Because CPR programs increasingly demand concrete pavement grinding, research is needed to develop high-production diamond grinding equipment and techniques. A new generation of grinding equipment that quickly grinds full 3.7-m (12-ft) lane widths or more in a single pass will meet the demands of CPR programs. New grinding equipment should incorporate slurry extraction and retention. If diamond grinding equipment cannot meet the new CPR requirements, alternative grinding equipment should also be investigated.

Tasks:

1. Identify the grinding production needs of contractors and owner-agencies.
2. Identify limitations on existing diamond grinding equipment.
3. Identify alternative grinding equipment and determine its suitability for concrete paving applications.
4. Work with industry representatives and contractors to modify existing equipment or develop new equipment to meet grinding production needs.

Benefits:	High-production grinding equipment that will permit faster, more efficient concrete pavement grinding, reducing construction time and ground surface variability by grinding a wider section of pavement with a single pass.
Products:	More efficient, high-production grinding equipment.
Implementation:	This work will result in equipment for high-production concrete pavement grinding.

Problem Statement EA 6.2. Automated Concrete Pavement Crack Sensing and Sealing

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 6. Concrete Pavement Restoration Equipment
Approximate Phasing:	Years 4–8
Estimated Cost:	$500 k–$1 M

Crack sealing is necessary maintenance that prevents water and debris from intruding into PCC pavement cracks. Water and debris intrusion can result in corrosion of the reinforcement and spalling at the cracks. However, crack sealing is time-consuming and labor-intensive. Research is needed to investigate the viability of automated crack sensing and crack sealing equipment. Automated processes would not only eliminate much of the manual labor involved, but also would create a safer working environment, possibly eliminating the need for traffic control during sealing operations. Automated crack sensing equipment could be vehicle-mounted and could use visual imaging, laser scanning, or other techniques to detect cracks. After crack detection, vehicle-mounted sealing equipment could then seal the crack with epoxy, asphalt, or other material. Although automated sealing would be impossible at high speeds, vehicle-mounted equipment would only require a moving traffic control setup.

Tasks:

1. Identify existing equipment or develop new automated concrete pavement crack sensing equipment.
2. Identify existing equipment or develop new automated crack sealing equipment.
3. Develop equipment for integrating crack sensing and crack sealing into a single operation.

Benefits:	Automated concrete pavement crack sensing and crack sealing equipment that requires less labor, minimal traffic control, and provides a safer working environment for crack sealing.
Products:	Automated crack sensing and crack sealing equipment/vehicle.
Implementation:	This work will result in automated concrete pavement crack sensing and crack sealing equipment.

Problem Statement EA 6.3. Fully Automated Concrete Pavement Restoration Equipment

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 6. Concrete Pavement Restoration Equipment
Approximate Phasing:	Years 6–10
Estimated Cost:	$1 M–$2 M

DBR have become a well-established and proven technique for restoring load transfer across concrete pavement cracks and joints. Full- and partial-depth patching techniques commonly repair failed slab segments and spalling, respectively. However, these techniques are still labor-intensive and time-consuming. This research will conceptualize and develop fully automated equipment for both DBR and slab patching. The equipment should complete these CPR techniques in a one-pass process. For DBR, this will include cutting and cleaning slots across a crack or joint, inserting the dowel bars, and patching the slots. If possible, the process will also incorporate diamond grinding. Patching will include sawing and removing the existing concrete, inserting tie/dowel bars as necessary, and placing, consolidating, and curing patching material. In all cases, the equipment should adequately retrofit an entire lane width in a single pass.

Tasks:

1. Determine the equipment feasibility for one-pass DBR and/or patching operations. Examine alternative patching materials and the feasibility of incorporating diamond grinding into the operation.
2. Determine the production requirements (speed of operation) for these CPR operations.
3. Conceptualize and develop one-pass CPR equipment.

Benefits:	Fully automated DBR and patching equipment that will expedite these CPR processes, requiring less labor and lowering costs.
Products:	Fully automated one-pass DBR and patching equipment.
Implementation:	This work will result in fully automated DBR and concrete slab patching equipment.

SUBTRACK EA 7. ADVANCED EQUIPMENT EVALUATION AND IMPLEMENTATION

This subtrack provides the resources for evaluating the new equipment on actual construction projects. Table 31 provides an overview of this subtrack.

Table 31. Subtrack EA 7 overview.

Problem Statement	Estimated Cost	Products	Benefits
EA 7.0. Framework for Advanced Equipment Evaluation and Implementation (Subtrack EA 7)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
EA 7.1. Advanced Concrete Paving Equipment Workshops and Demonstrations	$2 M–$5 M	Workshops and product demonstrations for advanced PCC construction/ rehabilitation equipment.	Workshops and product demonstrations that provide a cost effective opportunity for familiarizing contractors and owner-agencies with new equipment and technologies and training employees.
EA 7.2. Concrete Paving Equipment Purchases for States	$2 M–$5 M	Vehicle for helping States purchase advanced pavement construction/ rehabilitation equipment.	Advanced equipment for concrete pavement construction and rehabilitation that States can afford.

Problem Statement EA 7.0. Framework for Advanced Equipment Evaluation and Implementation (Subtrack EA 7)

Track: 5. Equipment Automation and Advancements (EA)
Subtrack: EA 7. Advanced Equipment Evaluation and Implementation
Approximate Phasing: Years 1–3
Estimated Cost: $150 k

Subtrack EA 7 (Advanced Equipment Evaluation and Implementation) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack EA 7 (Advanced Equipment Evaluation and Implementation), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract does not achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.

Products: A validated, sequenced, and detailed research framework for this subtrack.

Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack EA 7 (Advanced Equipment Evaluation and Implementation).

Problem Statement EA 7.1. Advanced Concrete Paving Equipment Workshops and Demonstrations

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 7. Advanced Equipment Evaluation and Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	$2 M–$5 M

As with many new technologies, transportation agencies often are slow to adopt new techniques and equipment because they are unfamiliar with these new technologies and lack research resources. Workshops and product demonstrations offer an ideal environment for familiarizing agencies with new and advanced equipment and technologies. These workshops and product demonstrations will train both contractors and owner-agencies in the new equipment through hands-on workshops and demonstrations. If a particular product generates enough interest, product demonstrations may even be taken to States.

Tasks:

1. Compile information on advanced concrete paving equipment and coordinate workshops and product demonstrations.
2. Present and demonstrate advanced equipment to workshop audiences, emphasizing the need for and benefits of such equipment.

Benefits:	Workshops and product demonstrations that provide a cost effective opportunity for familiarizing contractors and owner-agencies with new equipment and technologies and training employees.
Products:	Workshops and product demonstrations for advanced PCC construction/rehabilitation equipment.
Implementation:	This research will develop numerous workshops and product demonstrations for advanced concrete paving equipment at various venues throughout the United States.

Problem Statement EA 7.2. Concrete Paving Equipment Purchases for States

Track:	5. Equipment Automation and Advancements (EA)
Subtrack:	EA 7. Advanced Equipment Evaluation and Implementation
Approximate Phasing:	Years 5–10
Estimated Cost:	$2 M–$5 M

Most States lack the funding necessary to purchase their own new advanced equipment. Moreover, many contractors are reluctant to invest large amounts of capital in new equipment unless it is certain to be profitable. Guidelines should be established that help States purchase needed equipment and promote the use of such equipment for PCC pavement construction and rehabilitation.

Tasks:

1. Establish guidelines for helping States purchase advanced equipment for PCC pavement construction and rehabilitation.
2. Recommend a process for identifying, prioritizing, and obtaining needed equipment.

Benefits:	Advanced equipment for concrete pavement construction and rehabilitation that States can afford.
Products:	Vehicle for helping States purchase advanced pavement construction/rehabilitation equipment.
Implementation:	This work will result in a vehicle for helping States purchase advanced equipment for PCC pavement construction and rehabilitation.

Track 6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)

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TRACK 6 (IJ) OVERVIEW

Concrete has a propensity to crack. Because controlling cracks is essential for pavement performance, joints are an important feature of concrete paving. As the FHWA Technical Advisory on Concrete Pavement Joints (T 5040. 30) explains, "The performance of concrete pavements depends to a large extent upon the satisfactory performance of the joints. Most JCP failures can be attributed to failures at the joint, as opposed to inadequate structural capacity."[3]

Ideal joints must be relatively easy to install and repair, consolidate around the steel, provide adequate load transfer, seal the joint or provide for water migration, resist corrosion, open and close freely in temperature changes, enhance smoothness and low noise, and be aesthetically pleasing. Joint failure can result in faulting, pumping, spalling, corner breaks, blowups, and transverse cracking (if lockup occurs). The problem statements in this track address new and innovative joint design, materials, construction, and maintenance activities. There is much room in this research for innovative concrete pavement joint design, such as in research to address the coefficient of thermal expansion and shrinkage issues. Additional incremental improvements to joint design, such as tie bar design for longitudinal joints, are addressed under track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). Much of the proposed research in this track will develop important improvements, though the track also specifies research that will help develop breakthrough technologies. The problem statements also recognize that future joint repair will proceed quickly, and they propose research for accomplishing faster joint repair.

A few of the concepts that will be investigated:

- Private and public sector knowledge and experience will be used to identify ways to enhance jointed pavements.
- Many JCPs that have lasted many years without dowels will require retrofitting with dowels to control faulting. Techniques will be explored.
- Doweled joints will be designed to last 60 years in relatively heavy traffic.
- CRCP will solve the problem of joint lifespan by eliminating the joints entirely.
- Joints for concrete overlays (20-year-and-less performance life) have not been studied sufficiently. The cost of a doweled joint in thin pavement can be exceptionally high for the life expectancy. Research in this track will develop a scaled-down but fully functional joint for this product, with owners specifying a less robust but fully functional joint for the shorter design period.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

This track will identify, develop, and test new and innovative joint concepts for concrete pavements that are more cost effective, reliable, and durable than current alternatives.

Track Objectives

1. Identify new and innovative alternatives to handling the forming, opening/closing, load transfer, and sealing for transverse and longitudinal concrete pavement joints.
2. Identify criteria for the design, materials, and construction of exceptionally long-lasting joints (e.g., more than 50 years). Also see track 8 (Long Life Concrete Pavements).

3. Determine optimum joint design for concrete overlays.
4. Determine optimum joint design for low-volume, long life pavements.
5. Develop an advanced, high-speed computational model for joint condition analysis that can improve joint design, materials, and construction.
6. Develop and field test new and innovative joint designs to determine their cost-effectiveness, reliability, and durability.
7. Develop and validate rapid methodology for evaluating existing joint conditions so that joints can be preserved and repaired.

Research Gaps

- Lack of cost effective joint designs for all pavement types.
- A need for joint fillers and sealants.
- Lack of adequate joint materials.
- Lack of adequate joint construction.
- Lack of methodology for joint preservation and repairs.
- Lack of much-needed technology to provide adequate load transfer on low-volume roads (slab on grade) that costs less than dowels but remains fairly reliable.
- Insufficient understanding of base, subbase, and subdrainage selection for concrete pavements.

Research Challenges

- Provide adequate and cost effective joint designs for the several concrete pavement applications that require differing joint designs, including designs for low-volume rural and urban roadways.
- Determine the best joint designs, materials, and construction procedures for these applications (i.e., concrete overlays, low-volume solutions, heavy traffic, stage construction with low initial costs, and tunnels).
- Provide new and conclusive models and data that address the need for filling/sealing transverse and longitudinal joints.
- Determine the best solution for all concrete pavement applications located in various site conditions, filling a major gap in the knowledge.
- Consider that concrete joint materials endure saturation and freeze thaw as well as high pressures from incompressibles and determine ways in which concrete design can reduce joint deterioration.
- Determine ways to overcome the joint problems that result from construction inadequacies.
- Develop methodology and equipment for determining a joint’s structural and functional condition and selecting preservation and repair actions that maintain its effectiveness.
- Determine the optimum type of base, subbase, or subdrainage for joint performance.
- Determine the optimum site conditions and base types for joint performance.

Research Track 6 (IJ) Phasing

The horizontal bar chart in figure 6 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

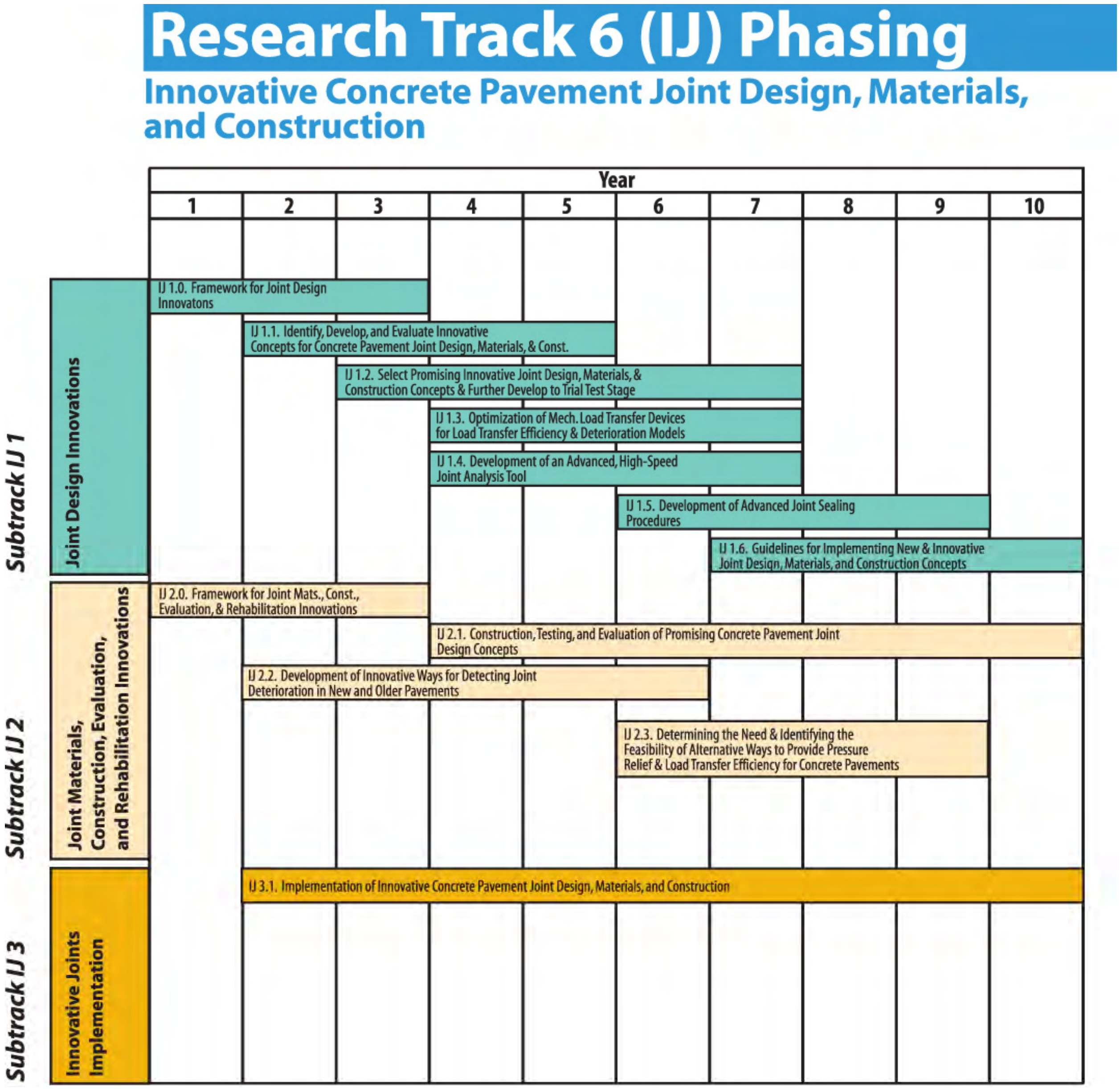

Figure 6. Track 6 (IJ) subtrack and problem statement phasing chart.

Research Track 6 (IJ) Estimated Costs

Table 32 shows the estimated costs for this research track.

Table 32. Research track 6 (IJ) estimated costs.

Problem Statement	Estimated Cost
Subtrack IJ 1. Joint Design Innovations	
IJ 1.0. Framework for Joint Design Innovations (Subtrack IJ 1)	$200 k
IJ 1.1. Identify, Develop, and Evaluate Innovative Concepts for Concrete Pavement Joint Design, Materials, and Construction	$700 k–$1 M
IJ 1.2. Select Promising Innovative Joint Design, Materials, and Construction Concepts and Further Develop to Trial Test Stage	$700 k–$900 k
IJ 1.3. Optimization of Mechanical Load Transfer Devices for Load Transfer Efficiency and Deterioration Models	$600 k–$800 k
IJ 1.4. Development of an Advanced High-Speed Joint Analysis Tool	$1 M–$2 M
IJ 1.5. Development of Advanced Joint Sealing Procedures	$1.5 M–$2.5 M
IJ 1.6. Guidelines for Implementing New and Innovative Joint Design, Materials, and Construction Concepts	$300 k–$500 k
Subtrack IJ 2. Joint Materials, Construction, Evaluation, and Rehabilitation Innovations	
IJ 2.0. Framework for Joint Materials, Construction, Evaluation, and Rehabilitation Innovations (Subtrack IJ 2)	$200 k
IJ 2.1. Construction, Testing, and Evaluation of Promising Concrete Pavement Joint Design Concepts	$2.5 M–$4 M
IJ 2.2. Development of Innovative Ways for Detecting Joint Deterioration in New and Older Pavements	$1 M–$1.5 M
IJ 2.3. Determining the Need and Identifying the Feasibility of Alternative Ways to Provide Pressure Relief and Load Transfer Efficiency for Concrete Pavements	$500 k–$700 k
Subtrack IJ 3. Innovative Joints Implementation	
IJ 3.1. Implementation of Innovative Joint Design, Materials, and Construction	$800 k–$1 M
Track 6 (IJ)	
Total	$10 M–$15.3 M

Track Organization: Subtracks and Problem Statements

Track 6 (IJ) problem statements are grouped into three subtracks:

- Subtrack IJ 1. Joint Design Innovations.
- Subtrack IJ 2. Joint Materials, Construction, Evaluation, and Rehabilitation Innovations.
- Subtrack IJ 3. Innovative Joints Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK IJ 1. JOINT DESIGN INNOVATIONS

This research in this subtrack will develop and implement detailed joint design and construction concepts. Table 33 provides an overview of this subtrack.

Table 33. Subtrack IJ 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
IJ 1.0. Framework for Joint Design Innovations (Subtrack IJ 1)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
IJ 1.1. Identify, Develop, and Evaluate Innovative Concepts for Concrete Pavement Joint Design, Materials, and Construction	$700 k–$1 M	Recommended new and innovative joint design, materials, and construction alternatives.	Jointing alternatives that are significantly more reliable, cost effective, and durable than those currently in use.
IJ 1.2. Select Promising Innovative Joint Design, Materials, and Construction Concepts and Further Develop to Trial Test Stage	$700 k–$900 k	Complete design, materials, and construction details on joint concepts.	Laboratory, accelerated field, and longer term field testing of one or more joint concepts.
IJ 1.3. Optimization of Mechanical Load Transfer Devices for Load Transfer Efficiency and Deterioration Models	$600 k–$800 k	Recommendations and guidelines for improved load transfer devices for LTE of joints; validated and implementable procedures and guidelines that optimize joint load transfer systems for use with transverse concrete pavement joints.	Cost effective, reliable, and durable load transfer devices for concrete pavement joints.
IJ 1.4. Development of an Advanced High-Speed Joint Analysis Tool	$1 M–$2 M	FEM model that provides advanced and high-speed analysis of complex joint systems under traffic and climatic loadings that researchers and designers can use to determine joint design adequacy.	Ability to analyze a wide variety of joint systems three-dimensionally to help evaluate and develop new and innovative joint systems.
IJ 1.5. Development of Advanced Joint Sealing Procedures	$1.5 M–$2.5 M	A lab- and field-validated comprehensive model for joint movement over annual climate cycles, joint infiltration models for water and incompressibles, and an FEM model of the joint and pavement structure that analyzes the impacts of water and incompressibles on pressure buildup, spalling, and base and subgrade erosion; research linked to the model developed under problem statement DG 1.3 (Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading) in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements).	Resolution to the sealing or nonsealing joint issue that improves long-term concrete pavement cost-effectiveness, performance, and reliability.
IJ 1.6. Guidelines for Implementing New and Innovative Joint Design, Materials, and Construction Concepts	$300 k–$500 k	Practical manuals and guidelines that can be used by those involved in designing and constructing innovative concrete pavement joint concepts; major applications of concrete pavements, including low-volume roads and streets, concrete overlays of varying thicknesses, high-traffic concrete pavements, and other special concrete pavement uses, as well as crack forming in CRCP and joint design for precast pavements.	Direct assistance for immediately implementing the entire work of this innovative joint track.

Problem Statement IJ 1.0. Framework for Joint Design Innovations (Subtrack IJ 1)

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 1–3
Estimated Cost:	$200 k

Subtrack IJ 1 (Joint Design Innovations) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack IJ 1 (Joint Design Innovations), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack IJ 1 (Joint Design Innovations).

Problem Statement IJ 1.1. Identify, Develop, and Evaluate Innovative Concepts for Concrete Pavement Joint Design, Materials, and Construction

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 2–5
Estimated Cost:	$700 k–$1 M

Joints consistently have been problematic in concrete pavements. Their designs have been very empirical, causing many failures over the years. The concrete material around the joint often deteriorates more rapidly than the rest of the slab due to greater moisture and freeze-thaw exposure as well as highly concentrated stress points caused by incompressibles. Many construction problems also have occurred in placing load transfer devices and tie bars and in joint-forming activities, such as late sawing or inadequate sawing depth. Innovative joint design, materials, and construction methods are needed to address these problems, along with innovative crack filling or sealing methods. This research should also consider the joints in CRCP, in which crack forming is critical, and examine previous research on this topic. Finally, this research should consider the joint design in precast concrete pavements.

Tasks:

1. Identify innovative joint design, materials, and construction concepts. Consider major concrete pavement applications, including low-volume roads and streets, concrete overlays of varying thicknesses, high-traffic concrete pavements, and other special concrete pavement uses. For example, examine the bobsled procedure for longitudinal joints developed in Iowa.
2. Develop each promising concept so that it can be evaluated.
3. Evaluate each concept, providing its expected reliability, durability, and cost-effectiveness. Include crack forming in CRCP.
4. Recommend concepts for further development and testing.

Benefits:	Jointing alternatives that are significantly more reliable, cost effective, and durable than those currently in use.
Products:	Recommended new and innovative joint design, materials, and construction alternatives.
Implementation:	The innovative joint concepts developed in this research will be used in many research activities throughout track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction).

Problem Statement IJ 1.2. Select Promising Innovative Joint Design, Materials, and Construction Concepts and Further Develop to Trial Test Stage

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 3–7
Estimated Cost:	$700 k–$900 k

Many new and innovative concepts are expected to be found for joint design, materials, and construction concepts. These concepts will be evaluated further for such key aspects as reliability, cost-effectiveness, durability, ease of construction, maintainability, and others. A national group of experts then will select the most promising concepts to be developed into more detailed designs, plans, experimental designs, and specifications for construction and testing in future tasks. This research should consider crack forming in CRCP.

Tasks:

1. Evaluate new and innovative joint design, materials, and construction concepts based on a wide range of criteria. Consider major concrete pavement applications, including low-volume roads and streets, concrete overlays of varying thicknesses, high-traffic concrete pavements, and other special concrete pavement uses.
2. Formally select the most promising concepts after further testing and development.
3. For each of the concepts selected, fully develop the concept so that it can be tested appropriately, using accelerated load facilities, laboratory testing, and full-scale field construction and testing on actual highways.
4. Summarize results and document reports that include everything needed for construction and testing.

Benefits:	Laboratory, accelerated field, and longer term field testing of one or more concrete pavement joint concepts.
Products:	Complete design, materials, and construction details on joint concepts.
Implementation:	The innovative joint designs, materials, and construction concepts resulting from this research will be tested and evaluated under problem statement IJ 2.1 (Construction, Testing, and Evaluation of Promising Concrete Pavement Joint Design Concepts). States may implement some of the concepts immediately.

Problem Statement IJ 1.3. Optimization of Mechanical Load Transfer Devices for Load Transfer Efficiency and Deterioration Models

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 4–7
Estimated Cost:	$600 k–$800 k

The *Mechanistic-Empirical Pavement Design Guide* and other mechanistic design procedures directly model the effects of dowel bar diameter on faulting performance.[1] However, other aspects of doweled joint design, such as dowel length and spacing, are not considered directly. While most States currently use 46-cm (18-inch)-long dowel bars with uniform, 30-cm (12-inch) spacing, the dowel bars located outside the wheel paths have little to no effect on critical pavement response and could be left out without adversely affecting pavement performance. Moreover, recent European research suggests that shorter dowel bars may be as effective as long dowel bars. European practice also suggests that smaller diameter dowels spaced more closely together (e.g., 25 cm (10 inches)) may produce good pavement performance. In addition, joint cost must be considered in implementation.

Innovative dowel bar designs, such as elliptical dowel bars recently tested and constructed in the United States, also may provide significant performance and/or cost advantages. In addition, dowels made of fiberglass, stainless steel, and a variety of other corrosion-resistant coverings are available. These alternative load transfer designs may substantially reduce initial pavement cost without reducing long-term pavement performance, at least in some cases. This research will optimize load transfer design by conducting comprehensive analytical modeling, laboratory testing, and field performance studies. The research findings will result in practical guidelines for load transfer design.

Tasks:

1. Conduct a worldwide literature search, interviews with experienced engineers, and field surveys of existing high-performance concrete pavement sites to determine the state-of-the-art mechanical load transfer.
2. Identify ways to optimize mechanical load transfer devices at transverse joints for various highway and street classes and evaluate each for feasibility (cost-effectiveness, reliability, constructability (consider, for example, bottom-up crack initiators), maintainability).
3. Investigate the conditions that require mechanical devices to control differential deflections, erosion, faulting, and cracking of JCPs for all functional classifications of highways and streets, as well as special applications.
4. Analyze and evaluate each proposed concept. Recommend concepts that should be developed and tested further. Develop a plan for this work.
5. Consider major concrete pavement applications, including low-volume roads and streets, concrete overlays of varying thicknesses, high-traffic concrete pavements, and other special concrete pavement uses.
6. Further develop and test concepts (lab, accelerated loading, full-scale field testing).
7. Prepare a final research report and implementation guide for optimizing mechanical load transfer devices.

Benefits:	Cost effective, reliable, and durable load transfer devices for concrete pavement joints.
Products:	Recommendations and guidelines for improved load transfer devices for LTE of joints; validated and implementable procedures and guidelines that optimize joint load transfer systems for use with transverse concrete pavement joints.
Implementation:	This research will be implemented directly into concrete pavement design procedures. Some agencies will implement experimental sections immediately.

Problem Statement IJ 1.4. Development of an Advanced, High-Speed Joint Analysis Tool

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 4–7
Estimated Cost:	$1 M–$2 M

Adequate joint design is essential to the long-term performance of JCPs. Consequently, evaluating the adequacy of joint designs depends on the ability to predict joint performance by considering the effects that combinations of pavement design, site, climate, and construction factors have on performance. Though the *Mechanistic-Empirical Pavement Design Guide* contains innovative methods for assessing joint design based on mechanistic principles (e.g., load transfer deterioration models, effect of dowels), no automated modeling tools exist that comprehensively evaluate joint design effectiveness and its impact on future pavement performance.(1) This study will develop such a tool. The model developed with this research could be implemented as a stand-alone procedure or incorporated into an overall design procedure, such as the *Mechanistic-Empirical Pavement Design Guide*. Results from this type of evaluation then can be included in mechanistic-based models to predict joint deterioration, pumping, and faulting.

Tasks:

1. Evaluate all available FEM and other joint models. Determine whether any might be used after further development or would fit the needs of this work.
2. Identify the specific goals, objectives, and scope of this joint analysis tool. Include data on crack deterioration in CRCP.
3. Develop an advanced, high-speed, computerized joint analysis tool.
4. Validate the tool using available experimental data.
5. Prepare a user's guide and technical documentation for the joint analysis tool, along with examples and limitations.

Benefits:	Ability to analyze a wide variety of joint systems three-dimensionally to help evaluate and develop new and innovative joint systems.
Products:	FEM model that provides advanced and high-speed analysis of complex joint systems under traffic and climatic loadings that researchers and designers could use to determine joint design adequacy.
Implementation:	This research will analyze joint designs for trial construction under problem statement IJ 2.1 (Construction, Testing, and Evaluation of Promising Concrete Pavement Joint Design Concepts). The model developed could also further research and development work and be used by States in special joint design for critical projects.

Problem Statement IJ 1.5. Development of Advanced Joint Sealing Procedures

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 6–9
Estimated Cost:	$1.5 M–$2.5 M (cost share of $1 M by industry)

Joint sealing has become a major issue in concrete pavement design. Sealing JCP joints (both immediately after construction and during routine maintenance and rehabilitation) is costly and can influence significantly the overall life cycle cost of JCPs. Joint sealing is thought to minimize the extent to which precipitation penetrates the pavement structure, thus preventing the base course or subgrade erosion that eventually causes joint faulting, loss of support, and related cracking. By minimizing moisture infiltration, joint sealing may also reduce durability-related distresses, such as PCC D-cracking. Joint sealing is also thought to prevent solid particles (including aggregates) from filling up joint openings, reducing the likelihood of joint spalling and blowups. However, whether joint sealing extends pavement life is questionable. At least one State has stopped sealing joints, replacing the seal with a single narrow sawcut, leaving nothing in the joints. Several others have constructed test sections with both thin-cut, nonsealed joints and alternative joint seals to evaluate performance. A major FHWA study currently underway will evaluate existing data on sealed and nonsealed joint performance. Meanwhile, studies show that the incompressibles that infiltrate joints can push bridge back walls and abutments and seriously damage them. Also, blowups caused by incompressibles have occurred on many longer jointed reinforced pavements (no longer built) and a few short jointed pavements. Clearly, more advanced joint modeling and testing with and without seals will shed more light on this issue and allow for more informed decisions. This study will develop a mechanistic model demonstrating joint infiltration by water and incompressibles that can analyze the impacts of both. The model should also be able to test nonsealed joints of optimum configurations.

Tasks:

1. Collect and summarize all research studying sealed and nonsealed joint performance and the current techniques for modeling water and incompressible intrusion and migration into PCC pavements. Synthesize the results.
2. Develop an advanced analytical approach to joint movement, sealing, and infiltration for use in this and future studies. Predict hourly movements over several years using EICMs and FEMs. Model the potential damage caused when incompressibles infiltrate joints and result in stress buildup. Ensure that the model handles all types of conventional concrete base courses, joint spacing, and thermal coefficients of expansion. Validate the model using laboratory and inservice pavements.
3. Identify new and innovative seals and nonsealed configurations that can be tested with the water and incompressible infiltration models and field tested to address long-term pavement needs.
4. Construct a series of test sections to evaluate the new sealing and nonsealing concepts. Document the results and recommend the most promising approach to sealing or not sealing joints, both longitudinal and transverse, in all geographic areas in the United States.

Benefits:	Resolution to the sealing or nonsealing joint issue that improves long-term concrete pavement cost-effectiveness, performance, and reliability.
Products:	A lab- and field-validated comprehensive model for joint movement over annual climate cycles, joint infiltration models for water and incompressibles, and an FEM model of the joint and pavement structure that analyzes the impacts of water and incompressibles on pressure buildup, spalling, and base and subgrade erosion; research linked to the model developed under problem statement DG 1.3 (Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading) in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements).
Implementation:	The results of this research will be implemented immediately into the *Mechanistic-Empirical Pavement Design Guide* and by States.

Problem Statement IJ 1.6. Guidelines for Implementing New and Innovative Joint Design, Materials, and Construction Concepts

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 1. Joint Design Innovations
Approximate Phasing:	Years 7–10
Estimated Cost:	\$300 k–\$500 k

The extensive research and development conducted under track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction) must be documented in detailed joint design guidelines. The research findings from this research track must also be documented. This will include detailing the design, materials, and construction of each of the concepts as well as assessing the overall performance of their promise to improve conventional joint technology and procedures.

Tasks:

1. Summarize the potential for the pavement joint design, materials, and construction procedures developed in track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction) to provide a significant improvement over conventional joint designs, materials, and construction procedures if fully implemented.
2. Develop practical manuals and guidelines for designing and constructing the innovative pavement joint concepts developed in this track.
3. Provide assistance for implementing the new innovative pavement joint designs, materials, and construction procedures.

Benefits:	Direct assistance for immediately implementing the entire work of this innovative joint track.
Products:	Practical manuals and guidelines that can be used by those involved in designing and constructing innovative concrete pavement joint concepts; major applications of concrete pavements, including low-volume roads and streets, concrete overlays of varying thicknesses, high-traffic concrete pavements, and other special concrete pavement uses, as well as crack forming in CRCP and joint design for precast pavements.
Implementation:	This research will result in a joint manual to be used by designers and engineers.

SUBTRACT IJ 2. JOINT MATERIALS, CONSTRUCTION, EVALUATION, AND REHABILITATION INNOVATIONS

This research in this subtrack will construct and rehabilitate joints in the field. Table 34 provides an overview of this subtrack.

Table 34. Subtrack IJ 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
IJ 2.0. Framework for Joint Materials, Construction, Evaluation, and Rehabilitation Innovations (Subtrack IJ 2)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
IJ 2.1. Construction, Testing, and Evaluation of Promising Concrete Pavement Joint Design Concepts	$2.5 M–$4 M	Laboratory tests, accelerated loading tests, and field tests of several new and innovative joint designs, materials, and construction concepts that have been developed and validated or proven inadequate. Successful and cost effective concepts will be well documented.	Laboratory and field validation of joint design, materials, and construction concepts.
IJ 2.2. Development of Innovative Ways for Detecting Joint Deterioration in New and Older Pavements	$1 M–$1.5 M	Validated and implementable procedures and guidelines for rapidly and reliably evaluating existing concrete pavement joints to determine preservation and repair treatments as well as structural and functional condition.	Procedures to evaluate and recommend preservation and repair actions for existing joints.
IJ 2.3. Determining the Need and Identifying the Feasibility of Alternative Ways to Provide Pressure Relief and Load Transfer Efficiency for Concrete Pavements	$500 k–$700 k	Guidelines for using pressure relief joints (PRJ) that will be made available to practicing engineers and highway agencies, resulting in better understanding of the needed locations and design of PRJs in concrete pavements.	Fewer problems associated with pressure buildup and PRJs in all aspects of concrete pavements.

Problem Statement IJ 2.0. Framework for Joint Materials, Construction, Evaluation, and Rehabilitation Innovations (Subtrack IJ 2)

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 2. Joint Materials, Construction, Evaluation, and Rehabilitation Innovations
Approximate Phasing:	Years 1–3
Estimated Cost:	$200 k

Subtrack IJ 2 (Joint Materials, Construction, Evaluation, and Rehabilitation Innovations) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack IJ 2 (Joint Materials, Construction, Evaluation, and Rehabilitation Innovations), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack IJ 2 (Joint Materials, Construction, Evaluation, and Rehabilitation Innovations).

Problem Statement IJ 2.1. Construction, Testing, and Evaluation of Promising Concrete Pavement Joint Design Concepts

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 2. Joint Materials, Construction, Evaluation, and Rehabilitation Innovations
Approximate Phasing:	Years 4–10
Estimated Cost:	\$2.5 M–\$4 M (excluding construction costs, only includes engineering and testing and reporting) (Cost sharing of \$1 M by industry)

Each new and innovative concept must be proven in the lab and field. With the results from problem statements IJ 1.1 (Identify, Develop, and Evaluate Innovative Concepts for Joint Design, Materials, and Construction) and IJ 1.2 (Select Promising Innovative Joint Design, Materials, and Construction Concepts and Further Develop to Trial Test Stage), this research will construct experimental joints using both accelerated loading equipment and inservice highways. The concepts recommended for ALFs will be the ones that primarily depend on repeated axle loads, as this is the primary tool for evaluating these concepts. The inservice joint concepts evaluated over the long term would be constructed on regular highways subjected to normal traffic loadings. These studies will consider major concrete pavement applications, including low-volume roads and streets, concrete overlays of varying thicknesses, high-traffic concrete pavements, and other special concrete pavement uses. This research will also consider crack forming in CRCP and precast pavement joints.

Tasks:

1. Construct the accelerated loading joint concepts, begin testing, and document findings.
2. Construct the inservice highway joint concepts, begin testing, and document findings. Work with States that have shown an interest in the work.
3. Document all research and testing results and modify the work plans as results become available. Determine the cost of the various concepts for use in cost-effectiveness studies.
4. Prepare detailed and comprehensive or brief summaries of the key findings obtained from the previous work.

Benefits:	Laboratory and field validation of joint design, materials, and construction concepts.
Products:	Laboratory tests, accelerated loading tests, and field tests of several new and innovative joint design, materials, and construction concepts that have been developed and validated or proven inadequate. Successful and cost effective concepts will be well documented.
Implementation:	This research will provide field validation for several innovative concrete pavement joint concepts.

Problem Statement IJ 2.2. Development of Innovative Ways for Detecting Joint Deterioration in New and Older Pavements

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 2. Joint Materials, Construction, Evaluation, and Rehabilitation Innovations
Approximate Phasing:	Years 2–6
Estimated Cost:	$1 M–$1.5 M

The condition of longitudinal and transverse joints is critical for identifying the appropriate preservation or rehabilitation strategy. Detailed joint condition information is also important for evaluating joint design effectiveness. Thus, the ability to detect and monitor potential problems such as the following is important for characterizing joint performance:

- Looseness.
- Problematic positioning.
- Aggregate interlock wearout.
- Consolidation.
- PCC deterioration around dowel bars.
- PCC fracture in the joint area.

Various devices capable of providing tomographic images of concrete may be used in this application, including the impact-echo device and the MIT scan for locating the dowels and tie bars. This research will develop a mostly nondestructive method for evaluating and quantifying functional (e.g., faulting, spalling) and structural joint condition (e.g., LTE, opening, and closing). Adequate concrete consolidation around the dowel bars is important for good joint performance, both immediately after construction and over time, also and must be measured.

Tasks:

1. Conduct a worldwide literature survey and interview experts to identify the technologies available for determining a joint's functional and structural condition to carry heavy traffic loadings over time. This joint could be a new or an older pavement.
2. Identify procedures, equipment, methodologies, and concepts that have been or could be used for joint evaluation. Summarize these in a concise document for an expert review panel. Based on the panel results, select the most promising technologies to produce a nearly or completely nondestructive testing procedure to evaluate concrete pavement joints.
3. Conduct a field survey and analysis of tie bar and X-stitching performance and installation for longitudinal joints and random cracks.
4. Analyze and evaluate each technology. Recommend technologies to be advanced for further development and testing. Develop a plan for this needed work.
5. Perform the additional development and testing work (lab, accelerated loading, and full-scale field testing).
6. Prepare a final research report and implementation guide for ways to evaluate concrete pavement joints to determine their functional and structural conditions.

Benefits:	Procedures to evaluate and recommend preservation and repair actions for existing joints.
Products:	Validated and implementable procedures and guidelines for rapidly and reliably evaluating existing concrete pavement joints to determine preservation and repair treatments as well as structural and functional condition.
Implementation:	The joint deterioration detection methods developed in this research will be implemented immediately.

Problem Statement IJ 2.3. Determining the Need and Identifying the Feasibility of Alternative Ways to Provide Pressure Relief and Load Transfer Efficiency for Concrete Pavements

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 2. Joint Materials, Construction, Evaluation, and Rehabilitation Innovations
Approximate Phasing:	Years 6–9
Estimated Cost:	\$500 k–\$700 k

Providing PRJs, both with and without mechanical load transfer, has created problems, because these joints often do not function properly and require premature maintenance. Controversy has arisen over where PRJs are needed and even whether they are useful, since some studies show that they may not have any positive value. This research will examine whether PRJs might be needed, locations at which PRJs might help avoid pressure buildup problems, and finally, ways in which PRJs can be designed with mechanical load transfer.

Tasks:

1. Conduct a worldwide literature search for PRJs and their design, use, and effectiveness. Summarize the findings, including case studies wherever available (e.g., the use of regular expansion joints on the Illinois State Toll Highway Authority and the experience several States have had placing and maintaining PRJs). Include a summary of the technical information available for calculating the pressures and mechanisms involved. Also summarize the designs of joint load transfer efficiencies where possible.
2. Based on field surveys and expert interviews (along with the literature survey), prepare a case-by-case study in which PRJs were incorporated into various projects, including the projects' performance and needs. Document these studies.
3. Based on these results, prepare guidelines for using PRJs that practicing engineers can use.

Benefits:	Fewer problems associated with pressure buildup and PRJs in all aspects of concrete pavements.
Products:	Guidelines for using PRJs that will be made available to practicing engineers and highway agencies, resulting in better understanding of the needed locations and design of PRJs in concrete pavements.
Implementation:	The PRJ methods resulting from this research will be implemented immediately.

SUBTRACK IJ 3. INNOVATIVE JOINTS IMPLEMENTATION

This research in this subtrack implements the results from the previous two subtracks. Table 35 provides an overview of this subtrack.

Table 35. Subtrack IJ 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
IJ 3.1. Implementation of Innovative Joint Design, Materials, and Construction	$800 k–$1 M	Strong technology transfer of innovative concrete pavement joint design, materials, and construction to the workforce, using workshops, conferences, and Web-based personnel training; a workforce and management that knows the new procedures, guidelines, and models to better design, construct, and specify materials related to concrete pavement joints.	A workforce with the basic knowledge and understanding to design, specify materials, and construct new and innovative concrete pavement joints.

Problem Statement IJ 3.1. Implementation of Innovative Concrete Pavement Joint Design, Materials, and Construction

Track:	6. Innovative Concrete Pavement Joint Design, Materials, and Construction (IJ)
Subtrack:	IJ 3. Innovative Joints Implementation
Approximate Phasing:	Years 2–10
Estimated Cost:	$800 k–$1M

Implementing innovative concrete pavement joint design, materials, and construction requires significant efforts, both in training the workforce and assuring management that the new concepts are feasible and reliable. This research will address both of these efforts. The results from many other tracks will help develop innovative joint concepts and will be coordinated closely with this research without duplicating efforts. For example, track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements) will provide new knowledge and procedures for base course erosion; see problem statement DG 1.3 (Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading).

Tasks:

1. Develop and present workshops dealing with many aspects of the mechanistic design process that focus on joint design, materials, and construction.
2. Organize national conferences and workshops about the joint design, materials, and construction process, at which States and other highway agencies share their findings.
3. Develop Web-based, online training tools.

Benefits:	A workforce with the basic knowledge and understanding to design, specify materials, and construct new and innovative concrete pavement joints.
Products:	Strong technology transfer of innovative concrete pavement joint design, materials, and construction to the workforce, using workshops, conferences, and Web-based personnel training; a workforce and management that knows the new procedures, guidelines, and models to better design, construct, and specify materials related to concrete pavement joints.
Implementation:	This work will provide the technology transfer critical to the success of the innovative joints track.

Track 7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)

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TRACK 7 (RC) OVERVIEW

For nearly 15 years, the concrete pavement industry has confronted both facts and perceptions about concrete pavement construction under high-speed traffic conditions. While the industry's record is generally positive, perceptions still determine concrete use in many situations. The traffic growth data presented in chapter 1 in the first volume of the CP Road Map show that, despite the gains made in the past decade, concrete pavements across the country will continue to be in need of rehabilitation under high-speed traffic conditions.

The next generation of construction and rehabilitation tools combines the software and hardware required to simulate system design and predict problems that might surface during high-speed construction. High-speed computer simulation can troubleshoot a pavement's response to environmental changes, as well. Effective construction management, however, remains critical for meeting the goals and objectives of this track.

Future high-speed construction challenges the industry to move away from slipform paving and identify ways to make precast construction a more viable alternative. Precast modular construction not only might replace ultrahigh-speed construction but also improve product quality and extend the paving system. Research in this track will include:

- Planning and simulation for high-speed construction and rehabilitation.
- Precast and modular options for concrete pavements.
- Fast-track concrete pavement construction and rehabilitation.
- Evaluation and technology transfer of high-speed construction and rehabilitation products and processes developed through research.

Some high-speed construction issues also are investigated in other research tracks, and those efforts will be coordinated closely with those in this track. For example, track 1 (Performance-Based Concrete Pavement Mix Design System) and track 3 (High-Speed Nondestructive Testing and Intelligent Construction Systems) contain many elements required in a high-speed option.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

This track will explore new and existing products and technologies that facilitate high-speed rehabilitation and construction of PCC pavements.

Track Objectives

1. Develop planning and simulation tools that allow contractors, designers, and owner-agencies to identify potential problems before construction begins and to identify the most efficient processes.
2. Explore and refine precast and modular pavement technology for new construction, rehabilitation, and maintenance.
3. Refine fast-track construction technologies and techniques, and synthesize them into best practice guidelines for contractors, designers, and owner-agencies.
4. Provide the means for all contractors, designers, and owner-agencies to learn about new high-speed construction and rehabilitation products and technologies.

Research Gaps

- Lack of easy-to-use and practical education tools.
- Insufficient data and methodology for calculating user benefits from high-speed construction.
- Insufficient understanding of ways to control potential long-term durability problems resulting from high-speed construction.
- Lack of user knowledge.

Research Challenges

- Develop easy-to-use and understandable products and portable user-friendly software for contractors, designers, and owner-agencies.
- Quantify the user costs versus benefits of high-speed rehabilitation and construction products to allow owner-agencies to realize the economic benefit.
- Assess the long-term durability of various high-speed rehabilitation and construction techniques.
- Address the perception that concrete is an inherently slow construction process.

Research Track 7 (RC) Phasing

The horizontal bar chart in figure 7 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

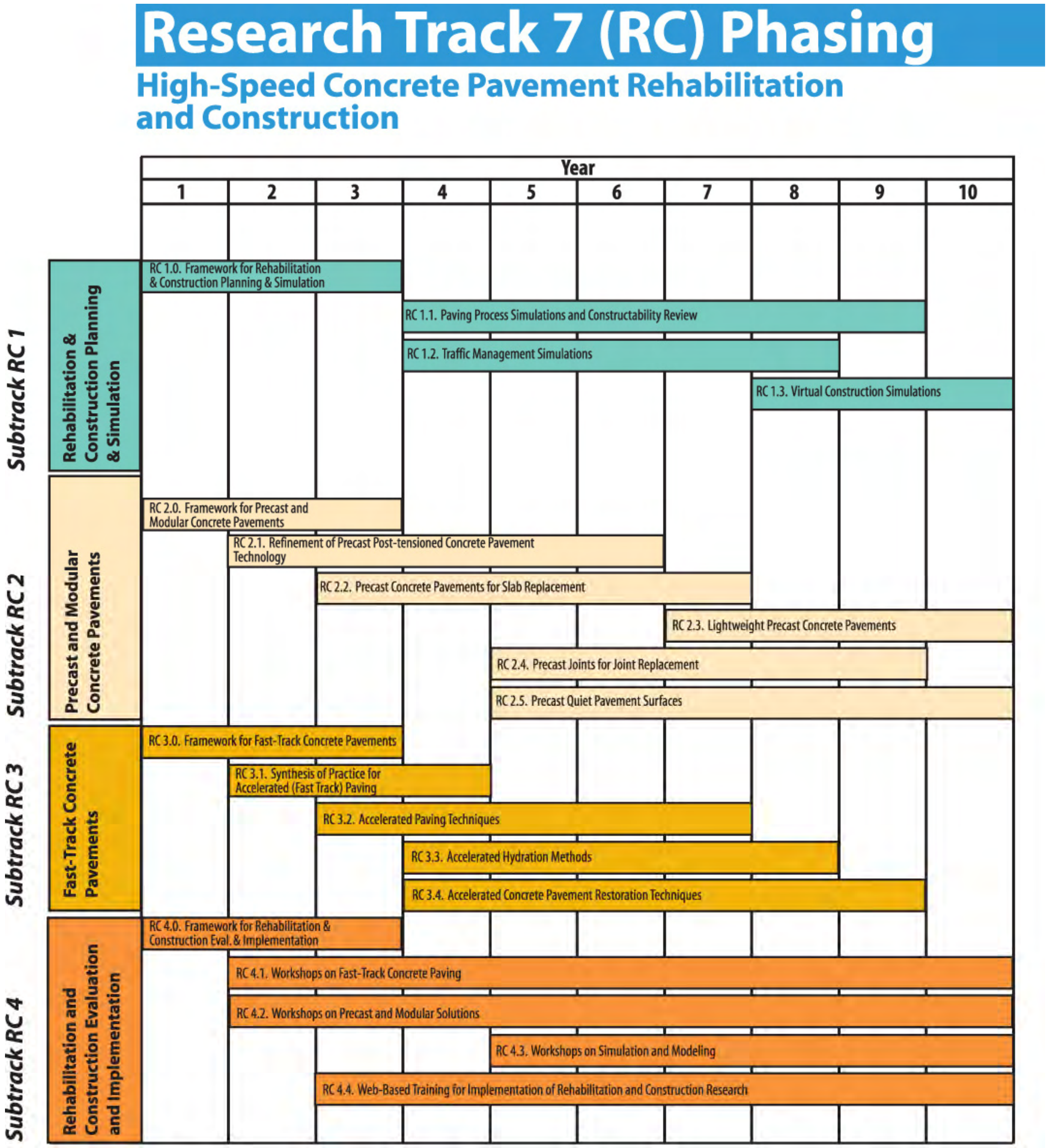

Figure 7. Track 7 (RC) subtrack and problem statement phasing chart.

Research Track 7 (RC) Estimated Costs

Table 36 shows the estimated costs for this research track.

Table 36. Research track 7 (RC) estimated costs.

Problem Statement	Estimated Cost
Subtrack RC 1. Rehabilitation and Construction Planning and Simulation	
RC 1.0. Framework for Rehabilitation and Construction Planning and Simulation (Subtrack RC 1)	$350 k
RC 1.1. Paving Process Simulations and Constructability Review	$1 M–$2 M
RC 1.2. Traffic Management Simulations	$500 k–$1 M
RC 1.3. Virtual Construction Simulations	$500 k–$1 M
Subtrack RC 2. Precast and Modular Concrete Pavements	
RC 2.0. Framework for Precast and Modular Concrete Pavements (Subtrack RC 2)	$400 k
RC 2.1. Refinement of Precast Posttensioned Concrete Pavement Technology	$500 k–$1 M
RC 2.2. Precast Concrete Pavements for Slab Replacement	$500 k–$1 M
RC 2.3. Lightweight Precast Concrete Pavements	$250 k–$500 k
RC 2.4. Precast Joints for Joint Replacement	$500k-$1 M
RC 2.5. Precast Quiet Pavement Surfaces	$500 k–$1 M
Subtrack RC 3. Fast-Track Concrete Pavements	
RC 3.0. Framework for Fast-Track Concrete Pavements (Subtrack RC 3)	$400 k
RC 3.1. Synthesis of Practice for Accelerated (Fast-Track) Paving	$250 k–$500 k
RC 3.2. Accelerated Paving Techniques	$500 k–$1 M
RC 3.3. Accelerated Hydration Methods	$500 k–$1 M
RC 3.4. Accelerated Concrete Pavement Restoration Techniques	$500 k–$1 M
Subtrack RC 4. Rehabilitation and Construction Evaluation and Implementation	
RC 4.0. Framework for Rehabilitation and Construction Evaluation and Implementation (Subtrack RC 4)	$150 k
RC 4.1. Workshops on Fast-Track Concrete Paving	$1 M–$2 M
RC 4.2. Workshops on Precast and Modular Concrete Pavement Solutions	$1 M–$2 M
RC 4.3. Workshops on Rehabilitation and Construction Simulation and Modeling	$500 k–$1 M
RC 4.4. Web-Based Training for Implementation of Rehabilitation and Construction Research	$500 k–$1 M
Track 7 (RC)	
Total	$10.3 M–$20.3 M

Track Organization: Subtracks and Problem Statements

Track 7 (RC) problem statements are grouped into four subtracks:

- Subtrack RC 1. Rehabilitation and Construction Planning and Simulation.
- Subtrack RC 2. Precast and Modular Concrete Pavements.
- Subtrack RC 3. Fast-Track Concrete Pavements.
- Subtrack RC 4. Rehabilitation and Construction Evaluation and Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK RC 1. REHABILITATION AND CONSTRUCTION PLANNING AND SIMULATION

This subtrack frames new and innovative ways to conduct high-speed rehabilitation and construction, relying on the creative use of simulation tools. Table 37 provides an overview of this subtrack.

Table 37. Subtrack RC 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
RC 1.0. Framework for Rehabilitation and Construction Planning and Simulation (Subtrack RC 1)	$350 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
RC 1.1. Paving Process Simulations and Constructability Review	$1 M–$2 M	Easy-to-use paving process simulation tools (software) and a constructability review manual for concrete paving.	New tools that contractors and owner-agencies can use to simulate the paving process before construction, allowing them to identify potential problems and optimize equipment and materials; a constructability review manual for concrete paving that will allow owner-agencies to assess rationally the potential for success of a given construction plan.
RC 1.2. Traffic Management Simulations	$500 k–$1 M	Easy-to-use traffic management simulation tools (software).	New tools that contractors, designers, and owner-agencies can use to simulate different traffic management scenarios before construction, allowing them to identify potential problems and select the optimal traffic management scenario.
RC 1.3. Virtual Construction Simulations	$500 k–$1 M	Construction simulation software that considers both the paving process and traffic management.	New tools that will allow contractors, designers, and owner-agencies to simulate the entire construction process virtually before actual construction, allowing them to identify potential problems.

Problem Statement RC 1.0. Framework for Rehabilitation and Construction Planning and Simulation (Subtrack RC 1)

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 1. Rehabilitation and Construction Planning and Simulation
Approximate Phasing:	Years 1–3
Estimated Cost:	$350 k

Subtrack RC 1 (Rehabilitation and Construction Planning and Simulation) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack RC 1 (Rehabilitation and Construction Planning and Simulation), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack RC 1 (Rehabilitation and Construction Planning and Simulation).

Problem Statement RC 1.1. Paving Process Simulations and Constructability Review

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 1. Rehabilitation and Construction Planning and Simulation
Approximate Phasing:	Years 4–9
Estimated Cost:	$1 M–$2 M

Recent projects, such as the 55-hour weekend reconstruction of I–10 near Pomona, CA, have demonstrated the viability of rapid pavement reconstruction. This and similar projects have also demonstrated the need for advanced planning and preparation to ensure project success under strict time constraints. Advanced planning will ensure optimal construction staging, equipment utilization, mixing procedures, and hauling processes. Time-motion and production-cost analyses are two examples of analysis techniques that can be used for this type of optimization. A formal constructability review manual will be developed to assist in better planning. Rehabilitation and construction process simulations, which incorporate time-motion and production-cost analyses, will be a powerful tool for optimizing project planning and preparation to ensure the success of time-restrictive pavement construction and rehabilitation. Simulations will allow contractors and transportation agencies to analyze the flow of rehabilitation or new construction projects well in advance of actual construction, anticipating potential problems that may prevent the time requirements from being met.

Tasks:

1. Identify construction process simulation techniques/models currently available (such as those used in the bridge and building industries). Identify problems or limitations of current simulation techniques/models based on contractor/agency experience.
2. Identify existing constructability review techniques and guidelines.
3. Evaluate the current simulation techniques and constructability review guidelines for their applicability to concrete paving projects.
4. Identify agency and contractor needs for expedited pavement construction (e.g., typical rehabilitation or construction timeframes required).
5. Identify constraints for expedited pavement construction (e.g., equipment limitations, concrete mix characteristics, and construction staging).
6. Develop simulation techniques/models that account for both contractor/agency requirements and constraints, building on the successes of existing simulation models.
7. Develop a case study that demonstrates the simulation technique/model on an actual construction project.
8. Refine the simulation techniques/models as needed based on the case study.
9. Develop a constructability review manual for concrete paving, employing peer review and revision during the development process.

Benefits:	New tools that contractors and owner-agencies can use to simulate the paving process before construction, allowing them to identify potential problems and optimize equipment and materials; a constructability review manual for concrete paving that will allow owner-agencies to assess rationally the potential for success of a given construction plan.
Products:	Easy-to-use paving process simulation tools (software) and a constructability review manual for concrete paving.
Implementation:	This research will result in easy-to-use tools (i.e., software and a constructability review manual) for contractors, designers, and owner-agencies to perform rehabilitation and construction process simulations and reviews.

Problem Statement RC 1.2. Traffic Management Simulations

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 1. Rehabilitation and Construction Planning and Simulation
Approximate Phasing:	Years 4–8
Estimated Cost:	$500 k–$1 M

Traffic management is a crucial aspect of any pavement rehabilitation/construction project but is particularly important for rapid rehabilitation and construction projects where construction often is conducted under traffic. Rapid rehabilitation/construction work under traffic burdens both the highway agency and contractor to produce a high-quality pavement while minimizing traffic delay and maximizing traffic safety. In some cases, the option of a long life pavement is ruled out for such projects because of skepticism that it can be built with minimal user delays. Moreover, in certain situations, user costs and delays can outweigh all other considerations for pavement construction, reconstruction, or rehabilitation. In these cases, special steps must be taken to minimize lane closures and reduced traffic access. Proper traffic management better ensures the safety of workers and helps minimize traffic congestion during construction. However, developing a traffic management plan to satisfy both objectives is extremely difficult and often very costly. Generally, traffic management plans are developed for a specific project based on previous experience within a localized region. Thus, for similar project circumstances across the country, significant variance in traffic handling options can and does occur. Many agencies employ less-than-optimal approaches to managing traffic, which result in extra costs, safety concerns, and significant user delays. A solution to this problem would be to develop techniques or models for simulating different traffic management scenarios based on the requirements of individual projects. These techniques/models will allow the contractor or owner-agency to simulate different traffic management strategies well in advance of construction, allowing them to identify problems and select the optimal strategy.

Tasks:

1. Identify traffic management techniques/models currently used by owner-agencies.
2. Identify problems or limitations of current techniques/models based on contractor/agency experience.
3. Identify agency constraints for traffic management (e.g., typical rehabilitation or construction timeframe, and restrictions on traffic diversion).
4. Identify viable models for user cost prediction of traffic management and life cycle cost models for concrete pavements.
5. Develop simulation techniques/models that account for both contractor/agency requirements and constraints.
6. Develop a case study that demonstrates the simulation technique/model on an actual construction project.
7. Refine the simulation techniques/models as needed based on the case study.
8. Develop agency/contractor interactive alternative models.

Benefits:	New tools that contractors, designers, and owner-agencies can use to simulate different traffic management scenarios before construction, allowing them to identify potential problems and select the optimal traffic management scenario.
Products:	Easy-to-use traffic management simulation tools (software).
Implementation:	This research will result in easy-to-use tools (i.e., software) that contractors, designers, and owner-agencies can use for traffic management simulations.

Problem Statement RC 1.3. Virtual Construction Simulations

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 1. Rehabilitation and Construction Planning and Simulation
Approximate Phasing:	Years 8–10
Estimated Cost:	$500 k–$1 M

Recently, a number of industries have been turning to simulation tools to assess potential issues that could arise during the execution of industry processes. A notable example is the aerospace industry, which conducts numerous tests of aircraft and aircraft components using virtual simulations. In these simulations, the components are “assembled” using computers, and the process is monitored at critical points and compared to threshold values. Stresses, for example, are compared to strengths. Time is recorded, and efficiency statistics derived. This research will explore and synthesize this technology and others like it in the hope of applying the same concepts to the concrete pavement construction process. The virtual simulations will consider both the paving process and traffic management strategies to optimize not only the construction process, but also the total cost, including user costs. The simulations will allow contractors and owner-agencies to perform virtual simulations of a complete concrete pavement construction or rehabilitation project to evaluate overall costs, identify problems, and determine an optimal construction process.

Tasks:

1. Identify and evaluate existing virtual simulation models used in different industries.
2. Evaluate aspects of existing virtual simulation models applicable to concrete pavement construction and rehabilitation simulation models.
3. Develop a virtual simulation model that considers both the paving or rehabilitation process and the traffic management strategy.
4. Develop a case study that applies the virtual simulation model to an actual construction project.
5. Refine the virtual simulation model as needed based on the case study.

Benefits:	New tools that will allow contractors, designers, and owner-agencies to simulate the entire construction process virtually before actual construction, allowing them to identify potential problems.
Products:	Construction simulation software that considers both the paving process and traffic management.
Implementation:	This research will result in easy-to-use tools (i.e., software) that contractors, designers, and owner-agencies can use for virtual construction simulations.

SUBTRACK RC 2. PRECAST AND MODULAR CONCRETE PAVEMENTS

This subtrack organizes the entire modular concrete pavement concept so that it can be used for both high-speed and high-durability situations. Table 38 provides an overview of this subtrack.

Table 38. Subtrack RC 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
RC 2.0. Framework for Precast and Modular Concrete Pavements (Subtrack RC 2)	$400 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
RC 2.1. Refinement of Precast Posttensioned Concrete Pavement Technology	$500 k–$1 M	Design standards, specifications, and best practice guides for precast, prestressed (posttensioned) concrete pavement.	Best practice guidelines for precast, prestressed concrete pavement technology, helping owner-agencies develop design standards and specifications.
RC 2.2. Precast Concrete Pavements for Slab Replacement	$500 k–$1 M	Design standards, specifications, and best practice guidelines for using precast concrete in full-depth slab replacement.	Best practice guidelines for using precast panels in full-depth slab replacement.
RC 2.3. Lightweight Precast Concrete Pavements	$250 k–$500 k	Recommendations for weight-reducing technologies for precast concrete pavement.	Exploration of possible weight-reducing technologies for precast concrete pavement.
RC 2.4. Precast Joints for Joint Replacement	$500k-$1 M	Design standards, specifications, and best practice guidelines for using precast panels for joint replacements.	Best practice guidelines for using precast concrete panels for joint replacement.
RC 2.5. Precast Quiet Pavement Surfaces	$500 k–$1 M	Recommendations for noise-reducing techniques for precast concrete pavement surfaces.	Exploration of noise-reducing techniques that may not be viable for conventional concrete pavements but that can be incorporated into precast concrete pavements.

Problem Statement RC 2.0. Framework for Precast and Modular Concrete Pavements (Subtrack RC 2)

Track: 7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack: RC 2. Precast and Modular Concrete Pavements
Approximate Phasing: Years 1–3
Estimated Cost: $400 k

Subtrack RC 2 (Precast and Modular Concrete Pavements) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack RC 2 (Precast and Modular Concrete Pavements), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.

Products: A validated, sequenced, and detailed research framework for this subtrack.

Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack RC 2 (Precast and Modular Concrete Pavements).

Problem Statement RC 2.1. Refinement of Precast, Posttensioned Concrete Pavement Technology

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 2. Precast and Modular Concrete Pavements
Approximate Phasing:	Years 2–6
Estimated Cost:	$500 k–$1 M

Precast concrete offers a durable, lasting solution for rapid construction of PCC pavement. A 1998 feasibility study, completed by the Center for Transportation Research at the University of Texas at Austin, concluded that precast, prestressed concrete pavement was a viable option for large-scale rapid reconstruction of PCC pavements. The concept that resulted from the feasibility study incorporates both pretensioning and posttensioning in the precast panels to reduce the required slab thickness as well as improve the durability of the finished pavement. Subsequent implementation studies resulted in the construction of precast, prestressed pavement demonstration projects in California and Texas. Despite the successes of these demonstration projects, however, refinements to the concept are needed for precast, prestressed concrete to become readily accepted as an expedited construction technique for PCC pavements. These refinements may include modifications to design details, fabrication processes, and construction techniques to make precast, prestressed concrete an economical alternative for expedited pavement construction. This research will aim to develop a refined concept that is incorporated easily into current PCC pavement practices and to familiarize owner-agencies with this technology.

Tasks:

1. Evaluate all aspects of previously constructed precast, prestressed concrete pavement demonstration projects (i.e., design details, fabrication, construction, performance, and cost).
2. Refine details and processes so that precast, prestressed pavement can meet the construction timeframe requirements of owner-agencies.
3. Work with precast concrete and concrete paving industries to make precast concrete pavement an economically viable alternative to other fast-track PCC paving techniques.
4. Familiarize contractors and owner-agencies with precast, prestressed concrete pavement construction technology.
5. Develop specifications, design standards, and/or best practice guidelines for precast, prestressed concrete pavement.
6. Construct precast, prestressed concrete pavement test sections under stringent (e.g., overnight, weekend) time constraints.

Benefits:	Best practice guidelines for precast, prestressed concrete pavement technology, helping owner-agencies develop design standards and specifications.
Products:	Design standards, specifications, and best practice guides for precast, prestressed (posttensioned) concrete pavement.
Implementation:	This research will be used to develop design standards, specifications, and best practice guidelines for precast, prestressed (posttensioned) concrete pavement.

Problem Statement RC 2.2. Precast Concrete Pavements for Slab Replacement

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 2. Precast and Modular Concrete Pavements
Approximate Phasing:	Years 3–7
Estimated Cost:	\$500 k–\$1 M

Precast concrete offers a durable, lasting solution for rapid full-depth slab replacement for PCC pavement. Recent projects in Colorado, Michigan, New York, and Virginia have demonstrated the viability of using precast concrete panels for rapid full-depth repairs of PCC pavement. The success of these projects has emphasized the need to make this technology available to all owner-agencies and contractors for rapid repair projects. This research will evaluate the performance of the different construction techniques used on previous projects. Recommendations and specifications then can be developed to help contractors and owner-agencies incorporate precast concrete pavement into common fast-track pavement rehabilitation practices. The recommendations and specifications should cover all aspects of precast pavement construction, including precast panel fabrication, construction staging, existing pavement removal, base preparation, and panel installation.

Tasks:

1. Evaluate performance of existing precast concrete pavement rehabilitation projects.
2. Develop specifications and design standards for precast pavement.
3. Make precast concrete an economically viable alternative to current fast-track rehabilitation techniques.
4. Familiarize contractors and owner-agencies with precast pavement technology and construction practices.

Benefits:	Best practice guidelines for using precast panels in full-depth slab replacement.
Products:	Design standards, specifications, and best practice guidelines for using precast concrete in full-depth slab replacement.
Implementation:	This research will result in design standards, specifications, and best practice guidelines for using precast concrete in full-depth slab replacements.

Problem Statement RC 2.3. Lightweight Precast Concrete Pavements

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 2. Precast and Modular Concrete Pavements
Approximate Phasing:	Years 7–10
Estimated Cost:	$250 k–$500 k

Recently, several projects throughout the United States have demonstrated the viability of using precast concrete panels for large-scale pavement construction and full-depth pavement rehabilitation. One key cost component of precast concrete panels is transportation. Precast panels used for current projects can weigh in excess of 22.67 metric tons (25 short tons) sometimes requiring special permits to transport. One way to improve the efficiency of precast concrete pavement transportation is to reduce the weight of the precast panels. Reducing panel weight by as little as 20 percent may permit the shipment of more panels on each truck or eliminate the need for a special permit. Technology such as lightweight aggregates and hollow-core panels have been used successfully by the precast industry for buildings and bridge decks, but have yet to be applied to precast pavement panels. This research will incorporate these technologies into precast concrete pavement practices.

Tasks:

1. Identify potential weight-reducing technologies for precast concrete pavement panels.
2. Evaluate the benefits versus costs of incorporating weight-reducing technology into precast concrete pavement practice, including evaluation of durability issues associated with weight-reducing technologies.
3. Recommend weight-reducing techniques for precast concrete pavement practice.

Benefits:	Exploration of possible weight-reducing technologies for precast concrete pavement.
Projects:	Recommendations for weight-reducing technologies for precast concrete pavement.
Implementation:	This research will result in recommendations for weight-reducing technologies for precast concrete pavement.

Problem Statement RC 2.4. Precast Joints for Joint Replacement

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 2. Precast and Modular Concrete Pavements
Approximate Phasing:	Years 5–9
Estimated Cost:	$500 k–$1 M

Recent projects in Colorado, Michigan, and New York have demonstrated the viability of using precast concrete panels for joint replacement. Often, heavily faulted joints, which have lost subbase support due to pumping, cannot simply be ground smooth or retrofitted with dowel bars. In these cases, it is necessary to replace the joint completely to restore subbase support and load transfer between faulted slabs. Unfortunately, these joint replacements often are required on heavily trafficked pavements that can only be closed to traffic overnight or over a weekend. Precast concrete offers a durable, long-lasting solution that permits construction overnight or over a weekend. This research will examine the performance of different precast concrete joint replacement techniques and familiarize contractors and owner-agencies with these techniques so they can be incorporated into common practice.

Tasks:

1. Document construction practices and performance of current precast concrete joint replacement techniques.
2. Develop design standards, specifications, and/or best practice guidelines for owner-agencies to incorporate into current practice.
3. Familiarize contractors and owner-agencies with precast concrete joint replacement technology.

Benefits:	Best practice guidelines for using precast concrete panels for joint replacement.
Products:	Design standards, specifications, and best practice guidelines for using precast panels for joint replacements.
Implementation:	This work will be coordinated closely with that in track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction). This research will result in precast concrete joint replacement specifications, design standards, and best practice recommendations.

Problem Statement RC 2.5. Precast Quiet Pavement Surfaces

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 2. Precast and Modular Concrete Pavements
Approximate Phasing:	Years 5–10
Estimated Cost:	$500 k–$1 M

Pavement noise, or the noise generated by tires on a pavement surface, is an important consideration in PCC pavement construction, particularly in urban areas. Different surface textures are being examined constantly for their effectiveness in reducing pavement noise. Unfortunately, many of the most promising surface textures are difficult to construct properly in the field. Precast concrete pavement panels, however, are cast in a controlled environment, affording a great deal of flexibility with surface texture. New surface texture technologies, such as extruded channels, currently are being evaluated abroad. While such textures may be difficult to construct in the field, they can be easy to incorporate into precast pavement panels. This research will identify new surface textures that show promise for reducing pavement noise and evaluate the feasibility of incorporating them into precast pavement panels.

Tasks:

1. Identify surface texture techniques that have been shown to reduce pavement noise.
2. Evaluate the feasibility of incorporating these surface textures into precast pavement panels versus conventional (slipform or fixed-form) PCC construction.
3. Evaluate the benefits versus costs of using precast panels with noise-reducing surface texture for PCC pavement construction.
4. Develop case studies or pilot projects that incorporate noise-reducing surface textures into precast pavement and evaluate their effectiveness.

Benefits:	Exploration of noise-reducing techniques that may not be viable for conventional concrete pavements but that can be incorporated into precast concrete pavements.
Products:	Recommendations for noise-reducing techniques for precast concrete pavement surfaces.
Implementation:	This research will be used to evaluate the viability of precast pavement with specialized, noise-reducing surface textures versus conventional pavement construction with conventional surface textures.

SUBTRACK RC 3. FAST-TRACK CONCRETE PAVEMENTS

This subtrack examines four specific issues related to the next generation of fast-track paving and fast-track CPR techniques. Table 39 provides an overview of this subtrack.

Table 39. Subtrack RC 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
RC 3.0. Framework for Fast-Track Concrete Pavements (Subtrack RC 3)	$400 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
RC 3.1. Synthesis of Practice for Accelerated (Fast-Track) Paving	$250 k–$500 k	Synthesis of the current state of the practice for accelerated paving techniques.	One-stop shopping for different accelerated paving techniques.
RC 3.2. Accelerated Paving Techniques	$500 k–$1 M	Possible new mix design recommendations for accelerated paving mixes and guidelines for use, including maturity methods.	Development of more economical, nonproprietary, fast-track paving mixes and guidelines for use.
RC 3.3. Accelerated Hydration Methods	$500 k–$1 M	New techniques for accelerating the hydration process in PCC.	More rapid achievement of target strength values (e.g., opening), which in turn can shorten the duration of a project.
RC 3.4. Accelerated Concrete Pavement Restoration Techniques	$500 k–$1 M	Best practice guidelines for accelerated CPR techniques.	Best practice guidelines for accelerated CPR techniques.

Problem Statement RC 3.0. Framework for Fast-Track Concrete Pavements (Subtrack RC 3)

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 3. Fast-Track Concrete Pavements
Approximate Phasing:	Years 1–3
Estimated Cost:	$400 k

Subtrack RC 3 (Fast-Track Concrete Pavements) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack RC 3 (Fast-Track Concrete Pavements), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack RC 3 (Fast-Track Concrete Pavements).

Problem Statement RC 3.1. Synthesis of Practice for Accelerated (Fast-Track) Paving

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 3. Fast-Track Concrete Pavements
Approximate Phasing:	Years 2–4
Estimated Cost:	$250 k–$500 k

In the mid-1980s, FHWA initiated a unique program that brought together individuals from the concrete pavement industry and State highway agencies. The goal of this program was to assess the state of the practice of fast-track (accelerated) concrete paving practices. Since then, numerous concrete paving projects have been constructed using the practices recommended under this effort. In addition, there have been significant advancements in technology, including new materials and construction techniques. For example, new fast-setting hydraulic cements currently are being employed by some agencies to place full-depth concrete pavements over a weekend. This project will document the current state of the practice of accelerated PCC paving technology. Literature searches, surveys of transportation agencies, and interviews with contractors and owner-agencies will help establish the current state of the practice, and will document pros, cons, successes, and failures associated with different accelerated paving technologies.

Tasks:

1. Perform a literature search to identify different accelerated paving technologies currently available.
2. Survey transportation agencies in the United States, Canada, and abroad to determine which technologies have been used previously or currently are being used.
3. Conduct site visits and interviews with owner-agencies to determine pros, cons, successes, and failures of different technologies.
4. Synthesize results of the literature search, surveys, and interviews into a current state of the practice.

Benefits:	One-stop shopping for different accelerated paving techniques.
Products:	Synthesis of the current state of the practice for accelerated paving techniques.
Implementation:	This research will produce a synthesis of the current state of the practice for accelerated paving techniques.

Problem Statement RC 3.2. Accelerated Paving Techniques

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 3. Fast-Track Concrete Pavements
Approximate Phasing:	Years 3–7
Estimated Cost:	$500 k–$1 M

A significant number of high-early strength concrete mixes have been developed and evaluated in recent years. However, some questions remain regarding the economics and long-term durability of these mixes. Many current high-early strength mixes use exotic cements and other admixtures that have not been proven for long-term durability and can be very costly. Also, these mixes generally do not account for factors such as climatic conditions during construction, curing techniques, and pavement characteristics, and thus cannot be adjusted for varying conditions. This research will evaluate current high-early strength mixes and the performance of existing pavements constructed with these mixes. The research will identify the most cost effective, nonproprietary materials and mixes for durable, fast-setting concrete suitable for paving operations. Mixes that are developed will be adjustable based on the pavement characteristics, climatic conditions, and the curing techniques available. Guidelines or software should be provided with the mix design that will recommend adjustments to the mix based on climatic conditions during construction. Additionally, maturity/strength gain characteristics for new mixes will be identified and incorporated into the recommendations so that maturity techniques can be used to monitor strength gain during construction.

Tasks:

1. Identify current high-early strength concrete mixes used for accelerated paving.
2. Evaluate the benefits versus costs of existing mixes, including an analysis of pavement performance.
3. Develop new accelerated paving mixes consisting of economical, nonproprietary materials.
4. Analyze maturity characteristics of the new paving mixes for inclusion in the guidelines.
5. Develop guidelines and/or software for using these new mixes, including recommendations for adjustment based on climatic conditions, pavement characteristics, and curing techniques.
6. Conduct pilot studies or field trials using the mix design and guidelines developed from the study.

Benefits:	Development of more economical, nonproprietary, fast-track paving mixes and guidelines for use.
Products:	Possible new mix design recommendations for accelerated paving mixes and guidelines for use, including maturity methods.
Implementation:	This research will result in new, economical mix designs for accelerated paving and guidelines for using these mixes, including maturity.

Problem Statement RC 3.3. Accelerated Hydration Methods

Track: 7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack: RC 3. Fast-Track Concrete Pavements
Approximate Phasing: Years 4–8
Estimated Cost: $500 k–$1 M

Hydration of the cementitious materials within a concrete mixture leads to strength development. Strength, in turn, drives a number of critical decisions during concrete pavement construction, including sawcutting and time to opening for traffic. A number of techniques have been advanced that could allow the hydration process to accelerate. Since an increase in mixture temperature is known to accelerate hydration, most of these techniques include heating the concrete slab. Both microwave heating and inductive heating are possible methods, with the latter involving adding metallic fibers to the concrete mixture.

Tasks:

1. Identify technically feasible techniques for heating a concrete pavement in the field.
2. Evaluate various techniques in the laboratory, assessing their ability to accelerate hydration and monitoring potentially adverse phenomena, such as moisture loss and differential heating.
3. Identify a technique that demonstrates the greatest potential for the field, and apply it to a large-scale operation.

Benefits: More rapid achievement of target strength values (e.g., opening), which in turn can shorten the duration of a project.

Products: New techniques for accelerating the hydration process in PCC.

Implementation: This research will result in a technique for accelerating the hydration process that may shorten the time it takes to construct concrete pavements.

Problem Statement RC 3.4. Accelerated Concrete Pavement Restoration Techniques

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 3. Fast-Track Concrete Pavements
Approximate Phasing:	Years 4–9
Estimated Cost:	\$500 k–\$1 M

Rehabilitation of high-volume rigid pavements requires techniques that minimize disruption to traffic. Usually this restricts construction to nighttime. However, many techniques that have been developed and proven effective for CPR have not been evaluated fully as they pertain to accelerated construction. Research is needed to develop guidelines to help select strategies for rehabilitating high-volume rigid pavements that consider constraints such as lane closures and construction windows. Repair of UTW is one such technique that needs to be investigated, as there are no established guidelines for UTW repair under short time constraints for lane closures. Likewise, partial-depth repair of PCC pavement has shown promise, but guidelines have not been developed for this technique. Full-depth repair of CRCP is another CPR technique that requires guidelines for materials and construction practices. Additionally, environmental effects of CPR techniques must be addressed. Slurry from the diamond grinding process, for example, is considered by some State regulatory agencies to be an environmental hazard that could contaminate groundwater supply. While many States do not regard the slurry as hazardous, the concrete pavement industry needs to examine ways to contain and dispose of the slurry in response to certain State regulatory agencies' decisions. In general, all aspects of accelerated CPR techniques need to be fully documented, including materials, construction practices, and environmental effects.

Tasks:

1. Identify common CPR techniques currently used by owner-agencies.
2. Conduct surveys and interviews of contractors and transportation agencies to determine the current state of the practice for different CPR techniques and successes and failures for different techniques.
3. Develop best practice guidelines for each of these techniques based on the surveys and interviews.
4. Develop a decision matrix for agencies to use in determining applicable CPR techniques, with consideration for accelerated construction.
5. Evaluate new CPR techniques as they are developed.

Benefits:	Best practice guidelines for accelerated CPR techniques.
Products:	Best practice guidelines for accelerated CPR techniques.
Implementation:	This research will result in best practice guidelines for common CPR techniques.

SUBTRACK RC 4. REHABILITATION AND CONSTRUCTION EVALUATION AND IMPLEMENTATION

This subtrack provides the implementation structure for new high-speed rehabilitation and construction products and procedures. Table 40 provides an overview of this subtrack.

Table 40. Subtrack RC 4 overview.

Problem Statement	Estimated Cost	Products	Benefits
RC 4.0. Framework for Rehabilitation and Construction Evaluation and Implementation (Subtrack RC 4)	$150 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
RC 4.1. Workshops on Fast-Track Concrete Paving	$1 M–$2 M	Workshops on fast-track concrete paving at various locations throughout the United States.	Technology transfer through workshops that are a minor investment (if any) for owner-agencies.
RC 4.2. Workshops on Precast and Modular Concrete Pavement Solutions	$1 M–$2 M	Workshops on precast concrete paving techniques at various locations throughout the United States.	Technology transfer through workshops at minimal or no cost to owner-agencies.
RC 4.3. Workshops on Rehabilitation and Construction Simulation and Modeling	$500 k–$1 M	Workshops on construction and traffic management simulation techniques at various locations throughout the United States.	Technology transfer through workshops at minimal or no cost to owner-agencies.
RC 4.4. Web-Based Training for Implementation of Rehabilitation and Construction Research	$500 k–$1 M	Web-based training modules and a continuously maintained Web site for new products and technologies.	Technology transfer available to anyone with access to a computer and Internet access.

Problem Statement RC 4.0. Framework for Rehabilitation and Construction Evaluation and Implementation (Subtrack RC 4)

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 4. Rehabilitation and Construction Evaluation and Implementation
Approximate Phasing:	Years 1–3
Estimated Cost:	$150 k

Subtrack RC 4 (Rehabilitation and Construction Evaluation and Implementation) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack RC 4 (Rehabilitation and Construction Evaluation and Implementation), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack RC 4 (Rehabilitation and Construction Evaluation and Implementation).

Problem Statement RC 4.1. Workshops on Fast-Track Concrete Paving

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 4. Rehabilitation and Construction Evaluation and Implementation
Approximate Phasing:	Years 2–10
Estimated Cost:	$1 M–$2 M

Proven materials and technologies are currently available for fast-track concrete paving. Unfortunately, many transportation agencies are slow to adopt new techniques due to unfamiliarity with these new technologies and a lack of resources to research them. Workshops provide an ideal environment for agencies to become familiar with and receive training in new technologies. Workshops on fast-track concrete paving should cover the spectrum of proven technologies currently available, including high-early strength concrete mixes, maturity methods for strength monitoring, early-age analysis software (HIPERPAV), and others. In addition, other fast-track rehabilitation techniques, such as precast pavement technology and UTW, also should be presented.

Tasks:

1. Compile pertinent information on existing fast-track concrete paving technologies, including case studies and the experience of various transportation agencies.
2. Present fast-track concrete paving techniques and case studies as well as best practices to audiences of contractors, industry representatives, and transportation agencies.
3. Develop an interactive or National Highway Institute (NHI) course on fast-track paving.

Benefits:	Technology transfer through workshops that are a minor investment (if any) for owner-agencies.
Products:	Workshops on fast-track concrete paving at various locations throughout the United States.
Implementation:	This project will result in numerous workshops on fast-track concrete paving at various venues throughout the country.

Problem Statement RC 4.2. Workshops on Precast and Modular Concrete Pavement Solutions

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 4. Rehabilitation and Construction Evaluation and Implementation
Approximate Phasing:	Years 2–10
Estimated Cost:	$1 M–$2 M

Several projects in recent years have demonstrated different applications for precast concrete pavement. These projects have included prestressed precast concrete pavement, jointed reinforced precast concrete pavement, precast concrete for slab replacement, and precast concrete for joint replacement. Each of these projects has demonstrated successfully the various techniques for precast and modular solutions for pavements. As with many new technologies, however, transportation agencies are often slow to adopt new techniques because they are unfamiliar with these new technologies and lack resources for researching them. Workshops will provide an ideal environment for agencies to become familiar with and receive training in current precast pavement technologies.

Tasks:

1. Compile pertinent information on existing precast concrete pavement technologies, including information on all recently completed projects.
2. Present the different precast concrete paving applications, addressing the advantages and disadvantages of each technique to contractors, industry representatives, and transportation agencies.

Benefits:	Technology transfer through workshops at minimal or no cost to owner-agencies.
Products:	Workshops on precast concrete paving techniques at various locations throughout the United States.
Implementation:	This project will result in numerous workshops on precast concrete paving techniques at various venues throughout the country.

Problem Statement RC 4.3. Workshops on Rehabilitation and Construction Simulation and Modeling

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 4. Rehabilitation and Construction Evaluation and Implementation
Approximate Phasing:	Years 5–10
Estimated Cost:	$500 k–$1 M

Simulation and modeling are very powerful tools for optimizing pavement construction and rehabilitation projects. Simulations allow contractors, designers, and owner-agencies to model construction operations in advance to ensure the most efficient use of equipment and materials. This allows contractors and owner-agencies to anticipate potential problems before construction begins. Simulations also allow designers and/or owner-agencies to analyze traffic management strategies to identify the most efficient strategy and minimize user impact. However, as with many new technologies, transportation agencies are often slow to adopt new techniques because they are unfamiliar with new technologies and lack resources for researching them. Workshops will provide an ideal environment for agencies to become familiar with and receive training in current simulation and modeling techniques.

Tasks:

1. Identify construction and traffic management simulation techniques. Also, identify case studies that have used the construction and traffic management simulation techniques.
2. Present the different construction and traffic management simulation tools and case studies, if available, to contractors, designers, and owner-agencies.

Benefits:	Technology transfer through workshops at minimal or no cost to owner-agencies.
Products:	Workshops on construction and traffic management simulation techniques at various locations throughout the United States.
Implementation:	This project will result in numerous workshops on construction and traffic management simulation techniques at various venues throughout the country.

Problem Statement RC 4.4. Web-Based Training for Implementation of Rehabilitation and Construction Research

Track:	7. High-Speed Concrete Pavement Rehabilitation and Construction (RC)
Subtrack:	RC 4. Rehabilitation and Construction Evaluation and Implementation
Approximate Phasing:	Years 3–10
Estimated Cost:	$500 k–$1 M

Every year, many new products and technologies are developed and made available for implementation. However, many transportation agencies are slow to adopt new products and technology because they are unfamiliar with these new technologies and lack resources to research them. Although workshops provide an opportunity for contractors and owner-agencies to learn about these new products and technologies, many agencies cannot afford to send employees to workshops or may be restricted from traveling to workshops outside their home State. Fortunately, Web-based training allows contractors, designers, and owner-agencies to explore new products and technologies from any computer with Internet access. On-demand Web-based training can take advantage of options such as video streaming for visual demonstrations of new products and technologies.

Tasks:

1. Compile information on products and technologies ready for implementation, including thorough descriptions, photos, and video.
2. Develop Web-based training modules for each new product or technology.
3. Create a Web site for accessing the training modules and maintain the Web site with updates for new products or refinements to existing products.

Benefits:	Technology transfer available to anyone with access to a computer and Internet access.
Products:	Web-based training modules and a continuously maintained Web site for new products and technologies.
Implementation:	This project will result in Web-based training modules for new research products and technologies.

Track 8. Long Life Concrete Pavements (LL)

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TRACK 8 (LL) OVERVIEW

Long life pavements are needed to handle the congestion and traffic loading that pavements will experience in their lifetime. To meet a 30-year calendar design life, a pavement built in 2005 may need 70–100 percent more axle loads per mile than a similar pavement built in 1995. But rather than simply building pavements to handle axle loading, pavement design must address what the public sees—the time between repairs.

The research areas needed to design and build long life pavements to be developed in this track are:

- Definition of long life concrete pavements (including various warrants for longer life, noting that low-volume roadways must be included in this definition and analysis); identification of long life concrete pavement types, design features, foundations, and rehabilitation/maintenance strategies; and design requirements.
- A design catalog for long life concrete pavements (thickness should not be a parameter included in this catalog, as thickness requires indepth analyses, but all other details of concrete pavement design that affect long life performance are important).
- Identification of material requirements and tests for long life concrete pavements.
- Strategic application of preservation treatments to preserve long life concrete pavements.
- QC/QA testing standards to ensure long life concrete pavements.
- Evaluation of experimental long life concrete pavements.
- Evaluation of concrete overlays for long life designs.

The research in this track will be coordinated closely with related research integrated across the Strategic Road Map. For example, other research tracks propose the following advancements to achieve long life pavements:

- PRS and advanced contracting techniques.
- Knowledge and control of construction variability.
- Advanced QC tools.
- Advanced life cycle cost analysis (LCCA) procedures.

This track addresses the operational conditions in which pavement performance is defined. For example, a 60-year pavement could be designed in several ways that determine its maintenance schedule:

- No maintenance with total reconstruction at the end of the pavement life.
- Periodic maintenance at 25 years and then at every 5 years thereafter, including surface characteristics maintenance, early foundation repairs, and potential drainage issues.
- Staged construction, in which a 60-year foundation is built and the slab is carpeted with a thin surfacing that can be renewed periodically to maintain surface characteristic performance requirements.
- Staged construction, in which a 60-year foundation is built, but with a wraparound concrete overlay to handle loads on the existing pavement and accommodate new pavement for lane increases.

Each of these options can be used in locations that experience light-to-moderate truck traffic today but anticipate long-term growth. However, it is not clear whether the time between fixes for already heavily loaded pavements can be extended beyond 25 years.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

The problem statements in this track will identify both conventional and innovative pavement types, design features, foundations, materials, construction QC/QA, and preservation treatments that will provide long service life reliably (e.g., more than 40 years).

Track Objectives

1. Develop clear and detailed definitions of long life pavements, including information about warrants, required maintenance, a range of low- to high-traffic roadways, and other information.
2. Identify pavement strategies (design, foundation, restoration, and rehabilitation) for long life.
3. Identify design and foundation features that are likely to result in long life concrete pavements.
4. Identify restoration treatments for preserving long life concrete pavements.
5. Identify concrete and other material tests and requirements for long life pavements.
6. Identify QC/QA procedures that will ensure quality long life pavement construction.
7. Construct test highways of the most promising concrete pavement types that include design features, foundations, materials, construction QC/QA, and preservation treatments that will ensure long life concrete pavements.

Research Gaps

- Insufficient understanding and application of the factors needed to improve concrete and aggregate durability.
- Insufficient understanding and application of the factors that impact dowel and tie bar durability.
- Insufficient understanding and application of the factors that impact joint longevity.
- Insufficient understanding and application of the factors that improve foundation longevity.
- Insufficient understanding and application of the factors that impact long-term surface texture characteristic performance.
- Lack of integrated design and mix factors in construction quality requirements.
- Insufficient understanding and application of new factors that influence traffic projections.
- Insufficient knowledge of concrete overlays over various types of existing pavements, particularly as it pertains to design and performance.

Research Challenges

- Develop concrete mixes and aggregates with long-term durability that are resistant to commonly occurring distress types, such as D-cracking and ASR.
- Develop corrosion-proof materials and construction techniques to ensure the long-term durability of dowels, reinforcing bars, and tie bars.
- Improve the design and materials used in joint construction for long life pavements.
- Improve the long-term durability of foundation courses. Base courses that exhibit long-term durability must be resistant to erosion, pumping, strength loss, and other forms of deformation or disintegration.
- Improve the long-term durability of pavement surface characteristics (e.g., surface texture) to maintain as-designed levels of surface friction, noise generation, smoothness, and surface drainage with minimal intermediate maintenance.
- Improve concrete quality to reduce the possibility of durability-related disintegration and deformation.
- Develop rational and acceptable long-term traffic projections greater than 40 years.
- Improve understanding of concrete overlay materials and layer bonding for long-term performance.

Research Track 8 (LL) Phasing

The horizontal bar chart in figure 8 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

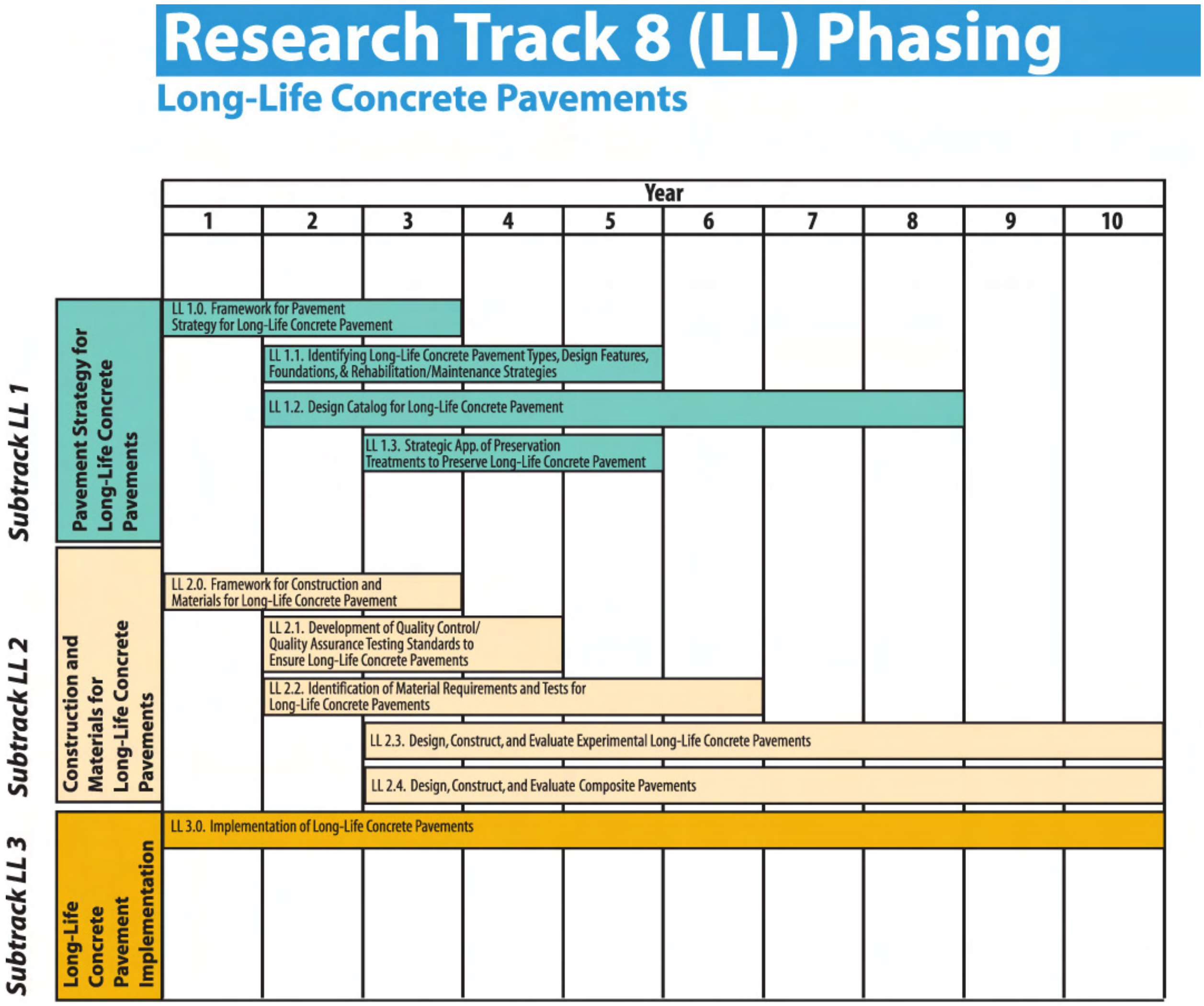

Figure 8. Track 8 (LL) subtrack and problem statement phasing chart.

Research Track 8 (LL) Estimated Costs

Table 41 shows the estimated costs for this research track.

Table 41. Research track 8 (LL) estimated costs.

Problem Statement	Estimated Cost
Subtrack LL 1. Pavement Strategy for Long Life Concrete Pavements	
LL 1.0. Framework for Pavement Strategy for Long Life Concrete Pavements (Subtrack LL 1)	$200 k
LL 1.1. Identifying Long Life Concrete Pavement Types, Design Features, Foundations, and Rehabilitation/Maintenance Strategies	$800 k–$1.2 M
LL 1.2. Design Catalog for Long Life Concrete Pavements	$500 k–$1 M
LL 1.3. Strategic Application of Preservation Treatments to Preserve Long Life Concrete Pavement	$500 k–$700 k
Subtrack LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays	
LL 2.0. Framework for Construction and Materials for Long Life Concrete Pavements (Subtrack LL 2)	$200 k
LL 2.1. Development of Quality Control/Quality Assurance Testing Standards to Ensure Long Life Concrete Pavements	$500 k–$600 k
LL 2.2. Identification of Material Requirements and Tests for Long Life Concrete Pavements	$1 M–$1.5 M
LL 2.3. Design, Construct, and Evaluate Experimental Long Life Concrete Pavements	$3 M–$5 M
LL 2.4. Design, Construct, and Evaluate Concrete Overlays	$3 M–$5 M
Subtrack LL 3. Long Life Concrete Pavement Implementation	
LL 3.1. Implementation of Long Life Concrete Pavements	$800 k–$1.2 M
Track 8 (LL)	
Total	$10.5 M–$16.6 M

Track Organization: Subtracks and Problem Statements

Track 8 (LL) problem statements are grouped into three subtracks:

- Subtrack LL 1. Pavement Strategy for Long Life Concrete Pavements.
- Subtrack LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays.
- Subtrack LL 3. Long Life Concrete Pavement Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK LL 1. PAVEMENT STRATEGY FOR LONG LIFE CONCRETE PAVEMENTS

This subtrack structures the approach to long life pavements from the strategic approaches to the design catalogs. The problem statements in this subtrack rely on the work conducted under track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). Table 42 provides an overview of this subtrack.

Table 42. Subtrack LL 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
LL 1.0. Framework for Pavement Strategy for Long Life Concrete Pavements (Subtrack LL 1)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
LL 1.1. Identifying Long Life Concrete Pavement Types, Design Features, Foundations, and Rehabilitation/ Maintenance Strategies	$800 k–$1.2 M	Feasible pavement strategies and promising features for providing long life for each type of concrete pavement selected; case studies of past long life concrete pavements.	Feasible pavement strategies for providing long life that will provide input throughout track 8 (Long Life Concrete Pavements).
LL 1.2. Design Catalog for Long Life Concrete Pavements	$500 k–$1 M	An interim design catalog of long life pavement designs (produced within 2 years of starting); contents that will be updated as more information obtained from research activities under this track becomes available.	A catalog of long life pavement designs that will provide practicing engineers with the tool for designing long life, cost effective pavements with minimal restoration and rehabilitation.
LL 1.3. Strategic Application of Preservation Treatments to Preserve Long Life Concrete Pavement	$500 k–$700 k	Recommendations on the type, design, construction, and optimum application timing of restoration or rehabilitation treatments for extending pavements service life or indefinitely preserving the original pavement structure.	Recommendations on the optimum application timing of restoration or rehabilitation treatments that will extend pavement service life or indefinitely preserve the original pavement structure; a tool for practicing engineers to use in designing long life, cost effective concrete pavements with minimal restoration.

Problem Statement LL 1.0. Framework for Pavement Strategy for Long Life Concrete Pavements (Subtrack LL 1)

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 1. Pavement Strategy for Long Life Concrete Pavements
Approximate Phasing:	Years 1–3
Estimated Cost:	$200 k

Subtrack LL 1 (Pavement Strategy for Long Life Concrete Pavements) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack LL 1 (Pavement Strategy for Long Life Concrete Pavements), modify as appropriate, and divide them into specific, manageable contracts. As part of this effort, provide detailed information on the ways long life is and should be defined. Include information about all levels of traffic, from low to very high volume types of roadways and define maintenance requirements and warrants for longer life.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack LL 1 (Pavement Strategy for Long Life Concrete Pavements).

Problem Statement LL 1.1. Identifying Long Life Concrete Pavement Types, Design Features, Foundations, and Rehabilitation/Maintenance Strategies

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 1. Pavement Strategy for Long Life Concrete Pavements
Approximate Phasing:	Years 2–5
Estimated Cost:	$800 k–$1.2 M

This research will identify both conventional and innovative pavement types likely to provide long life, including an evaluation of the advantages and limitations of different pavement designs for long life applications and the possible preservation strategies for each pavement type. With certain pavement types, pavement service life may be extended significantly through preservation treatments, although in some design situations, any major pavement treatment within a certain period may be unacceptable. Examples of promising design features include continuous reinforcement, widened slabs, stabilized base, positive subdrainage, large-diameter dowel bars, and uniform and stable foundations. This research will investigate various means of satisfying the long life pavement goals, considering the entire pavement life cycle and including rehabilitations where appropriate. Site conditions, such as traffic level, subgrade properties, climate, and local aggregate and material properties, significantly affect pavement performance, and feasible pavement strategies will be identified in light of such factors.

Tasks:

1. Evaluate existing concrete pavements that claim to be long life (those currently in design by States, those inservice, and those that have been previously rehabilitated, including existing high-performance concrete sites).
2. Identify concrete pavement design features that lend themselves to good long-term pavement performance and lower the risk of poor performance (e.g., continuous reinforcement, widened slabs, stabilized base, and large-diameter dowel bars).
3. Evaluate the effects of the design features identified under task 1 on long-term pavement performance and develop a short list of design features that significantly affect long-term pavement performance. Use existing survival curves in these studies where available.
4. Identify both conventional and innovative pavement types likely to provide long life. Consider at least the following:
    - Full-depth concrete for new construction.
    - Concrete overlay rehabilitation.
    - No foundation rehabilitation.
    - No pavement intrusion over its lifespan.
    - Additional thin concrete surfacing on the top.
    - Staged concrete over concrete construction that does not change the foundation.
5. Identify the various means of satisfying the long life pavement goals by considering the entire pavement life cycle, including restorations and rehabilitations where appropriate, maintenance done to the joint, and considering that site conditions, such as traffic level, subgrade properties, climate, and local aggregate, significantly affect pavement performance. Consider also environmental sustainability.
6. For each pavement type identified under task 1, evaluate advantages and limitations for the long life applications, including the factors identified in task 2, such as evaluating possible rehabilitation strategies for each pavement type, life cycle cost, and so on.
7. Determine promising pavement types and strategies for providing long life based on the results of tasks 1 through 3.

Benefits:	Feasible pavement strategies for providing long life that will provide input throughout track 8 (Long Life Concrete Pavements).
Products:	Feasible pavement strategies and promising features for providing long life for each type of concrete pavement selected; case studies of past long life concrete pavements.

Implementation: This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements), as well as track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction). Case studies and the identification of promising types and design features developed in this research will be essential to the rest of this track.

Problem Statement LL 1.2. Design Catalog for Long Life Concrete Pavements

Track: 8. Long Life Concrete Pavements (LL)
Subtrack: LL 1. Pavement Strategy for Long Life Concrete Pavements
Approximate Phasing: Years 2–8
Estimated Cost: $500 k–$1 M

This research will develop a catalog of long life pavement designs that lists feasible pavement design alternatives for different site conditions. The design conditions may be classified in terms of climatic region (or key climatic factors), traffic level, and subgrade or foundation type. Each design entry in the catalog will describe the structural section (base/subbase type and thickness and slab thickness), slab width, joint spacing, material requirements, and other design features, such as load transfer design and subsurface drainage. While the catalog will discuss slab thickness in relation to other design features, slab thickness will not be included in each section of the catalog, because thickness requires detailed analyses in light of all other design features and site conditions. The design catalog will instead focus on design aspects other than slab thickness. Additionally, the design catalog will provide QC/QA testing guidelines to ensure adequate construction quality for all layers and the foundation. Based on available information, an interim guide will be developed that will be updated based on the results of other research conducted under this track.

Tasks:

1. Identify all site factors that affect pavement performance and classify the identified factors accordingly (e.g., climatic region (or key climatic factors), traffic level, and subgrade or foundation type).
2. Identify feasible pavement design alternatives (e.g., by using existing performance models and pavement analysis tools) for different site conditions identified under task 1.
3. Develop a catalog of long life pavement designs for the different site conditions identified under task 1. Each design entry in the catalog will describe the structural section (base/subbase type and thickness and at most a general range of slab thicknesses) and many other aspects that include slab width, joint spacing, material requirements, load transfer design, subsurface drainage, foundation stability and uniformity, and QC/QA testing guidelines to ensure adequate construction quality. The design catalog should include information on low-volume rural and urban roadways.

Benefits: A catalog of long life pavement designs that will provide practicing engineers with tools for designing long life, cost effective pavements with minimal restoration and rehabilitation.

Products: An interim design catalog of long life pavement designs (produced within 2 years of starting); contents that will be updated as more information obtained from research activities under this track becomes available.

Implementation: This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). The research will result in a practical product for immediate use in designing long life concrete pavements.

Problem Statement LL 1.3. Strategic Application of Preservation Treatments to Preserve Long Life Concrete Pavement

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 1. Pavement Strategy for Long Life Concrete Pavements
Approximate Phasing:	Years 3–5
Estimated Cost:	$500 k–$700 k

Through strategic use of restoration and rehabilitation techniques, extending the service life of concrete pavements may be possible. This research will investigate the feasibility of applying restoration or rehabilitation treatments to preserve and further extend the service life of long life pavements. All possible alternatives should be considered, including CPR treatments and concrete overlays. The optimum application timing, based on pavement condition and rehabilitation objectives, also should be determined. Finally, the feasibility of indefinitely preserving the original pavement structure should be investigated.

Tasks:

1. Identify all available and other potential restoration or rehabilitation treatments for the pavement types identified under problem statement LL 1.1 (Identifying Long Life Pavement Types, Design Features, Foundations, and Rehabilitation/Maintenance Strategies). Conduct field surveys of promising treatments and document case studies.
2. Investigate the feasibility of preserving and further extending the service life of the identified pavement types by applying restoration or rehabilitation treatments.
3. Investigate the feasibility of indefinitely preserving the original pavement structure.
4. Recommend the optimum application timing of restoration or rehabilitation treatments, based on pavement condition, that will extend pavement service life or indefinitely preserve the original pavement structure.
5. Prepare detailed guidelines for designers.

Benefits:	Recommendations on the optimum application timing of restoration or rehabilitation treatments that will extend pavement service life or indefinitely preserve the original pavement structure; a tool for practicing engineers to use in designing long life, cost effective concrete pavements with minimal restoration.
Products:	Recommendations on the type, design, construction, and optimum application timing of restoration or rehabilitation treatments for extending pavements service life or indefinitely preserving the original pavement structure.
Implementation:	This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). The research will provide a product needed to ensure that long-term preservation treatments are considered fully and available.

SUBTRACK LL 2. CONSTRUCTION AND MATERIALS FOR LONG LIFE CONCRETE PAVEMENTS AND OVERLAYS

This subtrack addresses the materials, construction and QC requirements unique to long life concrete pavements and overlays. Table 43 provides an overview of this subtrack.

Table 43. Subtrack LL 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
LL 2.0. Framework for Construction and Materials for Long Life Concrete Pavements (Subtrack LL 2)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
LL 2.1. Development of Quality Control/Quality Assurance Testing Standards to Ensure Long Life Concrete Pavements	$500 k–$600 k	QC/QA procedures for assessing the overall construction quality to determine whether the construction quality can achieve long life.	QC/QA guidelines that provide practicing engineers with the tools for ensuring that concrete pavements are constructed as designed, thereby reducing possible discrepancies in anticipated service life.
LL 2.2. Identification of Material Requirements and Tests for Long Life Concrete Pavements	$1 M–$1.5 M	Materials requirements and testing guidelines for establishing the suitability of long life pavement materials for a wide variety of climates, considering concrete, base, and other materials.	Reliable requirements and testing guidelines for identifying suitable concrete materials as well as base and other materials; tools for practicing engineers that will design against possible material-related problems and distress.
LL 2.3. Design, Construct, and Evaluate Experimental Long Life Concrete Pavements	$3 M–$5 M	Design and construction of several promising concrete pavement types with appropriate design features, foundations, materials, construction, QC/QA, and preservation treatments, considering advancements from other research and development, including precast joints, and advanced materials; pavements monitored for performance over time.	Design, construction, and monitoring of several promising concrete pavements that will prove the long life pavement concept, strongly encouraging implementation of other such long life projects.
LL 2.4. Design, Construct, and Evaluate Concrete Overlays	$3 M–$5 M	Promising concrete overlay types with appropriate design features, surface characteristics, foundations, materials, construction, QC/QA, and preservation treatments.	An exceptionally strong, long life pavement with concrete overlay, combining the strengths of a solid concrete foundation with a renewable surface designed around functional requirements.

Problem Statement LL 2.0. Framework for Construction and Materials for Long Life Concrete Pavements (Subtrack LL 2)

Track: 8. Long Life Concrete Pavements (LL)
Subtrack: LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays
Approximate Phasing: Years 1–3
Estimated Cost: $200 k

Subtrack LL 2 (Construction and Materials for Long Life Concrete Pavements and Overlays) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack LL 2 (Construction and Materials for Long Life Concrete Pavements and Overlays), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits: An effective, coordinated, and productive research program.
Products: A validated, sequenced, and detailed research framework for this subtrack.
Implementation: This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack LL 2 (Construction and Materials for Long Life Concrete Pavements and Overlays).

Problem Statement LL 2.1. Development of Quality Control/Quality Assurance Testing Standards to Ensure Long Life Concrete Pavements

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays
Approximate Phasing:	Years 2–4
Estimated Cost:	\$500 k–\$600 k

This research will establish standards for QC/QA testing to ensure long-term pavement performance. The standard will specify the type of testing to be conducted, testing procedures, testing frequency, and reporting requirements. The acceptable construction tolerances will also be specified for key construction factors, including slab thickness, joint spacing, concrete strength, joint LTE, dowel bar alignment, tie bar placement accuracy, and foundation uniformity and stability. Repairs may be permissible for certain deficiency types. In such cases, the acceptable repairs for the deficiencies also will be specified. A procedure for assessing the overall construction quality also will be developed to determine whether the construction quality can achieve long life.

Tasks:

1. Identify the types of QC/QA testing required to ensure good long-term pavement performance. Identified testing standards will specify the type of testing to be conducted, testing procedures, testing frequency, and reporting requirements.
2. Determine acceptable construction tolerances for key construction factors (e.g., slab thickness, joint spacing, concrete strength, joint LTE, dowel bar alignment, tie bar placement accuracy, and foundation uniformity and stability) to ensure good long-term pavement performance.
3. Identify commonly occurring construction deficiencies and the permissible repairs that will ensure good long-term pavement performance.
4. Develop a procedure for assessing the overall construction quality to determine whether the construction quality can achieve long life.

Benefits:	QC/QA guidelines that provide practicing engineers with the tools for ensuring that concrete pavements are constructed as designed, thereby reducing possible discrepancies in anticipated service life.
Products:	QC/QA procedure for assessing the overall construction quality to determine whether the construction quality can achieve long life.
Implementation:	This research will ensure that long life concrete pavements are constructed with the appropriate quality and that no major construction problem will result in premature pavement failures.

Problem Statement LL 2.2. Identification of Material Requirements and Tests for Long Life Concrete Pavements

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays
Approximate Phasing:	Years 2–6
Estimated Cost:	\$1 M–\$1.5 M

Good material performance is essential for long life pavement. Materials that must perform well include concrete, a base layer, a subbase layer, tie bars, dowel bars, and deformed reinforcement. This research will document material problems that have caused premature pavement failures in the past, along with information about high-risk areas for such problems. A very long design life may not be practical in some areas due to a high risk of developing material problems. If such limitations exist, identifying the high-risk areas and materials, as well as the practical design-life limit, can optimize pavement design. Often, however, the material problem can be mitigated using various treatments and certain design features. This research will result in testing guidelines for identifying potential material problems as well as mitigation strategies.

Tasks:

1. Identify commonly occurring material problems that have caused premature pavement failures for different pavement types, along with information about high-risk areas for such problems.
2. Identify treatments and design features that can mitigate the identified material problem.
3. Identify high-risk sites (e.g., climate zones and subgrade types) for material problems that cause long pavement design life to be impractical or infeasible.
4. Identify tests and develop testing guidelines for identifying potential material problems as well as mitigation strategies.
5. Prepare comprehensive guidelines for selecting, specifying, and testing the materials required during construction for long life concrete pavements.

Benefits:	Reliable requirements and testing guidelines for identifying suitable concrete materials as well as base and other materials; tools for practicing engineers that will design against possible material-related problems and distress.
Products:	Materials requirements and testing guidelines for establishing the suitability of long life pavement materials for a wide variety of climates, considering concrete, base, and other materials.
Implementation:	This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements). The results of this research are essential to reliable long life concrete pavement designs, materials, and construction. Results will be useful immediately and will be used to design and construct the test sections under problem statement LL 2.3 (Design, Construct, and Evaluate Experimental Long Life Concrete Pavements).

Problem Statement LL 2.3. Design, Construct, and Evaluate Experimental Long Life Concrete Pavements

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays
Approximate Phasing:	Years 3–10
Estimated Cost:	$3 M–$5 M

This research will develop innovative designs that promise superior long-term performance and test them in an ALF, test roads (e.g., MnROAD), or as a highway test section (e.g., LTPP). The designs may include innovative structural section, including concrete overlays; precast designs and advanced materials; and innovative pavement service life management that considers rehabilitation strategy as a part of life cycle design. Based on the results of this research, the long life pavement design guidelines developed under this research track may be modified.

Tasks:

1. Identify new and innovative pavement structural sections, including concrete overlays and available innovative materials that promise superior long-term performance.
2. Determine the best method of testing the long-term performance of the promising designs using ALFs or full-scale test facilities and highways.
3. Design and prepare specifications and QC/QA tests and observe materials testing and other needed and feasible QA activities for several sites.
4. Analyze test section performance results over time and provide performance data to States and others.
5. Develop revised design, construction, and materials specifications and other products based on test results and analysis.

Benefits:	Design, construction, and monitoring of several promising concrete pavements that will prove the long life pavement concept, strongly encouraging implementation of other such long life projects.
Products:	Design and construction of several promising concrete pavement types with appropriate design features, foundations, materials, construction, QC/QA, and preservation treatments, considering advancements from other research and development, including precast joints, and advanced materials; pavements that will be monitored for performance over time.
Implementation:	This research will be coordinated closely with work in track 9 (Concrete Pavement Accelerated and Long-Term Data Collection). Constructing the most promising designs will demonstrate the feasibility of long-term concrete pavement. Results from design, construction, and materials will be useful immediately to States. Performance will be useful over time.

Problem Statement LL 2.4. Design, Construct, and Evaluate Concrete Overlays

Track: 8. Long Life Concrete Pavements (LL)
Subtrack: LL 2. Construction and Materials for Long Life Concrete Pavements and Overlays
Approximate Phasing: Years 3–10
Estimated Cost: $3 M–$5 M

Concrete overlays are discussed throughout the CP Road Map, especially in the problem statements addressing the use of asphalt bases throughout track 1 (Performance-Based Concrete Pavement Mix Design System). This problem statement will develop approaches to long life pavements that consider concrete overlay construction principles during initial construction and over the analysis period. The research in this problem statement addresses JCPs or CRCPs over an asphalt base or subbase with a cement/epoxy-type or porous concrete surface. For all surface types, the surface is renewable, and the concrete slab is expected to require little maintenance or rehabilitation for 30–50 years or more.

Tasks:

1. Determine operational strategies that could accommodate concrete overlay construction principles.
2. Determine ways to incorporate issues concerning asphalt bases with PCC surface courses (e.g., changes in temperature gradients and thickness and stiffness of the layers) into structural design. Develop the initial functional and performance requirements of the top surface course to meet economic, safety, and environmental concerns, and traffic loadings and volumes.
3. Determine the surface course material requirements for meeting two or three different life expectancy predictions before replacement is required. Identify any the adjustments required to properly integrate specific materials issues with the structural values developed in task 2. Determine the bonding requirements between surface and slab necessary for meeting the desired performance criteria. Consider issues of delaminating, reflection cracking, clogging and stability, and the impact of contained moisture in the structure. Study the effects of the concrete surface layer on the structural design of the slab.
4. Determine the construction issues unique to these concrete overlay sections, addressing each interlayer. Develop guide specifications for each significant type of concrete overlay.
5. Build, monitor, and evaluate the various test sections.

Benefits: An exceptionally strong, long life pavement with concrete overlay, combining the strengths of a solid concrete foundation with a renewable surface designed around functional requirements.

Products: Promising concrete overlay types with appropriate design features, surface characteristics, foundations, materials, construction, QC/QA, and preservation treatments.

Implementation: The research in this problem statement will be coordinated with work in track 9 (Concrete Pavement Accelerated and Long-Term Data Collection). This research also will be integrated with Future Strategic Highway Research Program Renewal Project 1–8.3 as it pertains to concrete overlays. Results from the design, construction, and materials aspects of this research will be useful immediately to States, while performance data will be useful over time. This research also may be addressed in other tracks—for example, track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements), track 4 (Optimized Surface Characteristics for Safe, Quiet, and Smooth Concrete Pavements), and track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction).

SUBTRACK LL 3. LONG LIFE CONCRETE PAVEMENT IMPLEMENTATION

This subtrack provides for the implementation of the long life pavement research developed in the track. Table 44 provides an overview of this subtrack.

Table 44. Subtrack LL 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
LL 3.1. Implementation of Long Life Concrete Pavements	$800 k–$1.2 M	Strong transfer of long life concrete pavement design and construction technology to the workforce, using workshops, conferences, and Web-based personnel training.	A knowledgeable workforce and management that can use the design procedure to design, construct, and specify materials, and preserve long life concrete pavements properly when long life designs are required.

Problem Statement LL 3.1. Implementation of Long Life Concrete Pavements

Track:	8. Long Life Concrete Pavements (LL)
Subtrack:	LL 3. Long Life Concrete Pavement Implementation
Approximate Phasing:	Years 1–10
Estimated Cost:	$800 k–$1.2 M

Implementing long life concrete pavement requires significant efforts in both training the workforce and convincing management that long life concrete pavement is feasible and reliable. This task addresses both of these efforts. The results from many other tracks and projects will help develop long life pavements, and these other efforts will be used in this task without being repeated. For example, track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements) offers a design procedure that is fully capable of designing long life pavements. However, additional design work will be needed to ensure a reliable design.

Tasks:

1. Develop and present workshops dealing with aspects of the mechanistic design process that focus on long life concrete pavements (e.g., history and case studies of past successes, structural modeling, materials characterization, distress and IRI prediction, concrete overlays, restoration, optimization, traffic, climate, and local calibration).
2. Organize national conferences and workshops on the mechanistic design process in which States and other highway agencies share their findings.
3. Develop Web-based, online training tools.
4. Develop a method for strong transfer of long life concrete pavement design technology, using workshops, conferences, and Web-based personnel training.

Benefits:	A knowledgeable workforce and management that can use the design procedure to design, construct, specify materials, and preserve long life concrete pavements properly, when long life designs are required.
Products:	Strong transfer of long life concrete pavement design and construction technology to the workforce, using workshops, conferences, and Web-based personnel training.
Implementation:	This work will provide the technology transfer critical to the success of the long life concrete pavement track.

Track 9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)

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TRACK 9 (DC) OVERVIEW

ALFs provide valuable performance data that allow engineers to improve current procedures and advance the state of the art. Throughout the 1980s and 1990s, many new accelerated testing programs with ALFs were installed. ALFs encourage innovation by eliminating the fear of failure associated with full-scale road testing, since ALFs can test innovations without the possibility of disastrous consequences that might occur on a real highway. ALFs also provide small-scale evaluation of full-scale designs to identify limitations and speed up the implementation of design improvements. At least 24 ALFs currently operate in the United States.

Test roads and data collection methods can be developed and expanded further. Additional data is needed for new materials, new test sections, model validation and calibration, innovative joint designs, and surface characteristics advancements. This data can contribute to many of the research tracks in the CP Road Map, which depend on quality data for validation or calibration and require experimental installations or access to long-term data.

This track provides the infrastructure for a future national program that will plan accelerated loading and long-term data needs, construct test sections, and collect and share data. The problem statements in this track will explore areas that will yield useful data and determine the amount of time needed to get it. This track also will research accelerated durability testing for concrete pavement materials and design.
The problem statements in this track will address the following areas:

- Identification of accelerated and long-term data needs.
- Planning and design of accelerated loading and long-term data collection.
- Accelerated and long-term data management and distribution.
- Development of a master plan for conducting accelerated product testing and full-scale road experiments.
- Development of experimental designs and a data collection and performance monitoring plan for accelerated loading and durability testing facilities and full-scale products testing.
- Preparation of data collection and testing procedures.
- Construction of accelerated loading sections and test road sections.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A phasing chart is included to show the approximate sequencing of the problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

The research in this track will collect, manage, and analyze concrete pavement performance data that will support the CP Road Map.

Track Objectives

1. Identify performance data needs for calibrating and validating performance models for jointed plain concrete, CRCPs, and other types of concrete pavements.
2. Develop an ALF and full-scale test road program for collecting materials, design, traffic, climate, and performance data from existing and future experimental pavements.

3. Establish reliable experimental testing programs along with testing protocols for ALFs and test road programs that include durability testing for materials and design.
4. Collect and analyze relevant test database programs that support the CP Road Map.

Research Gaps

- Insufficient databases to store and distribute long-term data.
- Inaccurate and inadequate LTPP Program and other research databases of concrete pavement performance.
- Lack of performance data for modern concrete pavements under both very heavy and very light traffic.
- Lack of performance data for concrete pavements more than 40 years old.
- Unstructured approach to testing new and innovative ideas.
- Insufficient use of the Nation's ALFs for testing concrete pavements.
- Insufficient understanding of the methods for conducting meaningful accelerated durability testing for concrete paving materials and design.

Research Challenges

- Convince FHWA, State highway agencies, and industry to expand the capabilities of existing databases or build new Web-based databases for storing and disbursing large amounts of performance and other data.
- Obtain new data that the LTPP Program and other sources do not collect to develop, validate, and calibrate the next generation of concrete pavement distress and smoothness models.
- Identify the proper pavement sections, populate the new databases with sufficient data, and convince FHWA, State highway agencies, and industry of the need for a long-term data collection program.
- Obtain data from older pavement sections (e.g., more than 40 years old) for evaluation and analysis and use an ALF to simulate realistically (accounting for traffic cycles, temperature cycles, moisture cycles, and so on) 40 or more years of traffic and climatic damage imposed on a test pavement.
- Apply the appropriate testing methodology (e.g., ALFs, road tests, or other) to obtain the required performance data for validating and improving new and innovative ideas.
- Identify the proper methodologies for concrete pavement testing using ALFs and convince owners of the benefits and necessity of conducting specific experiments.

Research Track 9 (DC) Phasing

The horizontal bar chart in figure 9 shows the approximate time phasing of the problem statements in this track grouped by subtrack across 10 years. The phasing information here is a summary of the approximate phasing included with the full written description of each problem statement in this track.

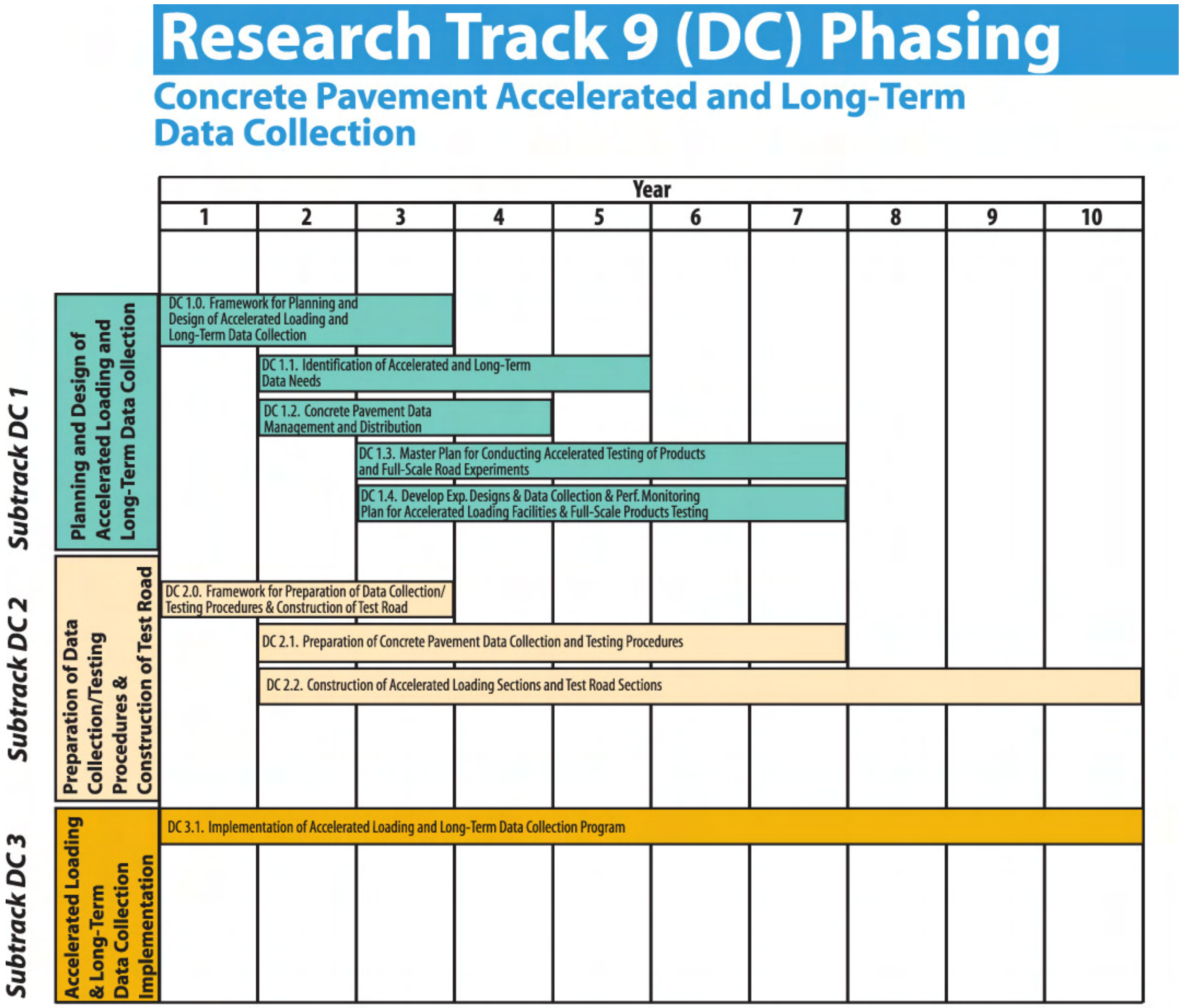

Figure 9. Track 9 (DC) subtrack and problem statement phasing chart.

Research Track 9 (DC) Estimated Costs

Table 45 shows the estimated costs for this research track.

Table 45. Research track 9 (DC) estimated costs.

Problem Statement	Estimated Cost
Subtrack DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection	
DC 1.0. Framework for Planning and Design of Accelerated Loading and Long-Term Data Collection (Subtrack DC 1)	$200 k
DC 1.1. Identification of Accelerated and Long-Term Data Needs	$750 k–$1.5 M
DC 1.2. Concrete Pavement Data Management and Distribution	$800 k–$1.2 M
DC 1.3. Master Plan for Conducting Accelerated Testing of Products and Full-Scale Road Experiments	$900 k–$1.5 M
DC 1.4. Develop Experimental Designs and a Data Collection and Performance Monitoring Plan for Accelerated Loading Facilities and Full-Scale Products Testing	$800 k–$1.5 M
Subtrack DC 2. Preparation of Data Collection/Testing Procedures and Construction of Test Road	
DC 2.0. Framework for Preparation of Data Collection/Testing Procedures and Construction of Test Road (Subtrack DC 2)	$200 k
DC 2.1. Preparation of Concrete Pavement Data Collection and Testing Procedures	$500 k–$1 M
DC 2.2. Construction of Accelerated Loading Sections and Test Road Sections	$4.8 M–$7.2 M
Subtrack DC 3. Accelerated Loading and Long-Term Data Collection Implementation	
DC 3.1. Implementation of Accelerated Loading and Long-Term Data Collection	$800 k–$1.2 M
Track 9 (DC)	
Total	$9.75 M–$15.5 M

Track Organization: Subtracks and Problem Statements

Track 9 (DC) problem statements are grouped into three subtracks:

- Subtrack DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection.
- Subtrack DC 2. Preparation of Data Collection/Testing Procedures and Construction of Test Road.
- Subtrack DC 3. Accelerated Loading and Long-Term Data Collection Implementation.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK DC 1. PLANNING AND DESIGN OF ACCELERATED LOADING AND LONG-TERM DATA COLLECTION

This subtrack addresses the full design of a new long-term data collection program for concrete pavements. This subtrack will provide the information necessary to support the modeling work identified in other tracks and the analysis of new experimental sections. Table 46 provides an overview of this subtrack.

Table 46. Subtrack DC 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
DC 1.0. Framework for Planning and Design of Accelerated Loading and Long-Term Data Collection (Subtrack DC 1)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
DC 1.1. Identification of Accelerated and Long-Term Data Needs	$750 k–$1.5 M	A detailed plan outlining data needs to support research planned under the CP Road Map, consisting of both accelerated loading sections and long-term road tests.	An effective and productive research program for collecting data through ALFs and full-scale road tests in support of the CP Road Map.
DC 1.2. Concrete Pavement Data Management and Distribution	$800 k–$1.2 M	A comprehensive plan for a Web-based, easy-to-access, and easy-to-use system for collecting, evaluating, and distributing data that incorporates a mechanism for importing data from other databases; reliable and accurate data for developing, calibrating, and validating tools required for pavement design, evaluation, rehabilitation, construction, and so on; a flexible system that allows data structure to be modified easily at any point.	Reliable and accurate data that pavement engineers can use to develop new tools or calibrate and validate existing tools or technology for pavement design, evaluation, rehabilitation, and so on.
DC 1.3. Master Plan for Conducting Accelerated Testing of Products and Full-Scale Road Experiments	$900 k–$1.5 M	An overall master plan for conducting accelerated testing of products developed under the CP Road Map, detailing the effectiveness of using ALFs in fast-track pavement testing, identifying appropriate testing needs for ALFs and new approaches that might improve the ALF testing process, and determining ways in which ALFs might accomplish research needs; a master plan for conducting full-scale, long-term road tests of products developed under the CP Road Map.	A program to test, verify, and validate products developed under the CP Road Map, giving credibility and validity to many of the individual research efforts.
DC 1.4. Develop Experimental Designs and a Data Collection and Performance Monitoring Plan for Accelerated Loading Facilities and Full-Scale Products Testing	$800 k–$1.5 M	Experimental designs and a data collection and performance monitoring plan for ALF and full-scale road testing of products developed under this track; four ALFs and four test roads.	Experimental design for testing products developed under this track using ALF or full-scale, inservice pavements; materials, construction, design, traffic, and materials data collected from both ALF and full-scale testing that will provide many years of reliable pavement analysis data.

Problem Statement DC 1.0. Framework for Planning and Design of Accelerated Loading and Long-Term Data Collection (Subtrack DC 1)

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection
Approximate Phasing:	Years 1–3
Estimated Cost:	$200 k

Subtrack DC 1 (Planning and Design of Accelerated Loading and Long-Term Data Collection) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack.

Tasks:

1. Examine the problem statements in subtrack DC 1 (Planning and Design of Accelerated Loading and Long-Term Data Collection), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack DC 1 (Planning and Design of Accelerated Loading and Long-Term Data Collection).

Problem Statement DC 1.1. Identification of Accelerated and Long-Term Data Needs

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection
Approximate Phasing:	Years 2–5
Estimated Cost:	$750 k–$1.5 M

This research will identify data needs and existing data sources to support other research planned under the CP Road Map.

Task:

1. Examine each research track to identify data needs. This task will require extensive interaction with expert task groups and others involved in the research tracks to identify the data needed to complete the individual projects successfully.
2. Examine databases from LTPP, MnROAD, FHWA's concrete pavement performance study,[4] and other sources to determine the amount of information available.
3. Determine the amount of additional data needed for specific new and innovative designs, materials, and construction techniques. For example, data should be needed for further calibrating distress and IRI models for JPCP and CRCP, as well as new pavement types, such as precast JCPs and thin concrete overlays. This analysis should consider accelerated durability testing for materials and designs.

Benefits:	A detailed plan that provides an effective and productive research program for collecting data through ALFs and full-scale road tests in support of the CP Road Map.
Products:	A detailed plan outlining data needs to support research planned under the CP Road Map, consisting of both ALFs and long-term road tests.
Implementation:	This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements), track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction), and track 8 (Long Life Concrete Pavements). The data needs identified in this research will be planned for and obtained throughout the CP Road Map.

Problem Statement DC 1.2. Concrete Pavement Data Management and Distribution

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection
Approximate Phasing:	Years 2–4
Estimated Cost:	$800 k–$1.2 M

This research will develop an initial comprehensive framework and then a computerized database for collecting, evaluating, and distributing data. The system will be Web-based and user-friendly and should incorporate a mechanism that easily imports data from existing databases. The database will be organized by specific objectives (e.g., modeling of slab cracking, faulting, smoothness, noise, productivity) to streamline the data elements for any given objective. The system must also allow the data structure to be modified easily and flexibly at any point, letting users add or delete data elements and reorganize the data tables as needed. The system will provide raw data as well as processed results. The type and format of the processed results offered should be established in light of various user needs (e.g., FHWA, State highway agencies, contractors, researchers, material suppliers, equipment manufacturers, trade organizations). The database initially will be populated by existing data from previous concrete pavement ALFs and road tests, but will include input for data identified under problem statement DC 1.1 (Identification of Accelerated and Long-Term Data Needs). The database will expand as new testing data is obtained.

Tasks:

1. Identify and document available Web-based systems for database assembly and management.
2. Determine whether the identified systems are suitable for this research.
3. Select the appropriate system and customize it in light of the data identified in problem statement DC 1.1.
4. Develop a framework for collecting, evaluating, and distributing data using data gathered under this track and the selected data management system.
5. Develop the data management system for this database.
6. Populate the database using data from previous or ongoing concrete pavement ALFs and road tests.

Benefits:	Reliable and accurate data that pavement engineers can use to develop new tools or calibrate and validate existing tools or technology for pavement design, evaluation, rehabilitation, and so on.
Products:	A comprehensive plan for a Web-based, easy-to-access, and easy-to-use system for collecting, evaluating, and distributing data that incorporates a mechanism for importing data from other databases; reliable and accurate data for developing, calibrating, and validating tools required for pavement design, evaluation, rehabilitation, construction, etc.; a flexible system that allows data structure to be modified easily at any point.
Implementation:	The results of this research will be used in many research activities throughout the design track.

Problem Statement DC 1.3. Master Plan for Conducting Accelerated Testing of Products and Full-Scale Road Experiments

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection
Approximate Phasing:	Years 3–7
Estimated Cost:	$900 k–$1.5 M

Several time-consuming factors (such as field trials and testing) are required to develop and launch an innovative idea or product successfully for concrete pavement design or construction. This is because the idea or product must be shown to improve current procedures genuinely in the short, intermediate, and long term and must be cost effective. For a concrete pavement structure, full-scale testing may include constructing inservice pavements that are subjected to both climate and traffic loads for more than 10 years. However, specific design aspects, such as transverse joints, could be tested more rapidly under an ALF.

Accelerated testing can reduce significantly the time needed to prove that an idea or a product is effective. This recently has been made possible by the development of several ALFs throughout the United States. ALFs can fast-track field testing and thus reduce the time between the development of an idea or concept and its implementation in the form of design guidelines or catalogues. However, ALFs do not always simulate field conditions entirely, and this shortcoming must be considered to determine whether ALFs effectively can obtain field performance data that assesses the usefulness of an innovative design. The following tasks will determine the effectiveness of using ALFs to fast-track pavement testing.

Tasks:

1. Identify specific testing needs appropriate for accelerated testing and long-term road testing. This will offer a global perspective of the various experiments and technical objectives, such as design guide calibration, joint program, and surface texture. The cost of these potential experiments must be estimated.
2. Document MnROAD ALFs, FHWA ALFs, and other ALFs in the United States and internationally to determine how PCC pavement tests are conducted, lessons learned, how to accomplish the needs identified in task one using this knowledge, and how new approaches might improve the process.
3. Develop an improved approach to accelerated concrete pavement testing. Include accelerated durability testing for materials and design, as well as accelerated repeated loading testing.
4. Develop an overall master plan for conducting accelerated testing of products developed under the CP Road Map.
5. Develop an overall master plan for conducting long-term road tests for products developed under the CP Road Map.

Benefits:	A program to test, verify, and validate products developed under the CP Road Map, giving credibility and validity to many of the individual research efforts.
Products:	A master plan for conducting accelerated testing of products developed under the CP Road Map, detailing the effectiveness of using ALFs in fast-track pavement testing, identifying appropriate testing needs for ALFs and new approaches that might improve the ALF testing process, and determining ways in which ALFs might accomplish research needs; a master plan for conducting full-scale, long-term road tests of products developed under the CP Road Map.
Implementation:	This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements), track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction), and track 8 (Long Life Concrete Pavements). The data needs identified in this research will be planned for and obtained throughout the CP Road Map.

Problem Statement DC 1.4. Develop Experimental Designs and a Data Collection and Performance Monitoring Plan for Accelerated Loading Facilities and Full-Scale Products Testing

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 1. Planning and Design of Accelerated Loading and Long-Term Data Collection
Approximate Phasing:	Years 3–7
Estimated Cost:	\$800 k–\$1.5 M

Each ALF and full-scale road testing experiment conducted under this track will require experimental designs. Well-designed experiments will maximize information while minimizing costs and offer the greatest chance for achieving reliable results. Each ALF and full-scale road testing experiment will require a data collection and performance monitoring plan to test products developed under this research. The research in this problem statement should account for experiments studying a range of traffic loadings, from low- to high-traffic volume roadways, as well as experiments that address accelerated durability testing for concrete paving materials and design.

Tasks: For each experiment conducted, the following must be done as a minimum:

1. Establish clear experiment scope and goals.
2. Identify factors involved and their experimental levels.
3. Design experiments and replicate test sections.
4. Analyze the data obtained.
5. Identify major uncertainties involved.
6. Review simulated experimental results to ensure design completeness (use existing data from ALFs and road tests).

Benefits: Experimental design for testing products developed under this track using ALF or full-scale, inservice pavements; materials, construction, design, traffic, and materials data collected from both ALF and full-scale testing that will provide many years of reliable pavement analysis data.

Products: Experimental designs and a data collection and performance monitoring plan for ALF and full-scale road testing of products developed under this track; four ALFs and four test roads.

Implementation: This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements), track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction), and track 8 (Long Life Concrete Pavements). The data needs identified in this research will be planned for and obtained throughout the CP Road Map.

SUBTRACK DC 2. PREPARATION OF DATA COLLECTION/TESTING PROCEDURES AND CONSTRUCTION OF TEST ROAD

This subtrack implements the specific aspects of the database system designed under problem statement DC 1.2 (Concrete Pavement Data Management and Distribution). The problem statements in this subtrack address the preparation of concrete pavement data collection and testing procedures and the construction of accelerated loading sections and test road sections. Table 47 provides an overview of this subtrack.

Table 47. Subtrack DC 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
DC 2.0. Framework for Preparation of Data Collection/Testing Procedures and Construction of Test Road (Subtrack DC 2)	$200 k	A validated, sequenced, and detailed research framework for this subtrack.	An effective, coordinated, and productive research program.
DC 2.1. Preparation of Concrete Pavement Data Collection and Testing Procedures	$500 k–$1 M	Development of data collection, testing procedures, protocols, and laboratory, ALF, and full-scale testing specifications for projects developed under problem statement DC 2.2.	Adoption of existing or development of new and more reliable test protocols for use in the pavement performance experiments.
DC 2.2. Construction of Accelerated Loading Sections and Test Road Sections	$4.8 M–$7.2 M	Execution of experimental plans developed under previous tasks, including the establishment of experimental test sections, a materials testing program, and performance monitoring to obtain data for developing pavement analysis and tools; data stored in the database developed under problem statement DC 1.4 that will be used for calibration, validation, and other activities for the pavement performance models used in the CP Road Map.	Available construction, design, traffic, and materials data collected from both ALFs and full-scale testing for pavement analysis.

Problem Statement DC 2.0. Framework for Preparation of Data Collection/Testing Procedures and Construction of Test Road (Subtrack DC 2)

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 2. Preparation of Data Collection/Testing Procedures and Construction of Test Road
Approximate Phasing:	Years 1–3
Estimated Cost:	$200 k

Subtrack DC 2 (Preparation of Data Collection/Testing Procedures and Construction of Test Road) provides a set of research problem statements that will culminate in a significantly improved state of the art and practice. As the funding becomes available, an initial effort will be necessary to develop a framework for the research to be accomplished within this subtrack. The framework developed in this problem statement should include accelerated durability testing for concrete pavement materials and designs.

Tasks:

1. Examine the problem statements in subtrack DC 2 (Preparation of Data Collection/Testing Procedures and Construction of Test Road), modify as appropriate, and divide them into specific, manageable contracts.
2. Arrange the contracts in a carefully sequenced plan that reflects a logical progress of research and available funding.
3. Expand each of the broad research problem statements included in the subtrack into a detailed research plan with specific objectives, tasks, and funding recommendations.
4. Review and provide direction for the various research contracts underway to ensure that they fulfill their objectives and allow future contracts to use their results. Guide the additional work required if a contract fails to achieve its objectives and additional work is necessary.

Benefits:	An effective, coordinated, and productive research program.
Products:	A validated, sequenced, and detailed research framework for this subtrack.
Implementation:	This research will provide the organization and validation essential for the success of this subtrack. Implementation of this problem statement will set the stage for the rest of the problem statements in subtrack DC 2 (Preparation of Data Collection/Testing Procedures and Construction of Test Road).

Problem Statement DC 2.1. Preparation of Concrete Pavement Data Collection and Testing Procedures

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 2. Preparation of Data Collection/Testing Procedures and Construction of Test Road
Approximate Phasing:	Years 2–7
Estimated Cost:	$500 k–$1 M

Because consistent and calibrated testing is critical to the success of all research in this track, substantial efforts must be mobilized to achieve this goal. The research in this problem statement will adopt existing or develop new standard data collection and testing procedures and specifications for laboratory, ALFs, and test road experimental sections. The plan will specify the testing to be conducted for each data element identified in previous problem statements.

Tasks:

1. If not accomplished previously under other projects, document MnROAD ALF, FHWA ALF, California DOT (Caltrans) ALF, University of Illinois ALF, and other ALFs in the United States and internationally to determine how PCC pavement tests are conducted, lessons learned, how the needs generated in task one could be accomplished using this knowledge, and how new approaches might improve the testing process.
2. Develop data collection and testing plans, protocols for all data, and ALF and full-scale construction and testing specifications for experimental projects developed under problem statement DC 2.2 (Construction of Accelerated Loading Sections and Test Road Sections). Extensive use will be made of AASHTO, ASTM, LTPP, and State highway agency protocols and tests.

Benefits:	Adoption of existing or development of new and more reliable test protocols for use in the pavement performance experiments.
Products:	Development of data collection, testing procedures, protocols, and laboratory, ALF, and full-scale testing specifications for projects developed under problem statement DC 2.2.
Implementation:	The results of this research will be used in many research activities throughout the design track.

Problem Statement DC 2.2. Construction of Accelerated Loading Sections and Test Road Sections

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 2. Preparation of Data Collection/Testing Procedures and Construction of Test Road
Approximate Phasing:	Years 2–10
Estimated Cost:	\$4.8 M–\$7.2 M (see note below)

This task will execute the experimental plans developed under problem statements DC 1.4 (Develop Experimental Designs and a Data Collection and Performance Monitoring Plan for Accelerated Loading Facilities and Full-Scale Products Testing) and DC 2.1 (Preparation of Concrete Pavement Data Collection and Testing Procedures). An expert panel consisting of State highway agencies, FHWA, academia, industry representatives, and consultants will prioritize different experiments and set schedules. To the extent practical, standard procedure will be established and followed in documenting the attributes of the as-built experimental section, and standard protocol will be followed in monitoring and reporting performance.

Tasks:

1. Construct the ALF sections. These sections likely will be constructed early so that the remaining studies can obtain and use the results.
2. Construct the test road sections. Designing and planning these major experiments will require time, and many years of monitoring will be needed to obtain results.
3. Conduct monitoring and data collection at all sites and feed the results directly to the projects that sponsor the experiments.

Benefits:	Available construction, design, traffic, and materials data collected from both ALFs and full-scale testing for pavement analysis.
Products:	Execution of experimental plans developed under previous tasks, including the establishment of experimental test sections, a materials testing program, and performance monitoring to obtain data for developing pavement analysis and tools; data stored in the database developed under problem statement DC 1.4 that will be used for calibration, validation, and other activities for the pavement performance models used in the CP Road Map.
Implementation:	This research will be coordinated closely with work in track 2 (Performance-Based Design Guide for New and Rehabilitated Concrete Pavements), track 6 (Innovative Concrete Pavement Joint Design, Materials, and Construction), and track 8 (Long Life Concrete Pavements). The data needs identified in this research will be planned for and obtained throughout the CP Road Map. These results also will be used immediately in calibration, validation, and other activities for models and engineering procedures developed in various research projects conducted under the CP Road Map.

Note: Assume 4–6 ALFs and 4–6 test roads will be constructed and tested each at approximately \$600,000. Some funds from the private sector may be available (\$1,000,000). These costs include engineering, testing, instrumentation, weather stations, construction, QC/QA, and monitoring, but not actual construction costs, except for ALFs. For economy or expediency, any of these experimental test sites could be adjacent to asphalt test roads.

SUBTRACK DC 3. ACCELERATED LOADING AND LONG-TERM DATA COLLECTION IMPLEMENTATION

This subtrack provides the funding necessary for training and educating State highway agencies to use the database and sharing the results from the various testing facilities. Table 48 provides an overview of this subtrack.

Table 48. Subtrack DC 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
DC 3.1. Implementation of Accelerated Loading and Long-Term Data Collection	$800 k–$1.2 M	Immediate transfer of results from the accelerated or long-term test facilities to researchers working on the overall concrete pavement research plan, using various research contracts conducting the work, the Internet, and summary reports presented at onsite workshops and conferences; construction, testing, and monitoring of the several experimental ALFs and full-scale road test sections, producing unbiased results that are useful for calibrating, validating, and developing various key prediction models in the CP Road Map.	Field-proven performance data that theory has predicted, important for calibrating and validating studies for the various models and predictions developed under the CP Road Map.

Problem Statement DC 3.1. Implementation of Accelerated Loading and Long-Term Data Collection

Track:	9. Concrete Pavement Accelerated and Long-Term Data Collection (DC)
Subtrack:	DC 3. Accelerated Loading and Long-Term Data Collection Implementation
Approximate Phasing:	Years 1–10
Estimated Cost:	$800 k–$1.2 M

Implementing the accelerated loading and long-term data collection advancements developed in this track will support many projects in the CP Road Map. The project research team will work extensively with contractors from other projects that need either accelerated or long-term performance data to ensure that the data needed is obtained properly.

Tasks:

1. Conduct accelerated loading and long-term data collection implementation on an experiment-by-experiment basis.
2. Document the results and field data as needed.

Benefits:	Field-proven performance data that theory has predicted, important for calibrating and validating studies for the various models and predictions developed under the CP Road Map.
Products:	Immediate transfer of results from the accelerated or long-term test facilities to researchers working on the overall concrete pavement research plan, using various research contracts conducting the work, the Internet, and summary reports presented at onsite workshops and conferences; construction, testing, and monitoring of the several experimental ALFs and full-scale road test sections, producing unbiased results that are useful for calibrating, validating, and developing various key prediction models in the CP Road Map.
Implementation:	This work will provide the technology transfer critical to the success of track 9 (Concrete Pavement Accelerated and Long-Term Data Collection).

Track 10. Concrete Pavement Performance (PP)

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TRACK 10 (PP) OVERVIEW

This track addresses key elements of the pavement management and asset management systems. These systems determine whether the sum of all the work done meets the required and desired concrete pavement performance characteristics for highway agencies and users.

In the past, concrete pavement performance requirements have focused on serviceability (i.e., ride quality) and friction. However, performance indicators, such as tire-pavement noise, tire spray, hydroplane potential resulting from wheel path wear, light reflection, fuel economy, and the availability of open traffic lanes (i.e., those not closed for construction or maintenance), are now of much greater interest to highway agencies and users. Future concrete pavement designs will be expected to provide for all of these functional performance indicators to produce surfaces and structures that meet the needs of highway agencies and users.

Structural and functional pavement performance is the output from all of the design, materials, and construction processes, and thus can be predicted using mathematical and computer models that systematically analyze data to predict pavement performance.

Monitoring concrete pavement performance indicators using PMS will be crucial to highway agencies. Developing a performance feedback loop to provide continuous condition reports will allow prompt improvements to existing pavements that fall short of user needs. Continuously monitoring pavement performance will also help improve concrete pavement design procedures (particularly functional considerations related to surface characteristics), construction standards and specifications, and rehabilitation techniques.

The research in this track will determine and address the functional aspects of concrete pavement performance, particularly factors such as tire-pavement noise, friction, smoothness, and others. Research will also provide rapid concrete pavement performance feedback and consider ways to schedule surface characteristics and conditions improvements. Developing feedback loops in highway agencies' PMS will be crucial to monitoring performance effectively and rapidly and suggesting improvements that minimize lane closures.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A chart is included to show an overview of the subtracks and problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

The research in this track will provide the traveling public with excellent concrete pavement surface characteristics and minimal lane closures for maintenance or rehabilitation over the design life.

Track Objectives

1. Develop ways to collect real-time data on concrete pavement conditions, including surface characteristics (e.g., friction, noise, distress, and smoothness), climate parameters (temperature and moisture), traffic loading, moisture sensors beneath the slab, and structural factors using a combination of embedded electronics, high-speed assessment equipment, traffic measurement devices, and performance prediction equations.

2. Determine concrete pavement condition using a new generation of equipment that addresses structural support, smoothness, friction, noise, moisture beneath the slab, drainage, and other factors.
3. Loop concrete pavement performance data back to agency maintenance, planning, traffic, design, materials, and construction units using improved management systems. This feedback will allow the required concrete pavement surface and structural improvements to be scheduled cost effectively and the pavement technology to be improved quickly.
4. Plan and schedule concrete pavement preservation and maintenance activities based on feedback condition and performance data to minimize lane closures and congestion.
5. Optimize the volume, type, and flow characteristics of traffic through long-lasting traffic monitoring sensors embedded in the pavement.

Research Gaps

- The real-time concrete pavement performance data are insufficient for such factors as surface characteristics (e.g., friction, noise, distress, and smoothness), climate, traffic, and structural concerns. Data collection methods could include a combination of embedded electronics, high-speed assessment equipment, traffic measurement devices, and performance prediction equations. Collecting this data will require a new generation of equipment and standard test methods that address structural support, smoothness, friction, noise, moisture, drainage, and other factors.

- The feedback data are insufficient for continuous performance improvement. PMS do not provide adequate feedback data for improving the performance of concrete pavements. Many of these systems cannot even relate performance monitoring data to original construction project information and traffic data. This critical gap can be remedied by developing improved data measurement and storage systems that not only provide this information rapidly, but also assist with its analysis. These new systems will provide rapid feedback for scheduling improvements in response to user feedback and continuously improving design, construction, materials selection, rehabilitation, and other factors that affect concrete pavement performance.

- The performance data on innovations developed using accelerated test roads is insufficient, and design, construction, materials, and rehabilitation factors require further validation. Many innovative ideas are never tested due to the risks and costs of failure. However, full-scale testing or, in some cases, testing at existing ALFs would provide sufficient and validated performance data rapidly and efficiently for concrete pavement innovations. Some performance concerns, such as early opening to traffic, can be tested using ALFs (i.e., through testing machines in buildings). Others will require full-scale traffic testing in the field using regular mixed traffic (similar to MnROAD) or special trucks only (similar to WesTrack). This performance data research plan provides an excellent way to test new and innovative ideas for concrete pavement design, construction, and rehabilitation. Supplementing and developing the results from LTPP and MnROAD are greatly needed.

Research Challenges

- Overcome obstacles to real-time pavement performance inspection, testing, and distress recording.
- Improve the data quality from PMS to improve concrete pavement performance.

Research Track 10 (PP) Phasing

The horizontal bar chart in figure 10 shows the problem statements in this track grouped by subtrack. Because this track is unphased, no time phasing is shown.

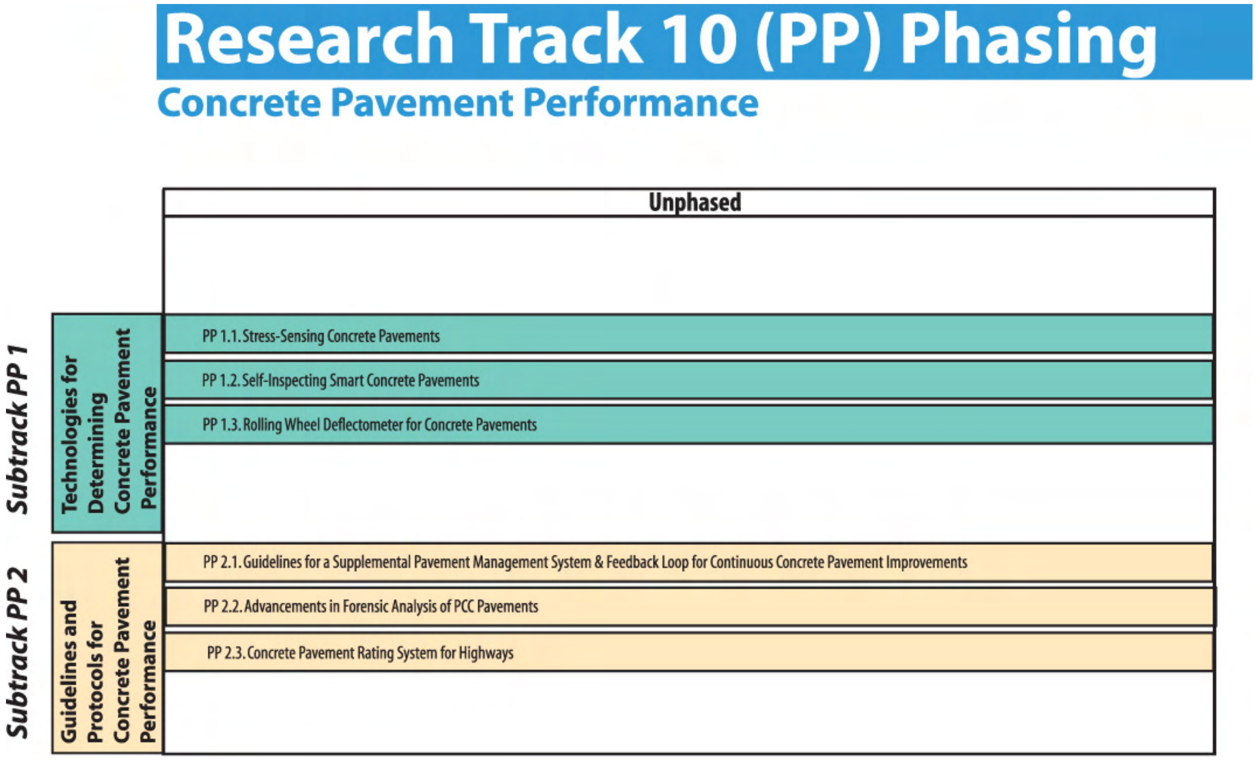

Figure 10. Track 10 (PP) unphased subtrack and problem statement chart.

Research Track 10 (PP) Estimated Costs

Table 49 shows the estimated costs for this research track.

Table 49. Research track 10 (PP) estimated costs.

Problem Statement	Estimated Cost
Subtrack PP 1. Technologies for Determining Concrete Pavement Performance	
PP 1.1. Stress-Sensing Concrete Pavements	\$500 k–\$750 k
PP 1.2. Self-Inspecting Smart Concrete Pavements	\$500 k–\$750 k
PP 1.3. Rolling Wheel Deflectometer for Concrete Pavements	\$500 k–\$750 k
Subtrack PP 2. Guidelines and Protocols for Concrete Pavement Performance	
PP 2.1. Guidelines for a Supplemental Pavement Management System and Feedback Loop for Continuous Concrete Pavement Improvements	\$500 k–\$750 k
PP 2.2. Advancements in Forensic Analysis of Concrete Pavements	\$500 k–\$750 k
PP 2.3. Concrete Pavement Rating System for Highways	\$200 k–\$400 k
Track 10 (PP)	
Total	\$2.7 M–\$4.15 M

Track Organization: Subtracks and Problem Statements

Track 10 (PP) problem statements are grouped into two subtracks:

- Subtrack PP 1. Technologies for Determining Concrete Pavement Performance.
- Subtrack PP 2. Guidelines and Protocols for Concrete Pavement Performance.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK PP 1. TECHNOLOGIES FOR DETERMINING CONCRETE PAVEMENT PERFORMANCE

This subtrack will develop and evaluate new technologies for determining concrete pavement performance. Table 50 provides an overview of this subtrack.

Table 50. Subtrack PP 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
PP 1.1. Stress-Sensing Concrete Pavements	\$500 k–\$750 k	Evaluation of stress-sensing monitors that record actual wheel load stresses over concrete pavement life.	Measurement of actual wheel load stresses over concrete pavement life.
PP 1.2. Self-Inspecting Smart Concrete Pavements	\$500 k-\$750 k	Evaluation of potential smart sensing and communicating technologies that could be integrated into the concept of self-inspecting concrete pavements.	Smart and self-inspecting concrete pavements.
PP 1.3. Rolling Wheel Deflectometer for Concrete Pavements	\$500 k–\$750 k	A rolling wheel deflectometer that can be operated at various speeds and that addresses specific concrete pavement technology issues.	Assessment of pavement condition using a rolling wheel deflectometer at operating speed.

Problem Statement PP 1.1. Stress-Sensing Concrete Pavements

Track:	10. Concrete Pavement Performance
Subtrack:	PP 1. Technologies for Determining Concrete Pavement Performance
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$750 k

When concrete pavements are designed, fatigue damage is anticipated by estimating the total number of all weights and types of axle loads that the pavement will experience over its lifetime. Because weigh-in-motion (WIM) sites often are unavailable, however, fully measuring the number and weight of axle loads that the pavement actually experiences over its lifetime is nearly impossible. Overweight trucks are known to damage a pavement more significantly than trucks with legal axle weights, but special permit trucks with heavier than legal weights are allowed to use the pavement.

This problem statement will investigate the viability of stress-sensing pavements that can measure and log wheel load stresses over the pavement life. Stress can be measured indirectly through instantaneous strain or deflection under a wheel load. Pavement stresses from environmental loading also can be measured. This stress-sensing technology can lead to smart pavements that predict remaining pavement life or time until rehabilitation. The technology also will provide better information to pavement designers about when and how to design a rehabilitation alternative.

Tasks:

1. Identify sensors that can be used for stress-sensing pavement. These sensors will operate by measuring strain, pressure, deflection, or other factors.
2. Conduct small-scale laboratory or field tests to determine the reliability, durability, and economics of these sensors.
3. Develop methods for remotely monitoring these sensors.
4. Incorporate sensors into a pilot project and evaluate sensor performance.
5. Develop recommendations and/or specifications for large-scale deployment of this technology on new paving projects.

Benefits:	Measurement of actual wheel load stresses over concrete pavement life.
Products:	Evaluation of stress-sensing monitors that record actual wheel load stresses over concrete pavement life.
Implementation:	This research will provide the groundwork for additional research into other sensing and self-inspecting concepts, such as that in problem statement PP 1.2 (Self-Inspecting Smart Concrete Pavements).

Problem Statement PP 1.2. Self-Inspecting Smart Concrete Pavements

Track:	10. Concrete Pavement Performance
Subtrack:	PP 1. Technologies for Determining Concrete Pavement Performance
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$750 k

This problem statement will investigate the viability of a pavement that is capable of continuously and remotely monitoring key behaviors that ultimately can be tied to structural or functional degradation. For example, embedded sensors can be used to monitor load (stresses or strains), compressive stress buildup over time (blowups), climatic changes (temperature and moisture), and deflections (joint LTE, joint faulting, corner deflection). This smart pavement concept will benefit the industry in a number of ways. For example, critical events such as an overloaded vehicle or a climatic anomaly can be detected. Potential blowups can be detected long before the probability of one is significant, so that action can be taken to relieve the pressure. In addition, the collected data can help improve concrete pavement design, construction, and maintenance continuously and establish more rational performance standards for concrete paving.

Tasks:

1. Identify sensors that can monitor pavement performance or key variables that affect pavement performance.
2. Determine the effect of these key variables on pavement performance and the threshold values for these variables.
3. Conduct laboratory or small-scale field tests to determine the reliability, durability, and economics of these sensors, using accelerated load testing to accelerated pavement distress.
4. Develop recommendations and/or specifications for deploying this technology on new paving projects.

Benefits:	Smart and self-inspecting concrete pavements.
Products:	Evaluation of potential smart sensing and communicating technologies that could be integrated into the concept of self-inspecting concrete pavements.
Implementation:	This research may require a preceding investigation of available sensors (see problem statement PP 1.1 (Stress-Sensing Concrete Pavements)), which may in turn lead to more long-range research efforts.

Problem Statement PP 1.3. Rolling Wheel Deflectometer for Concrete Pavements

Track:	10. Concrete Pavement Performance
Subtrack:	PP 1. Technologies for Determining Concrete Pavement Performance
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$750 k

Operating speed deflection testing equipment that determines deflections in concrete pavements is missing from today's pavement condition assessments. Systemwide deflection data are the missing component of a network analysis method that requires IRI, distress survey, climatic, and traffic data to understand pavement performance fully and evaluate pavement rehabilitation strategies adequately. The currently used falling weight deflectometer (FWD) test can perform individual test setups, but gaining access to busy roadways during the peak measurement times is becoming increasingly difficult. FHWA is developing a rolling deflectometer based on laser technology, but has yet to prove the concept sufficiently for concrete pavements. The rolling dynamic deflectometer at the University of Texas has produced excellent data, but is only a prototype and moves at 2.4 km/h (1.5 mi/h). This research will evaluate prototype defection equipment at various operating speed capabilities.

Tasks:

1. Conduct a full literature search of current deflection equipment, sorting by speed of operation.
2. Evaluate the potential for the FHWA rolling deflectometer device to produce data for concrete pavements.
3. Determine other suitable deflection techniques rated by operating speed.
4. Determine the best deflection technique for further development and evaluation.
5. Determine ways to produce repeatable results from this deflection equipment, connect them back to FWD measurements, and develop procedures that could be used to determine remaining pavement life.
6. Develop a long-term implementation strategy for promising deflection prototype devices.

Benefits:	Assessment of pavement condition using a rolling wheel deflectometer at operating speed.
Products:	A rolling wheel deflectometer that can be operated at various speeds and that addresses specific concrete pavement technology issues.
Implementation:	This work will result in a long-term implementation strategy for promising deflection prototype devices. While this technology should operate at typical highway speeds, devices that operate at lower speeds will be evaluated due to the unique concrete pavement response issues.

SUBTRACK PP 2. GUIDELINES AND PROTOCOLS FOR CONCRETE PAVEMENT PERFORMANCE

This subtrack will develop guidelines for a supplemental PMS, forensic analysis manual, and high-speed highway concrete pavement rating system for optimized concrete pavement performance. Table 51 provides an overview of this subtrack.

Table 51. Subtrack PP 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
PP 2.1. Guidelines for a Supplemental Pavement Management System and Feedback Loop for Continuous Concrete Pavement Improvements	\$500 k–\$750 k	Guidelines for developing a supplemental PMS that includes design, construction, materials, and rehabilitation data in a format conducive to engineering decisionmaking.	PMS that provide sufficient information for improving design, construction, materials, and rehabilitation; guidelines that produce information sufficient for key engineering decisions.
PP 2.2. Advancements in Forensic Analysis of Concrete Pavements	\$500 k–\$750 k	A state-of-the-art forensic study manual.	Forensic analysis that could be tied with the determination of remaining life to develop criteria for selecting appropriate rehabilitation and pavement strengthening actions to extend the existing pavement performance life.
PP 2.3. Concrete Pavement Rating System for Highways	\$200–\$400 k	Guidelines for State highway agencies to improve their pavement rating systems; implementation documents to be used directly by highway agencies to make use of high-speed highway pavement rating procedures.	A more accurate and efficient high-speed highway pavement rating system for use by State highway agencies.

Problem Statement PP 2.1. Guidelines for a Supplemental Pavement Management System and Feedback Loop for Continuous Concrete Pavement Improvements

Track:	10. Concrete Pavement Performance
Subtrack:	PP 2. Guidelines and Protocols for Concrete Pavement Performance
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$750 k

Current highway agency PMS are used primarily for programming highway rehabilitation activities. However, with few exceptions, they cannot provide sufficient information for improving the engineering aspects of design, construction, materials, and rehabilitation. The key reason is that many of these systems cannot link various types of information (e.g., design, construction, rehabilitation, maintenance, and traffic) on specific segments of the current highway network to each other. Another reason is that insufficient data are being collected. These deficiencies make it very difficult to use the system to assess problems, enhance designs, improve material and construction specifications, or optimize rehabilitation and life cycle costing.

This research will develop guidelines for a supplement to a PMS that includes concrete pavement design, construction, materials, and rehabilitation data in a format conducive to engineering decisionmaking. NCHRP 1–19 developed a system for concrete pavements in the 1980s that could serve as a starting point for this work.(5) In addition, recent FHWA research into the use of PMS data for engineering decisions should be reviewed fully, including an existing NHI course on the engineering uses of PMS data.

Tasks:

1. Review State highway agency PMS to determine which might improve engineering decisionmaking capabilities. For example, the Illinois PMS for pavements and materials was developed specifically for this purpose.
2. Review previous research studies (e.g., NCHRP 1–19, FHWA, Illinois and Arizona PMS development, and NHI courses) that address the use of PMS data for engineering decisionmaking.
3. Develop guidelines that State highway agencies can use to improve their PMS so that they can be used to make key engineering decisions.
4. Prepare implementation documents that highway agencies can use to assess their PMS and to extend them to help engineering decisions improve design, construction, materials, and rehabilitation.

Benefits:	PMS that provide sufficient information for improving design, construction, materials, and rehabilitation; guidelines that produce information sufficient for key engineering decisions.
Products:	Guidelines for developing a supplemental PMS that includes design, construction, materials, and rehabilitation data in a format conducive to engineering decisionmaking.
Implementation:	This research will produce implementation documents that highway agencies can use to assess their PMS and make better design, construction, materials, and rehabilitation engineering decisions.

Problem Statement PP 2.2. Advancements in Forensic Analysis of Concrete Pavements

Track: 10. Concrete Pavement Performance
Subtrack: PP 2. Guidelines and Protocols for Concrete Pavement Performance
Approximate Phasing: N/A
Estimated Cost: $500 k–$750 k

Many highway departments must evaluate inservice pavements and determine the reasons for good, marginal, or poor pavement performance. Often, a clear understanding of the all the elements of design, materials, construction, and inservice data is necessary to determine precisely what occurred or caused some action. In the past several years, the concrete paving industry has examined many pavements to determine the specific causes of a distress and have spent large amounts of time and money pulling together data. This problem statement will create a structure to examining pavements and develop a better way to determine remaining pavement life.

Tasks:

1. Conduct a literature review of projects that have undergone significant inservice evaluations to identify the key methods used to obtain and test samples of the pavements.
2. Identify the key forensic tests that could help identify various problems, focusing on durability, loss of smoothness, surface texture changes, and joint deterioration.
3. Develop a statistically based method to conduct a forensic study that will determine the probability that a distress was caused by a specific series of actions.
4. Develop a forensic study manual that includes the visual distress survey techniques, suggested tests, the sampling and testing of such samples, and the most likely cause of certain visual distresses based on these tests.
5. Conduct a literature search for the current methods to determine remaining structural and surface characteristic life for concrete pavements, including concrete overlay sections.
6. Identify ways to calculate remaining life based on current design methodologies, including the new *Mechanistic-Empirical Pavement Design Guide*. Include the field tests, sample size, and reliability.
7. Develop a forensic study manual that includes methods to determine the structural and surface characteristic life for concrete pavements and ways to calculate remaining life based on current design methodologies.
8. Develop an integrated forensic study manual that considers both manuals (from tasks 4 and 7) and that can be used to produce an overall pavement condition status report with remaining life.

Benefits: Forensic analysis that could be tied with the determination of remaining life to develop criteria for selecting appropriate rehabilitation and pavement strengthening actions to extend the existing pavement performance life.

Products: A state-of-the-art forensic study manual.

Implementation: This research may be divided into separate contracts for tasks 1–4, 5–7, and 8. The research results will be implemented through technology transfer of the forensic study manual.

Problem Statement PP 2.3. Concrete Pavement Rating System for Highways

Track:	10. Concrete Pavement Performance
Subtrack:	PP 2. Guidelines and Protocols for Concrete Pavement Performance
Approximate Phasing:	N/A
Estimated Cost:	$200 k–$400 k

State highway agencies use many procedures to rate their pavements for management and engineering purposes. These vary widely from State to State. This research will develop guidelines for State highway agencies to improve their pavement rating systems.

The pavement condition index (PCI) procedure was developed in the 1970s and 1980s for airport pavements and city street pavements. The main scope of the PCI was to provide a simple yet consistent tool for rating pavements that would reflect the experience of many experienced engineers. The rating scale, from 0 to 100, was divided into categories such as excellent, very good, good, fair, poor, and very poor. This procedure found wide use and acceptance by the U.S. military, Federal Aviation Administration (FAA), and some cities. Its main advantage is that it provides a simple, consistent, and uniform way to rate pavements with an overall score, but also includes individual distresses to determine the causes of deterioration, making it possible to better recommend rehabilitation treatments. In the 1980s, FHWA sponsored research to adapt the PCI to high-speed highways, and an initial procedure was completed. This initial work needs further consideration regarding its value today for State highway agencies as a consistent rating procedure.

Tasks:

1. Review State highway agency PMS and summarize their procedures to rate highway pavements. Compare the State highway rating systems with the PCI procedures used by the USACE, FAA, and APWA.
2. Assess whether the PCI procedure, appropriately modified as necessary to handle high-speed highways, would be useful to State highway agencies and FHWA in providing a uniform and consistent rating procedure.
3. If feasible, develop guidelines for all types of concrete pavements for use by State highway agencies to improve their pavement rating systems.
4. Prepare implementation documents for highway agencies to make use of the PCI procedures for high-speed highways.

Benefits:	A more accurate and efficient high-speed highway pavement rating system for use by State highway agencies.
Products:	Guidelines for State highway agencies to improve their pavement rating systems; implementation documents to be used directly by highway agencies to make use of high-speed highway pavement rating procedures.
Implementation:	This work will result in implementation documents to be used directly by highway agencies to use the PCI procedures for high-speed highways.

Track 11. Concrete Pavement Business Systems and Economics (BE)

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TRACK 11 (BE) OVERVIEW

The problem statements in this track address business and economics issues in concrete paving. The research outlined here will quantify the value and benefits of concrete pavements and ensure that an adequate delivery mechanism is in place to supplement the low bid system. This track, when implemented, will help clarify the relationship between concrete pavements and economic issues, capital availability, risk and risk transfer, and alternative contracting.

The research in this track will develop:

- An administrative support group to provide professional management services for the CP Road Map Research Management Plan.
- An innovative concrete pavement technology procurement program.
- Methods for achieving sustainability with concrete pavements.
- An improved understanding of the economic and systemic impacts of concrete pavement mix-of-fixes strategies for all levels of roadways, from low to very high traffic.
- Advanced methods for concrete pavement LCCA that include user costs.
- Optimized concrete pavement life cycle decisions.
- Innovative contracting methods that consider performance-based maintenance and warranties.
- The next generation of incentive-based concrete pavement construction specifications.
- A concrete pavement best practices manual.
- Accelerated technology transfer and rapid education programs for the future concrete paving workforce.
- An analysis of and recommendations about specific concrete pavement decisions with environmental impacts.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A chart is included to show an overview of the subtracks and problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

The research in this track will clarify the relationship between concrete pavements and economic issues, capital availability, risk and risk transfer, and alternative contracting.

Track Objectives

1. Understand more clearly the economics of concrete pavements, fix alternatives, and the cost implications of engineering improvements as they relate to pavement performance.
2. Determine the best combination of concrete pavement solutions (mix of fixes) that balances funds, traffic impact, and network efficiency.
3. Develop an array of alternate contracting techniques that enhance the procurement of concrete pavements with a clear determination of risk between the owner and the contractor.
4. Develop optimum technology transfer, training, and outreach for the entire concrete paving workforce that the new generation of efficient, targeted, high-quality, cross-disciplined, and available-on-demand pavements will require.

Research Gaps

- The impact of today's concrete pavement preservation alternatives (e.g., diamond grinding, DBR, joint and crack resealing) on future pavement life and performance is either insufficiently understood or accepted. Full-scale test sections for innovative preservation activities that function under actual traffic loadings will provide information that can establish the cost and benefits of such activities. These tests would develop information gained through the limited LTPP studies (Specific Pavement Studies (SPS)–4, SPS–6). Because well-timed preservation activities can extend the service life of concrete pavements cost effectively, appropriate research studies must address this significant gap in knowledge.

- Misconceptions about the economics of concrete pavements are common. In most markets, concrete pavements generally are considered a higher priced option than asphalt solutions when examining initial costs, but are considered equal or lower priced options when addressing life cycle costs. This belief is common under current design procedures. However, few existing tools can determine the actual initial costs effectively—these include the price of items such as joints, sealers, and tie bars in various designs and in specific projects. Instead, most estimating is based on previous bid estimates. In addition, long-term LCCAs lack the ability to improve maintenance analyses and user impacts. Additionally, alternative contracting techniques such as design-build, best value, or warranties have cost implications that have not been studied. Importantly, the relationship between the risk involved for the concrete pavement designer/builder and the best methods for equalizing or quantifying the risk is insufficiently understood. If warranties continue to gain popularity, with or without maintenance requirements, then new bonding, insurance, and guarantee mechanisms must be explored. Government and industry roles are changing, and tools need to be developed that equitably evaluate the risks.

- The current concrete pavement research system often stifles innovation. Much of the current research develops incremental improvements to concrete pavement products, while creative entrepreneurs have no place to present their ideas, and funds assist innovators only in the development path. Contracting methods that allow the contractor to innovate (design-build, warranties, incentive specifications) face bureaucratic hurdles that need to be reconsidered.

- Information is transferred too slowly to policymakers, engineers, and the concrete paving workforce. The concrete paving industry lacks innovation; this is due to both the return on investment and the considerable time it takes to transfer innovation into practice across the United States.

- The societal impacts of concrete pavements that result from cement manufacturing, transport, construction, and the impact of recycling on sustainability are insufficiently understood.

Research Challenges

- Understand more clearly the impact that today's concrete pavement preservation alternatives (e.g., diamond grinding, DBR, and joint and crack resealing) have on future pavement life and performance. Full-scale test sections for innovative preservation activities under actual traffic loadings will provide valuable information to establish the costs and benefits of preservation activities. This research should include all levels of roadways, from low to very high traffic volumes.

- Organize and conduct fair, valid, and easy-to-use economical studies for industry practitioners. These studies will obtain valid cost information that had been exclusive to the industry.

- Examine options for increased public-private partnerships that balance initial costs, maintenance operations, traffic growth, and toll revenues. Interest is developing in public-private partnerships that allow investors to consider financing the capital expenditures in return for either real or shadow tolls. The pavement costs can be 40 to 60 percent of a capital expenditure, and various options have a significant impact when compared to traffic and tolling.

- Move the concrete paving industry beyond incremental improvements to innovative technologies. The industry often has only incrementally improved concrete pavement technology. This research system has limited concrete paving development to JCP and CRCP, with the latter generally on the decline. Government agencies ask for innovation, but lack the funds and refuse to take risks to avoid public embarrassment.

- Facilitate the implementation of incentive-based contracting. Incentive-based contracting is discussed at the policy level, but faces many obstacles for both developing details and conducting experimental projects.

- Create strategies for developing the concrete paving workforce. The diverse workforce does not always commit to addressing concrete pavement issues on a national or regional basis, and funding for such efforts often is difficult.

- Consider sustainability issues in pavement selection criteria. National highway community policymakers often do not consider global sustainability issues in pavement selection criteria. This complicated issue requires considering many assumptions.

Research Track 11 (BE) Phasing

The horizontal bar chart in figure 11 shows the problem statements in this track grouped by subtrack. Because this track is unphased, no time phasing is shown.

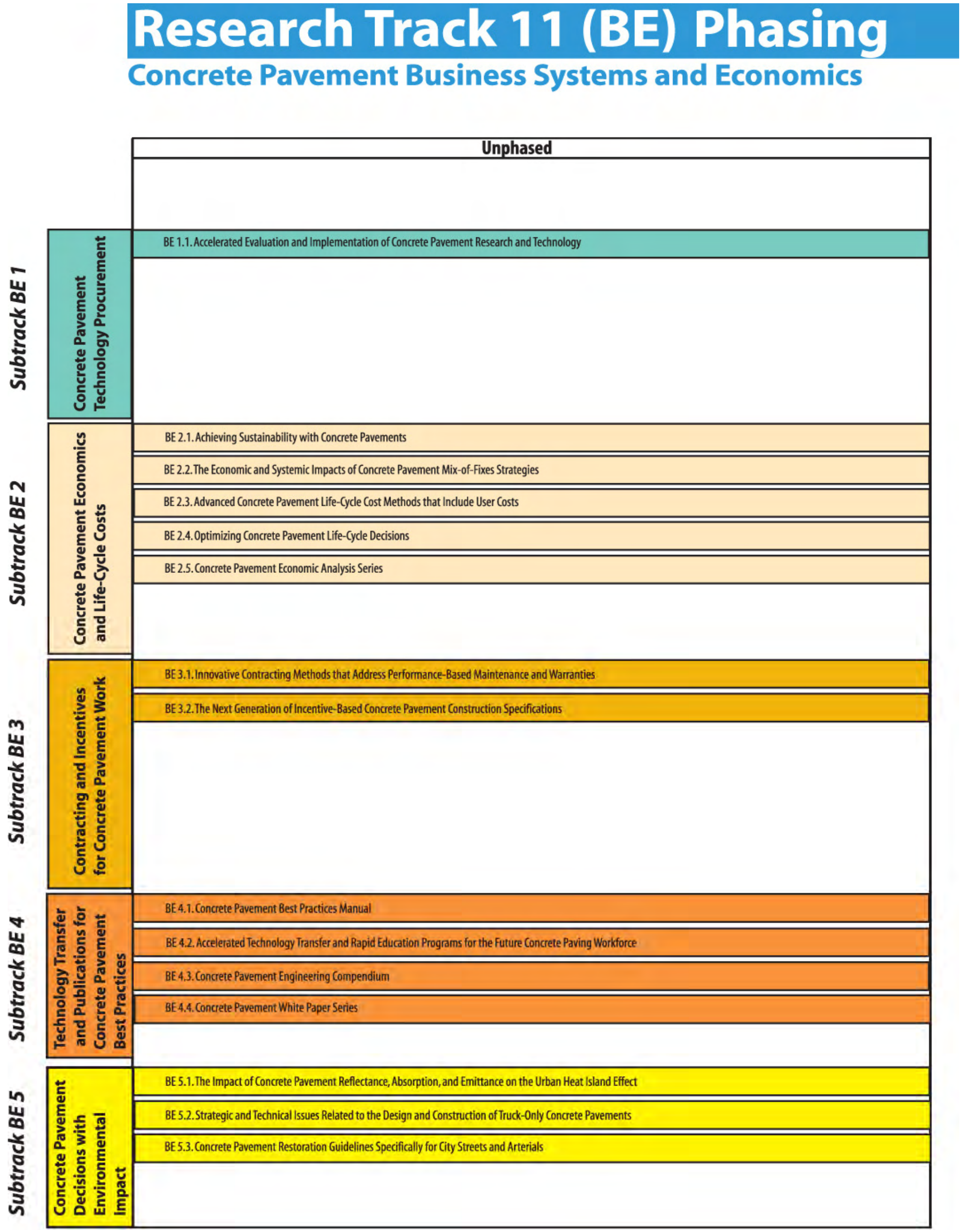

Figure 11. Track 11 (BE) unphased subtrack and problem statement chart.

Research Track 11 (BE) Estimated Costs

Table 52 shows the estimated costs for this research track.

Table 52. Research track 11 (BE) estimated costs.

Problem Statement	Estimated Cost
Subtrack BE 1. Concrete Pavement Research and Technology Management and Implementation	
BE 1.1. The CP Road Map Research Management Plan Administrative Support Group	$8.5 M ($850 k/year)
BE 1.2. Accelerated Evaluation and Implementation of Concrete Pavement Research and Technology	$5 M–$10 M (50% from public sector)
Subtrack BE 2. Concrete Pavement Economics and Life Cycle Costs	
BE 2.1. Achieving Sustainability with Concrete Pavements	$500 k–$750 k
BE 2.2. The Economic and Systemic Impacts of Concrete Pavement Mix-of-Fixes Strategies	$250 k–$500 k
BE 2.3. Advanced Concrete Pavement Life Cycle Cost Methods That Include User Costs	$500 k–$1 M
BE 2.4. Optimizing Concrete Pavement Life Cycle Decisions	$1 M–$2 M
BE 2.5. Concrete Pavement Economic Analysis Series	$500 k–$750 k
Subtrack BE 3. Contracting and Incentives for Concrete Pavement Work	
BE 3.1. Innovative Contracting Methods That Address Performance-Based Maintenance and Warranties	$750 k–$1 M
BE 3.2. The Next Generation of Incentive-Based Concrete Pavement Construction Specifications	$1.25 M–$1.75 M
Subtrack BE 4. Technology Transfer and Publications for Concrete Pavement Best Practices	
BE 4.1. Concrete Pavement Best Practices Manual	$750 k–1.25 M
BE 4.2. Accelerated Technology Transfer and Rapid Education Programs for the Future Concrete Paving Workforce	$750 k–$1 M
BE 4.3. Concrete Pavement Engineering Compendium	$500 k–$1 M
BE 4.4. Concrete Pavement White Paper Series	$150 k–$200 k
Subtrack BE 5. Concrete Pavement Decisions with Environmental Impact	
BE 5.1. The Impact of Concrete Pavement Reflectance, Absorption, and Emittance on the Urban Heat Island Effect	$250 k–$500 k
BE 5.2. Strategic and Technical Issues Related to the Design and Construction of Truck-Only Concrete Pavements	$250 k–$500 k
BE 5.3. Concrete Pavement Restoration Guidelines Specifically for City Streets and Arterials	$250 k–$500 k
Track 11 (BE)	
Total	$21.15 M–$31.2 M

Track Organization: Subtracks and Problem Statements

Track 11 (BE) problem statements are grouped into five subtracks:

- Subtrack BE 1. Concrete Pavement Research and Technology Management and Implementation.
- Subtrack BE 2. Concrete Pavement Economics and Life Cycle Costs.
- Subtrack BE 3. Contracting and Incentives for Concrete Pavement Work.
- Subtrack BE 4. Technology Transfer and Publications for Concrete Pavement Best Practices.
- Subtrack BE 5. Concrete Pavement Decisions with Environmental Impact.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK BE 1. CONCRETE PAVEMENT RESEARCH AND TECHNOLOGY MANAGEMENT AND IMPLEMENTATION

This subtrack provides the framework and funding for the CP Road Map Research Management Plan Administrative Support Group. This subtrack also assesses the successful Netherlands' Roads to the Future program to develop an accelerated evaluation and implementation system for innovative concrete pavement technologies. The system will link long-term vision to short-term action. Table 53 provides an overview of this subtrack.

Table 53. Subtrack BE 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
BE 1.1. The CP Road Map Research Management Plan Administrative Support Group	$8.5 M ($850 k/year)	–	–
BE 1.2. Accelerated Evaluation and Implementation of Concrete Pavement Research and Technology	$5 M–$10 M (50% from public sector)	An innovative program for accelerated evaluation and implementation of concrete pavement research and technology to successfully meet future needs.	Innovative concrete pavement technologies and processes that will move from concept to field evaluation to implementation in a compressed period of time; future concrete pavement needs met for agency-owners; an opportunity for contractors to innovate and generate new solutions to problems.

Problem Statement BE 1.1. The CP Road Map Research Management Plan Administrative Support Group

Track: 11. Concrete Pavement Business Systems and Economics (BE)
Subtrack: BE 1. Concrete Pavement Research and Technology Management and Implementation
Approximate Phasing: N/A
Estimated Cost: $8.5 M ($850 k/year)

The CP Road Map Research Management Plan outlines a progressive, cooperative approach to managing and conducting the CP Road Map research. Under this plan, organizations identify common interests, partner with each other in executing specific contracts, and, in the end, produce and share a product that is greater than the sum of its parts.

The research management plan emphasizes scope control, research phasing, reporting, systems integration, voluntary peer review, maintenance of the research database, program-wide technology transfer, and assistance to organizations that want to leverage their funds and human resources.

The research management plan outlines a four-tier system of participation and responsibility: an executive advisory committee, an administrative support group, track coordinators, and sustaining organizations.

A triparty executive advisory committee, representing FHWA, State DOTs, and industry, will provide broad oversight of CP Road Map. It will be a decisionmaking and policymaking facilitating group.

An administrative support group will provide professional management services for the executive advisory committee and, to a lesser degree, the research track coordinators. It will be the "doing" body for all coordinating and support activities, like maintaining the research database.

Research track coordinating teams will coordinate and oversee all activities within a specific research track.

Sustaining organizations—agencies, consultants, universities, professional associations, and other organizations that have specialized interests and skills and are interested in pooling earmarked or dedicated funds—will assume responsibility for conduct of research through cooperation, partnering, and funding agreements.

This problem statement represents the work and funding of the administrative support group.

Problem Statement BE 1.2. Accelerated Evaluation and Implementation of Concrete Pavement Research and Technology

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 1. Concrete Pavement Research and Technology Management and Implementation
Approximate Phasing:	N/A
Estimated Cost:	\$5 M–\$10 M (50 percent from public sector)

Major technological advancements often take many years to make it through the concept, research, demonstration, validation, and implementation stages before becoming part of practice. Highway agency-owners and the concrete paving industry cannot wait 10–15 years for the technologies and processes developed in the CP Road Map. A method is needed to accelerate the process of research and technology evaluation and implementation.

The successful Netherlands' Roads to the Future program should be considered as a model for or as input into an accelerated concrete pavement research and technology evaluation and implementation program in the United States. The Netherlands' Roads to the Future program is an innovative approach to developing and testing long-range solutions to future highway demands in a relatively short period of time. In the program, the highway agency, in cooperation with external partners, identifies future highway functional requirements in areas such as traffic expectations, environmental concerns, and pavement performance. Contractors are invited to offer solutions, no matter how unconventional, to the predefined highway functional requirements. Proposals are selected for field demonstration and evaluation within 2 years. In this way, long-term vision is linked to innovative, short-term action. Technical advancements that previously might take 10–15 years are now made possible in 2–3 years.

This research will evaluate the Netherlands' Roads to the Future model and develop a similar research and technology evaluation and implementation program to accelerate concrete pavement technology advancements in the United States.

Tasks:

1. Examine the Netherlands' Roads to the Future program, including identification of future highway requirements, the request for proposals, cooperative funding, demonstration projects, short-term methods of proving long-term requirements will be met, and intellectual property agreements.
2. Identify specific challenges that the U.S. concrete pavement industry will face in meeting the needs of the next generation of pavements, 30 years from now. Consider end product functional requirements such as rapid construction and rehabilitation, traffic expectations, noise abatement, and environmental advancements. Select the highest priority challenges.
3. Develop a request for proposals for each challenge selected.
4. Review and select the most promising proposals.
5. Build the required demonstration projects. Evaluate the demonstration projects to prove the concrete pavement will meet the specified future requirements.
6. Use technology transfer activities identified throughout the CP Road Map to ensure rapid implementation of successfully proven technologies and processes.

Benefits:	Innovative concrete pavement technologies and processes that will move from concept to field evaluation to implementation in a compressed period of time; future concrete pavement needs met for agency-owners; an opportunity for contractors to innovate and generate new solutions to problems.
Products:	An innovative program for accelerated evaluation and implementation of concrete pavement research and technology to meet future needs successfully.
Implementation:	This work will provide the mechanism for many concrete pavement technology innovations developed in the CP Road Map to be evaluated in the field and implemented at an accelerated rate.

SUBTRACK BE 2. CONCRETE PAVEMENT ECONOMICS AND LIFE CYCLE COSTS

This subtrack addresses the economics of concrete pavements, including macroeconomics analysis and whole life cycle costs. Table 54 provides an overview of this subtrack.

Table 54. Subtrack BE 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
BE 2.1. Achieving Sustainability with Concrete Pavements	\$500 k–\$750 k	Macroanalysis of whole-life factors related to concrete pavements.	A study of the broader issues associated with cement, aggregate, construction, rehabilitation, and concrete pavement salvaging that allows policymakers and engineers to examine the full societal value of concrete pavements and recommend improvements.
BE 2.2. The Economic and Systemic Impacts of Concrete Pavement Mix-of-Fixes Strategies	\$250 k–\$500 k	Advanced mix-of-fixes strategies that address a variety of performance and budget requirements; demonstration of the need to develop additional concrete pavement products that meet price and performance criteria.	Quantifications of a reasonable percentage of concrete pavement work with service life needs anywhere from 10 to 60 years.
BE 2.3. Advanced Concrete Pavement Life Cycle Cost Methods That Include User Costs	\$500 k–\$1 M	User cost factors that more accurately show value derived from smoothness, skid, noise, traffic shutdown, rolling resistance, and other factors associated with pavements.	More accurately and effectively determined user costs; ability for the owner to examine the interrelationships between product cost, performance, and user impact more accurately within the LCC framework; a more informed pavement selection decision.
BE 2.4. Optimizing Concrete Pavement Life Cycle Decisions	\$1 M–\$2 M	All-in-one tool for optimizing material selection, structural and functional design, construction, preservation, rehabilitation, and user impacts; a high-speed software program that integrates elements of the research from other tracks.	Better life cycle decision tools.
BE 2.5. Concrete Pavement Economic Analysis Series	\$500 k–\$750 k	Software and case studies that address microeconomic issues (engineering details such as tie bars, and cement content) and macroeconomic issues (pavement selection types).	Engineers and managers who better understand the initial costs associated with engineering details as they relate to long-term performance; engineers and managers who understand the overall economics that link construction costs with different pavement options and performance requirements.

Problem Statement BE 2.1. Achieving Sustainability with Concrete Pavements

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 2. Concrete Pavement Economics and Life Cycle Costs
Approximate Phasing:	N/A
Estimated Cost:	\$500 k–\$750 k

Sustainable development is defined as development that meets present needs without compromising the ability of future generations to meet their own needs. Concrete pavements use products and processes that can offer a broad set of benefits and opportunities for a more sustainable environment. To understand these benefits, decisionmakers must understand how pavement structure can support the three pillars of sustainability: environmental, social, and economic benefits. Concrete pavements can improve air quality, reduce energy consumption and heat load, manage storm water, reduce raw material consumption, increase the use of industrial waste and byproducts as replacement material, and increase the durability and longevity of the pavement structure itself. This research will identify and substantiate the roles concrete pavements play in sustainable development and develop a sustainability model protocol that the U.S. highway community can use to assess future product changes.

Tasks:

1. Conduct a literature review and identify the various sustainability models that are used to analyze pavement systems. Identify the model most conducive to the United States.
2. Identify the strong and weak points of the model, addressing energy consumption in manufacture, use of industrial byproducts in production, haul and build criteria, user energy requirements (for trucks and vehicles), maintenance requirements, reconstruction, and recycling. User requirements should consider safety factors, including skid, splash and spray, night visibility, noise, and delay time. The model also should develop a sustainability value that can assess the effectiveness of different applications.
3. Upgrade the model to include any variable omitted as a result of task 2.
4. Demonstrate the effectiveness of the model through a series of case studies.
5. Prepare and conduct three regional workshops.
6. Write the final documents and report.

Benefits:	A study of the broader issues associated with cement, aggregate, construction, rehabilitation, and concrete pavement salvaging that allows policymakers and engineers to examine the full societal value of concrete pavements and recommend improvements.
Products:	Macroanalysis of whole-life factors related to concrete pavements.
Implementation:	The whole-life, sustainability analysis resulting from this research will be made available and useful through technology transfer workshops and publications.

Problem Statement BE 2.2. The Economic and Systemic Impacts of Concrete Pavement Mix-of-Fixes Strategies

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 2. Concrete Pavement Economics and Life Cycle Costs
Approximate Phasing:	N/A
Estimated Cost:	\$250 k–\$500 k

The mix-of-fixes concept, developed by the Michigan DOT, identifies a family of renewal solutions for pavements and bridges that can be incorporated into capital improvement projects. These solutions vary in cost and expected service life. Relative costs could vary greatly per square unit of work, while service life could vary, from 3 to 5 years for surface treatments and thin overlays to 50 years or more for total reconstruction. Generally, a longer desired service life (one that minimizes downstream project traffic disruptions) requires a higher initial cost. However, while the Michigan DOT recognizes the need for the mix of fixes, it also recognizes the limited effectiveness of certain preservation strategies. The need for accelerated renewal and minimal disruption does not necessarily mark all infrastructure elements within a corridor for total reconstruction, replacement, and longest life solutions. How, then, can mix-of-fixes options be applied cost effectively while minimizing both current and downstream disruption?

Tasks:

1. Identify the concrete pavement mix-of-fixes strategies currently available to State highway agencies, including representative costs, service life, and the downstream impact of future renewal efforts. Strategies should describe the design lives of various key work elements for 15 to 60 years in various pavement scenarios. The strategies should also consider fixes known to be heavy maintenance items, such as CPR, whitetopping, and bonded and unbonded concrete overlays.
2. Evaluate how these mix-of-fixes strategies can be integrated into renewal strategies to optimize the funds available, minimize impact on traffic, and maintain desired service levels. Determine the overall reliability of assumptions about the life of each renewal strategy and the impact that shortened life may have on downstream traffic disruptions. Determine the number of back-to-back short life strategies that could be applied to bridges and pavements.
3. Determine the optimal time for selecting the proper fix, including advanced methodologies for determining current structure or pavement condition and remaining life.
4. Prepare case studies that demonstrate the impact of integrating mix-of-fixes strategies into the corridor and broader network funding demands.

Benefits:	Quantifications of a reasonable percentage of concrete pavement work with service life needs anywhere from 10 to 60 years.
Products:	Advanced mix-of-fixes strategies that address a variety of performance and budget requirements; demonstration of the need to develop additional concrete pavement products that meet price and performance criteria.
Implementation:	The analysis of economic and systemic impacts of mix-of-fixes strategies resulting from this research will be made available and useful through technology transfer activities.

Problem Statement BE 2.3. Advanced Concrete Pavement Life Cycle Cost Methods That Include User Costs

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 2. Concrete Pavement Economics and Life Cycle Costs
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

Advanced methods for developing concrete pavement life cycle costs are needed. These methods should include user costs.

Tasks:

1. Develop user cost factors that accurately show value from smoothness, skid, noise, traffic shutdown, rolling resistance, and other factors associated with pavements.
2. Develop new life cycle cost procedures that include these user costs.

Benefits:	More accurately and effectively determined user costs; ability for the owner to examine the interrelationships between product cost, performance, and user impact more accurately within the life cycle cost framework; a more informed pavement selection decision.
Products:	User cost factors that more accurately show value derived from smoothness, skid, noise, traffic shutdown, rolling resistance, and other factors associated with pavements.
Implementation:	The new user cost methodologies will update the life cycle cost procedures developed under FHWA Demonstration Project 115 (Probabilistic Life Cycle Cost Analysis in Pavement Design) that are now incorporated in the *Mechanistic-Empirical Pavement Design Guide*.[1]

Problem Statement BE 2.4. Optimizing Concrete Pavement Life Cycle Decisions

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 2. Concrete Pavement Economics and Life Cycle Costs
Approximate Phasing:	N/A
Estimated Cost:	$1 M–$2 M

A tool is needed for optimizing concrete pavement life cycle decisions. The tool should be all inclusive and integrate elements of related ongoing research.

Tasks:

1. Develop an all-in-one tool for optimizing concrete pavement life cycle decisions.
2. Create a high-speed software program that integrates elements of the research from other tracks.

Benefits:	Better life cycle decision tools.
Products:	All-in-one tool for optimizing material selection, structural and functional design, construction, preservation, rehabilitation, and user impacts; a high-speed software program that integrates elements of the research from other tracks.
Implementation:	Related research from other tracks will be integrated into a software program that will provide necessary life cycle data. The life cycle decision tools generated from this research will be shared through technology transfer.

Problem Statement BE 2.5. Concrete Pavement Economic Analysis Series

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 2. Concrete Pavement Economics and Life Cycle Costs
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$750 k

Though economic factors are crucial for concrete pavement design and construction, researchers often have only a loose sense of costs, usually initial or life cycle costs as well as one or two ingredients. Concrete pavement solutions normally have high initial costs that are returned with a lower life cycle cost. Additionally, engineers develop ideas and technologies to improve concrete pavement performance with little knowledge about the overall cost impacts. Two elements of the cost issue need to be considered.

The first element is the microeconomic determinations that estimate the impact of various engineering details on overall pavement price and performance. The ACPA has done this kind of estimate, looking at the cost implications of individual items, such as longitudinal tie bars, drainable bases, and cement content, in relation to a standard design. The research in this problem statement will develop a more robust model that more accurately determines the impact of the engineering details, including new and innovative details, on materials, labor, and equipment costs.

The second element is the macroeconomic determinations that estimate the cost-to-performance relationship for various concrete pavement solutions, comparing them to each other as well as to other pavement types. This element includes the economics of long life pavement solutions; short life solutions such as UTW; rehabilitation using recycled materials from the existing pavement; the impacts of traffic on costs, warranty and insurance issues; and foundation selection.

Tasks:

1. Develop a software program for conducting concrete pavement economic studies, including first-cost study, life cycle costs, and user costs. The software may be divided into two programs, one addressing microeconomics and the other addressing macroeconomics. Consider using probabilistic approaches, estimates, ranges, inflation rates, etc.
2. Identify a series of concrete pavement economic study topics and conduct studies.
3. Compile a list of current important cost topics and conduct a series of analyses using the new software and guidelines developed in task 1. Prepare full study reports on the topics.
4. Ensure that the final products and case studies will help engineers clearly and professionally distinguish the cost differentials between alternatives.

Benefits:	Engineers and managers who better understand the initial costs associated with engineering details as they relate to long-term performance; engineers and managers who understand the overall economics that link construction costs with different pavement options and performance requirements.
Products:	Software and case studies that address microeconomic issues (engineering details such as tie bars, and cement content) and macroeconomic issues (pavement selection types).
Implementation:	The economic analysis software and case studies resulting from this research will be made available through technology transfer efforts.

SUBTRACK BE 3. CONTRACTING AND INCENTIVES FOR CONCRETE PAVEMENT WORK

This subtrack addresses innovative contracting approaches, including performance-based and incentive-based contracting. Table 55 provides an overview of this subtrack.

Table 55. Subtrack BE 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
BE 3.1. Innovative Contracting Methods That Address Performance-Based Maintenance and Warranties	$750 k–$1 M	An innovative contracting manual with background information, contract methodologies, and specific language that will address design build, best value, cost + time (A+B) warranties, and performance-based maintenance contracting.	Contracting methods that account for the slightly higher initial costs, lower life cycle costs, and different maintenance and rehabilitation options for concrete pavements compared to asphalt pavements; a manual that will help decisionmakers integrate the design, procurement, maintenance, and warranties into packages that resolve these issues and develop consensus with the industry to provide the services.
BE 3.2. The Next Generation of Incentive-Based Concrete Pavement Construction Specifications	$1.25 M–$1.75 M	A manual of innovative incentives for concrete pavements that will move beyond the current A+B, lane rental, and smoothness incentives and focus on such issues as total pavement structure, advanced surface characteristics, functional issues, traffic management, and cost + time + quality (A+B+Q).	A new series of incentives that will significantly improve pavement attributes, such as noise or skid, and the overall concrete pavement product allowing contractors who pay attention to detail, workmanship, and sound planning to distinguish themselves from those producing borderline work; the first new incentive-based specifications to emerge since the early 1990s.

Problem Statement BE 3.1. Innovative Contracting Methods That Address Performance-Based Maintenance and Warranties

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 3. Contracting and Incentives for Concrete Pavement Work
Approximate Phasing:	N/A
Estimated Cost:	\$750 k–\$1 M

This research will organize, evaluate, and further implement alternative contracting mechanisms to accommodate a greater variety of contracting methods for specific concrete pavement applications. Many States are exploring contracting options that might accelerate project completion time, reduce overall costs, improve quality, and reward contractors for exceptional performance. However, inherent risks are associated with any new contracting procedure. Fully understanding and evaluating different options and applying those that will most benefit the States is important. The ways in which various alternative contracting strategies can be used effectively in concrete pavement technology must be determined. Risk sharing or transfer as a result of these strategies must also be quantified between the State highway agencies and the concrete paving industry. Performance-based maintenance and warranties will be addressed.

Tasks:

1. Identify and organize the alternative concrete pavement contracting strategies used in the United States over the past 10 to 15 years.
2. Identify and organize the alternative concrete pavement contracting strategies currently emerging or in practice in the international communities. Organize the alternative contracting procedures to help determine the potential benefits of the procedure in terms of time, quality, innovation, cost containment, services, risk sharing, etc. Identify the legal and administrative barriers that may impact implementation, as well as barriers that result from insufficiently understanding the risk involved.
3. Examine warranties and postconstruction responsibilities placed on the contractor to determine the risk and risk transfer required. Include a rational approach for determining the impact of warranty costs compared to the costs of the State highway agency doing repairs compared to repairs done without a warranty.
4. Develop guide language for the various contracting techniques.
5. Conduct national and regional outreach efforts to present the information and collect feedback from State highway agencies and the construction industry.
6. Conduct national experiments and evaluations.
7. Prepare final reports.

Benefits:	Contracting methods that account for the slightly higher initial costs, lower life cycle costs, and different maintenance and rehabilitation options that concrete pavements have compared to asphalt pavements; a manual that will help decisionmakers integrate the design, procurement, maintenance, and warranties into packages that resolve these issues and develop consensus with the industry to provide the services.
Products:	An innovative contracting manual with background information, contract methodologies, and specific language that will address design build, best value, A+B, warranties, and performance-based maintenance contracting.
Implementation:	This research will result in experimental projects and an innovative contracting manual.

Problem Statement BE 3.2. The Next Generation of Incentive-Based Concrete Pavement Construction Specifications

Track: 11. Concrete Pavement Business Systems and Economics (BE)
Subtrack: BE 3. Contracting and Incentives for Concrete Pavement Work
Approximate Phasing: N/A
Estimated Cost: $1.25 M–$1.75 M

Since the mid-1980s, incentives (e.g., A+B contracting and lane-by-lane rental) have been used in highway construction to optimize attributes such as construction time management and pavement strength and smoothness. The many benefits include a noticeable improvement in concrete pavement smoothness. However, the state of the art has not advanced beyond the current incentives. For example, many experts call for an incentive for overall concrete pavement quality, rather than for one or two attributes. Quality becomes an even larger issue in A+B contracting, where speed is sometimes thought to compromise quality. This research addresses construction incentives, proposing innovative new ideas, developing guide language, and organizing experimental projects. The new incentives will allow contractors who pay attention to detail, workmanship, and sound planning to distinguish themselves from those producing borderline work.

Tasks:

1. Synthesize the background and state of the art of concrete pavement incentives.
2. Identify areas where incentives may prove valuable in improving quality, construction speed, product selection, etc. The areas should address functional considerations, such as smoothness, skid, drainage, and noise, as well as structural adequacy. Incentive or disincentive amounts should take into account probabilistic methodologies using performance-based design models.
3. Identify a methodology that identifies a quality factor for an entire concrete pavement section. Incentive or disincentive amounts should take into account probabilistic methodologies using performance-based design models.
4. Develop guide specification language for individual attributes and overall quality.
5. Conduct experimental projects and prepare a summary report.

Benefits: A new series of incentives that will significantly improve pavement attributes, such as noise or skid, and the overall concrete pavement product allowing contractors who pay attention to detail, workmanship, and sound planning to distinguish themselves from those producing borderline work; the first new incentive-based specifications to emerge since the early 1990s.

Products: A manual of innovative incentives for concrete pavements that will move beyond the current A+B, lane rental, and smoothness incentives and focus on such issues as total pavement structure, advanced surface characteristics, functional issues, traffic management, and A+B+Q.

Implementation: This project will result in standard specifications for a new generation of incentives.

SUBTRACK BE 4. TECHNOLOGY TRANSFER AND PUBLICATIONS FOR CONCRETE PAVEMENT BEST PRACTICES

This subtrack addresses technology transfer efforts beyond those identified in the other tracks in the CP Road Map. The educational and training work identified here—best practices manual, workforce education programs, engineering compendium, and white paper series—will be conducted in coordination with other problem statements as appropriate. Table 56 provides an overview of this subtrack.

Table 56. Subtrack BE 4 overview.

Problem Statement	Estimated Cost	Products	Benefits
BE 4.1. Concrete Pavement Best Practices Manual	\$750 k–\$1.25 M	A national compilation of concrete pavement best practices for design, construction, materials, and maintenance.	Continuously defined best practice, allowing the concrete paving industry to keep pace with innovation that has moved into practice and offering incentives for doing work in a certain way; a community unified around consensus.
BE 4.2. Accelerated Technology Transfer and Rapid Education Programs for the Future Concrete Paving Workforce	\$750 k–\$1 M	An innovative technology transfer program with new methods and procedures for advancing concrete pavement industry technology quickly and efficiently; an innovative way for identifying and educating the workforce that addresses new technology, new workers on current technology, and reinforcement training.	A new approach to technology transfer that will help the industry reduce its current 15-year timeframe dramatically in evaluating and accepting new products, helping entrepreneurs develop and share new ideas and technologies.
BE 4.3. Concrete Pavement Engineering Compendium	\$500 k–\$1 M	A concrete pavement engineering compendium and library of key historical engineering source documents.	A book that will provide a solid history of concrete pavement research and decisionmaking, clearly showing the fundamental decisions made; a resource document for the next generation of concrete pavement engineers and researchers, who will build on this knowledge as they advance toward full-scale mechanistic approaches.
BE 4.4. Concrete Pavement White Paper Series	\$150 k–\$200 k	A concrete pavement white paper series that provides a framework for entrepreneurs and innovators within government, industry, and academia to organize their thoughts and create discussion about new concepts, products, and methodologies within the industry.	A white paper program that will call attention to ideas, help educate the concrete paving industry about important policy and technical issues, and implement critical strategies more quickly.

Problem Statement BE 4.1. Concrete Pavement Best Practices Manual

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 4. Technology Transfer and Publications for Concrete Pavement Best Practices
Approximate Phasing:	N/A
Estimated Cost:	$750 k–$1.25 M

Many variables complicate the chemistry of concrete pavement mixtures, including multiple aggregate and cement sources, different pavement characteristics required for different situations, and numerous and sometimes incompatible mineral and chemical admixtures. Construction variables such as weather, mix delivery times, finishing practices, and pavement opening schedules further complicate mixtures. However, mixture materials, mix design, and pavement construction are not isolated steps in the road building process. All affect and are affected by the others in ways that determine overall concrete pavement durability and long-term performance. Optimizing pavement performance, therefore, requires an integrated systems approach to designing and building pavements.

Significant research advancements have been made in concrete mixture materials and design, and in construction technologies and practice. However, actual field practice has not kept pace. A resource is needed to help engineers, QC personnel, contractors, suppliers, technicians, and trades people appreciate new technologies, tests, and practices that can identify materials or concrete properties and construction practices that lead to premature pavement distress; learn to implement these technologies, tests, and practices in the field; and access how-to and troubleshooting information quickly.

Tasks:

1. Describe concrete pavement construction as an integrated system in which materials selection, mix design, and construction practices all affect each other in many ways.
2. Describe critical mix properties that predict overall quality of the final product.
3. Compile information about technologies, tests, and new practices that will optimize materials selection, mix design, and construction practices when more widely used. Describe how and why to implement these technologies.
4. Provide a detailed, easy-to-use decision tree or matrix for using recommended technologies, tests, and new practices as well as a thorough and convenient troubleshooting guide.
5. Develop a new and innovative approach to supplement written text with video.

Benefits:	Continuously defined best practice, allowing the concrete paving industry to keep pace with innovation that has moved into practice and offering incentives for doing work in a certain way; a community unified around consensus.
Products:	A national compilation of concrete pavement best practices for design, construction, materials, and maintenance.
Implementation:	The concrete pavement best practices resulting from this research will be implemented through technology transfer.

Problem Statement BE 4.2. Accelerated Technology Transfer and Rapid Education Programs for the Future Concrete Paving Workforce

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 4. Technology Transfer and Publications for Concrete Pavement Best Practices
Approximate Phasing:	N/A
Estimated Cost:	$750 k–$1 M

Concrete pavement technology transfer in the United States can take up to 15 years from introduction to adoption. The concrete pavement industry can cite many case studies to support this timeframe and could make a case for one even longer. This length of time discourages investment in the industry and frustrates those trying to invest. The many barriers include State border issues, lack of State highway agency experience and resources, method specifications, and highly variable local practices and customs, to name a few. This research will develop accelerated technology transfer and rapid education programs with a high certainty of success.

Tasks:

1. Examine the current technology transfer system and identify how items enter a national, regional, and State agenda for technology transfer.
2. Examine how technologies are sorted in terms of evaluation, experimentation, implementation, or general training.
3. Identify ways that FHWA, industry, and State highway agencies can agree on topics of mutual interest that are worthy of acceleration.
4. Identify innovative ways to transfer technology, going beyond ideas such as teleconferencing, Web-based initiatives, and listservs. Concepts to investigate should include the management decisionmaking process, technology white papers, and mutual training course development. Joint training among all parties, including the concrete industry workforce, also should be examined. In this effort, the researcher should develop different structures for executives, engineers, technicians, and laborers.
5. Develop and implement an integrated technology transfer system that identifies, develops, and implements new methodologies that FHWA, industry, and State highway agencies can use to accelerate technology transfer.

Benefits:	A new approach to technology transfer that will help the industry reduce its current 15-year timeframe dramatically in evaluating and accepting new products, helping entrepreneurs develop and share new ideas and technologies.
Products:	An innovative technology transfer program with new methods and procedures for advancing concrete pavement industry technology quickly and efficiently; an innovative way for identifying and educating the workforce that addresses new technology, new workers on current technology, and reinforcement training.
Implementation:	The technology transfer program resulting from this work will include the necessary mechanisms for its own implementation.

Problem Statement BE 4.3. Concrete Pavement Engineering Compendium

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 4. Technology Transfer and Publications for Concrete Pavement Best Practices
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

Much of the principle research for current concrete pavement design was done more than 80 years ago. Pioneer work from that time is still the basis of the knowledge used by today's engineers. However, while many of the original researchers have passed away and many more are retiring from active work, the community has neither organized their work, gathered the original manuscripts, nor prepared an all-inclusive concrete pavement engineering manual. A small group of civil engineers recently outlined a potential manual that would contain at least 56 technical chapters. That same group identified nearly 900 base documents that capture elements of concrete pavement engineering principles. Clearly, the next generation stands to lose an enormous amount of history. Because no single library in world contains original works, these documents are often difficult to find. With the advent of mechanistic designs, many mechanistic design principles require a working knowledge of these base principles. This work will compile a comprehensive concrete pavement engineering compendium.

Tasks:

1. Outline an all-inclusive concrete pavement engineering manual.
2. Develop strategies for collecting the original works and documenting them electronically.
3. Organize a working group of recognized experts that are willing to prepare summary documents that would be included in the manual.
4. Prepare the concrete pavement engineering compendium.
5. Identify and select a location for the document that will update it every 10 years as knowledge continues to develop.

Benefits:	A book that will provide a solid history of concrete pavement research and decisionmaking, clearly showing the fundamental decisions made; a resource document for the next generation of concrete pavement engineers and researchers, who will build off this knowledge as they advance towards full-scale mechanistic approaches.
Products:	A concrete pavement engineering compendium and library of key historical engineering source documents.
Implementation:	The results of this research will be made available through distribution and marketing of the concrete pavement engineering compendium.

Problem Statement BE 4.4. Concrete Pavement White Paper Series

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 4. Technology Transfer and Publications for Concrete Pavement Best Practices
Approximate Phasing:	N/A
Estimated Cost:	\$150 k–\$200 k

A white paper is a brief government report that typically argues a specific position or solution to a problem. They have become a common tool for introducing technological innovations and products. For the concrete pavement industry, a white paper program can serve several functions. First, white papers can educate a reader using unbiased, authoritative, neutral, and factual information on any topic from policy to highly technical subjects. White papers also describe a position that a company or organization can take as a leader in concrete pavement technology. Finally, white papers can help key decisionmakers and influence peddlers use data and facts to justify implementing solutions.

The intent of the research is to allow entrepreneurs to organize new ideas, provide a vehicle for calling attention to these ideas, develop a consensus opinion, and eventually lead to informed decisions about research, implementation, policy, or training.

Tasks:

1. Develop the structure for a concrete pavement white paper program, defining information type, length, tone, visual appearance, and purpose. Identify ways that white papers can be accepted for review, commented on, and recorded.
2. Identify the lead organization that will manage the white paper program.
3. Develop an outreach and communication program.
4. Develop a series of white papers to provide momentum to the effort.
5. Complete a final report that organizes the effort.

Benefits:	A white paper program that will call attention to ideas, help educate the concrete paving industry about important policy and technical issues, and more quickly implement critical strategies.
Products:	A concrete pavement white paper series that provides a framework for entrepreneurs and innovators within government, industry, and academia to organize their thoughts and create discussion about new concepts, products, and methodologies within the industry.
Implementation:	The results of this research will be made available through distribution and marketing of the concrete pavement white series.

SUBTRACK BE 5. CONCRETE PAVEMENT DECISIONS WITH ENVIRONMENTAL IMPACT

This subtrack collects research on specific concrete pavement issues that impact the environment. Other environmental topics are integrated across the CP Road Map. See cross-reference table A in appendix A for an index of problem statements that relate to environmental advancements. Table 57 provides an overview of this subtrack.

Table 57. Subtrack BE 5 overview.

Problem Statement	Estimated Cost	Products	Benefits
BE 5.1. The Impact of Concrete Pavement Reflectance, Absorption, and Emittance on the Urban Heat Island Effect	\$250 k–\$500 k	A report detailing the impact of the reflectance of various concrete pavement types on the heat island effect.	An examination of existing efforts to understand and reduce the heat island effect to determine their applicability to concrete pavements and help determine the impact of concrete pavements on the heat island effect, as well as the costs associated with reducing the effect.
BE 5.2. Strategic and Technical Issues Related to the Design and Construction of Truck-Only Concrete Pavements	\$250 k–\$500 k	A thorough examination of the strategic policy and technical issues involved in designing concrete pavements for truck-only roadways or lanes.	Research that will help the highway community address the issue of truck-only lanes, specifically examining how concrete pavements might handle the loads associated with truck-only lanes.
BE 5.3. Concrete Pavement Restoration Guidelines Specifically for City Streets and Arterials	\$250 k–\$500 k	CPR guidelines for city engineers and inspectors.	Simplified guidelines that cities and counties can use to determine when and how to use CPR techniques; guide specifications that will let cities and counties more rationally decide how to use CPR techniques on their streets.

Problem Statement BE 5.1. The Impact of Concrete Pavement Reflectance, Absorption, and Emittance on the Urban Heat Island Effect

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 5. Concrete Pavement Decisions with Environmental Impact
Approximate Phasing:	N/A
Estimated Cost:	$250 k–$500 k

As urban centers continue to expand and/or rehabilitate their network of streets, roads, highways, parking lots, runways, taxiways, and their industrial and modal centers, local temperature increases resulting from solar absorption and associated heat emission are becoming a major concern. The problem stems from the extensive network of dark colored horizontal structures such as roofs and pavements in the built environment. The loss of vegetation and trees in and around cities due to urban and suburban growth patterns and practices exacerbate the temperature increases. The temperature increases due to the color and reflectance characteristics of horizontal structures create what is known as the urban heat island effect. To mitigate this effect, the U.S. Environmental Protection Agency and other groups are developing a variety of techniques and processes that can reduce temperature and the overall impact of heat absorption and emittance. However, the research done to date has only focused on roof structures. The research suggested here will expand the scope to include concrete pavements.

Tasks:

1. Conduct a literature survey of the different reflectance values and methodologies that can help reduce the heat island effect, focusing on the U.S. Green Building Council’s Leadership in Energy and Environmental Design Program and the Environmental Council of Concrete Organizations efforts such as the Warm Community Program.
2. Determine constituent materials that can deliver reflectant surfaces and demonstrate the reflectance characteristics. Examine cement types, aggregate and sand types, and various color admixtures.
3. Determine the change in reflectance over time in various exposures to the environment.
4. Develop comparative cost analysis techniques that examine both initial and life cycle costs.
5. Prepare final report.

Benefits:	An examination of existing efforts to understand and reduce the heat island effect to determine their applicability to concrete pavements and help determine the impact of concrete pavements on the heat island effect, as well as the costs associated with reducing the effect.
Products:	A report detailing the impact of the reflectance of various concrete pavement types on the heat island effect.
Implementation:	The results of this research will be implemented through technology transfer activities.

Problem Statement BE 5.2. Strategic and Technical Issues Related to the Design and Construction of Truck-Only Concrete Pavements

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 5. Concrete Pavement Decisions with Environmental Impact
Approximate Phasing:	N/A
Estimated Cost:	$250 k–$500 k

The United States has seen dramatic increases in truck traffic over the past several decades, with truck traffic on some roadways approaching 50 percent. Private vehicle drivers often resent this level of truck traffic. Under the Public-Private Transportation Act, the Virginia DOT (VDOT) is examining proposals that would use exclusive truck lanes along the I–81 corridor. This research will consider the unique options involved in designing concrete pavement for truck-only lanes.

Tasks:

1. Examine the geometrics associated with truck-only lanes, including shoulders, lane widths, curvatures, speed limits, and breaking distances.
2. Examine size and weight issues for various concrete pavement designs, examining JCP and CRCP options.
3. Develop several pavement life cycle options, including a maintenance tree and user costs for various rehabilitation options.

Benefits:	Research that will help the highway community address the issue of truck-only lanes, specifically examining how concrete pavements might handle the loads associated with truck-only lanes.
Products:	A thorough examination of the strategic policy and technical issues involved in designing concrete pavements for truck-only roadways or lanes.
Implementation:	The results of this research will be implemented through technology sharing and application.

Problem Statement BE 5.3. Concrete Pavement Restoration Guidelines Specifically for City Streets and Arterials

Track:	11. Concrete Pavement Business Systems and Economics (BE)
Subtrack:	BE 5. Concrete Pavement Decisions with Environmental Impact
Approximate Phasing:	N/A
Estimated Cost:	$250 k–$500 k

While many State highway agencies have specifications for CPR, cities could benefit from specifications that directly address the unique problems associated with city streets and arterials. These problems include design methodologies, construction specification language, materials specifications, and installation guidelines.

Tasks:

1. Develop a simplified pavement evaluation technique that includes criteria for specific techniques.
2. Develop a simplified CPR design procedure that addresses problems unique to city streets. Examine lateral injection thoroughly in the study.
3. Develop guide specification language that includes warranties and an area management approach.
4. Update existing installation guidelines to assure that they relate to city and county officials.
5. Develop final construction evaluation techniques that cities can use to determine compliance.

Benefits:	Simplified guidelines that cities and counties can use to determine when and how to use CPR techniques; guide specifications that will let cities and counties more rationally decide how to use CPR techniques on their streets.
Products:	CPR guidelines for city engineers and inspectors.
Implementation:	The results of this research will be implemented through technology transfer activities.

Track 12. Advanced Concrete Pavement Materials (AM)

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TRACK 12 (AM) OVERVIEW

If the concrete pavement industry continues to use the same types of materials, the same problems and limitations will persist in concrete pavement applications. Fortunately, innovative concrete paving materials continually are being developed to enhance performance, improve construction, and reduce waste. The problem statements in this track will develop new materials and refine or introduce existing advanced materials. Many existing materials that the problem statements study have been used thus far only on a small scale, such as in laboratory tests. Most existing materials have not been used in the United States, but have been used successfully in other countries. This track will bring new concrete paving materials into common practice by experimenting with them on a larger scale and developing standards and recommendations for their use. Moreover, this research will foster innovation in the development of new and innovative concrete pavement materials.

The problem statements in this track are grouped into three subtracks: performance-enhancing, construction-enhancing, and environment-enhancing concrete pavement materials. Performance-enhancing materials will improve pavement durability and long-term performance, perhaps extending pavement life further than conventional materials. Construction-enhancing materials will improve the construction process by reducing material requirements, labor requirements, or construction time. Finally, environment-enhancing materials show promise not only by reducing waste through pavement reclamation, but also for reducing raw consumer and industrial waste. Clearly, many of these materials fit into more than one category. A material that improves the construction process, for example, also may improve pavement durability and performance. Likewise, a material that uses consumer waste also may improve pavement performance.

The emphasis on environment-enhancing materials is significant. Not only are contractors and agencies paying heavily to dispose of reclaimed asphalt and concrete pavement, but also other industries are looking for environmentally responsible ways to dispose of industrial and consumer waste to reduce the burden on landfills. Environmental concerns are expected to become more important in the next few decades as landfills quickly fill.

The following introductory material summarizes the goal and objectives for this track and the gaps and challenges for its research program. A chart is included to show an overview of the subtracks and problem statements in the track. A table of estimated costs provides the projected cost range for each problem statement, depending on the research priorities and scope determined in implementation. The problem statements, grouped into subtracks, follow.

Track Goal

New materials will be evaluated and existing materials will be refined to improve concrete pavement performance, enhance construction, and lessen environmental impact.

Track Objectives

1. Improve pavement durability and long-term performance to extend pavement life further than conventional materials.
2. Improve the construction process by reducing material requirements, labor requirements, or construction time.
3. Reduce waste through pavement reclamation.

Research Gaps

- Lack of understanding of how advanced materials impact concrete pavement performance, construction, and the environment.
- Limited full-scale testing of new and innovative materials.

Research Challenges

- Experiment with advanced concrete pavement materials on a larger scale than previously done.
- Developing standards and recommendations for the use of advanced concrete pavement materials.
- Foster innovation in the development of new and innovative concrete pavement materials.

Research Track 12 (AM) Phasing

The horizontal bar chart in figure 12 shows the problem statements in this track grouped by subtrack. Because this track is unphased, no time phasing is shown.

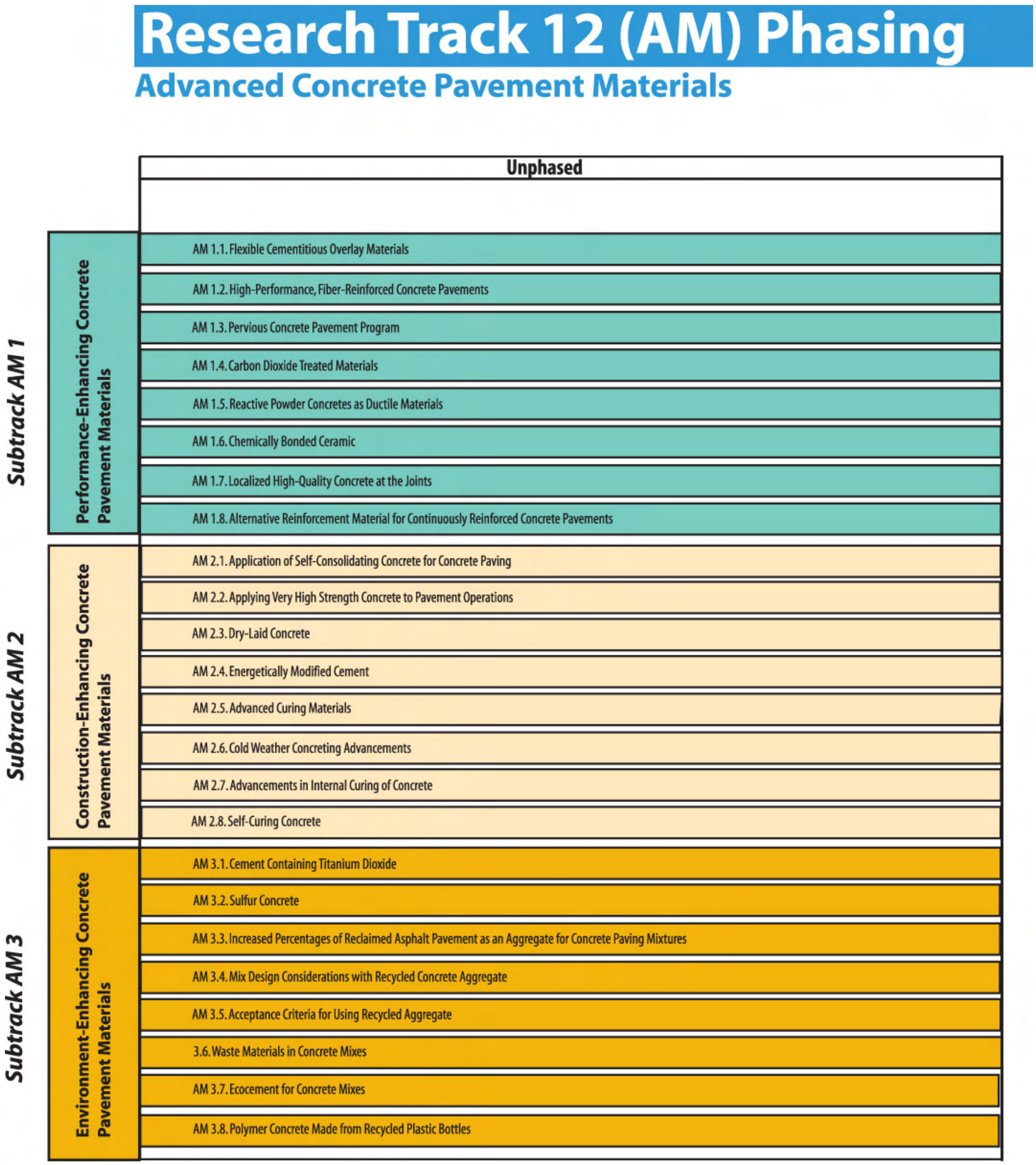

Figure 12. Track 12 (AM) unphased subtrack and problem statement chart.

Research Track 12 (AM) Estimated Costs

Table 58 shows the estimated costs for this research track.

Table 58. Research track 12 (AM) estimated costs.

Problem Statement	Estimated Cost
Subtrack AM 1. Performance-Enhancing Concrete Pavement Materials	
AM 1.1. Flexible Cementitious Overlay Materials	$500 k–$1 M
AM 1.2. High-Performance, Fiber-Reinforced Concrete Pavements	$1 M–$2 M
AM 1.3. Pervious Concrete Pavement Program	$500 k–$1 M
AM 1.4. Carbon Dioxide-Treated Materials	$100 k–$250 k
AM 1.5. Reactive Powder Concretes as Ductile Materials	$500 k–$1 M
AM 1.6. Chemically Bonded Ceramic	$100 k–$250 k
AM 1.7. Localized High-Quality Concrete at the Joints	$1 M–$2 M
AM 1.8. Alternative Reinforcement Material for Continuously Reinforced Concrete Pavements	$500 k–$1 M
Subtrack AM 2. Construction-Enhancing Concrete Pavement Materials	
AM 2.1. Application of Self-Consolidating Concrete for Concrete Paving	$500 k–$1 M
AM 2.2. Applying Very High-Strength Concrete to Pavement Operations	$1 M–$2 M
AM 2.3. Dry-Laid Concrete	$500 k–$1 M
AM 2.4. Energetically Modified Cement	$100 k–$250 k
AM 2.5. Advanced Curing Materials	$250 k–$500 k
AM 2.6. Cold Weather Concreting Advancements	$500 k–$1 M
AM 2.7. Advancements in Internal Curing of Concrete	$250 k–$500 k
AM 2.8. Self-Curing Concrete	$250 k–$500 k
Subtrack AM 3. Environment-Enhancing Concrete Pavement Materials	
AM 3.1. Cement Containing Titanium Dioxide	$100 k–$250 k
AM 3.2. Sulfur Concrete	$100 k–$250 k
AM 3.3. Increased Percentages of Reclaimed Asphalt Pavement as an Aggregate for Concrete Paving Mixtures	$1 M–$2 M
AM 3.4. Mix Design Considerations with Recycled Concrete Aggregate	$1 M–$2 M
AM 3.5. Acceptance Criteria for Using Recycled Aggregate	$500 k–$1 M
AM 3.6. Waste Materials in Concrete Mixes	$1M-2 M
AM 3.7. Ecocement for Concrete Mixes	$100k-250 k
AM 3.8. Polymer Concrete Made from Recycled Plastic Bottles	$100k-250 k
Track 12 (AM)	
Total	$11.45 M–$23.25 M

Track Organization: Subtracks and Problem Statements

Track 12 (AM) problem statements are grouped into three subtracks:

- Subtrack AM 1. Performance-Enhancing Concrete Pavement Materials.
- Subtrack AM 2. Construction-Enhancing Concrete Pavement Materials.
- Subtrack AM 3. Environment-Enhancing Concrete Pavement Materials.

Each subtrack is introduced by a brief summary of the subtrack's focus and a table listing the titles, estimated costs, products, and benefits of each problem statement in the subtrack. The problem statements follow.

SUBTRACK AM 1. PERFORMANCE-ENHANCING CONCRETE PAVEMENT MATERIALS

The innovative materials developed in this subtrack may meet requirements that conventional concretes do not meet as efficiently. The materials developed are specialty concrete varieties for specific, unique applications. Table 59 provides an overview of this subtrack.

Table 59. Subtrack AM 1 overview.

Problem Statement	Estimated Cost	Products	Benefits
AM 1.1. Flexible Cementitious Overlay Materials	\$500 k–\$1 M	Specifications, design criteria, and construction procedures for flexible cementitious overlays.	New, more durable overlay material that is less susceptible to rutting and shoving than asphalt and can be placed in thin, flexible layers.
AM 1.2. High-Performance, Fiber-Reinforced Concrete Pavements	\$1 M–\$2 M	Design recommendations, construction procedures, and specifications for fiber-reinforced concrete pavement.	Fiber reinforcement that will result in high-performance concrete pavement that is less susceptible to microcracking from concrete shrinkage than other pavements, resulting in a more durable, long-lasting pavement.
AM 1.3. Pervious Concrete Pavement Program	\$500 k–\$1 M	Design recommendations, construction procedures, and specifications for pervious concrete pavement for highways.	Pervious concrete pavements that will drain water from the pavement surface without the need for a cross slope, improving the safety of the pavement surface; promotion of the breakdown of chemical pollutants due to the large surface area within the pavement surface.
AM 1.4. Carbon Dioxide-Treated Materials	\$100 k–\$250 k	Recommendations for using carbon dioxide-treated materials for concrete pavements.	Carbon dioxide-treated materials that will increase strength and the rate of strength development, while significantly decreasing permeability, resulting in more durable pavements that can be opened to traffic faster.
AM 1.5. Reactive Powder Concretes as Ductile Materials	\$500 k–\$1 M	Design and material recommendations and construction procedures for using reactive powder concrete (RPC) for ultrahigh-performance concrete pavements.	Ultrahigh-performance concretes using RPC that are very high-strength concretes with ductility and very low permeability; the possibility of thinner pavement sections and reduced or eliminated reinforcement, resulting in a more durable pavement that is cheaper to construct.
AM 1.6. Chemically Bonded Ceramic	\$100 k–\$250 k	Recommendations for using Ceramicrete in concrete paving applications.	Better corrosion resistance and strength characteristics for concrete pavements, resulting from Ceramicrete's very low permeability and higher compressive strength than normal-strength concrete.
AM 1.7. Localized High-Quality Concrete at the Joints	\$1 M–\$2 M	Recommendations for using high-quality materials at the joints in concrete pavements.	High-quality material at the joint regions in concrete pavements that may not be affordable for use in the rest of the slab, ensuring better joint toughness and durability and enhancing pavement life.
AM 1.8. Alternative Reinforcement Material for Continuously Reinforced Concrete Pavements	\$500 k–\$1 M	Recommendations for alternative reinforcing materials for CRCP.	Alternative reinforcing materials that provide better corrosion resistance, bond strength, and modulus of elasticity; lighter materials that reduce labor costs during placement and dependence on a volatile steel market.

Problem Statement AM 1.1. Flexible Cementitious Overlay Materials

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$500 k–\$1 M

The majority of HMA pavements ultimately will fail due to rutting. Increased axle loads, higher tire pressures, and increasing traffic volume contribute to this problem; today, more than 90 percent of roads are being overloaded. Developing a cementitious overlay material that can be used as a strengthening and wearing course on flexible pavements, even when applied in thin layers, would be extremely useful. Ductility of the material is obtained through controlled microcracking and fiber reinforcement. A major project is currently underway in the European Union to look at porous polymer concretes. Several different compositions such as this could be used, resulting in the selection of a few types to be used for full-scale testing as overlays on appropriate highways. A similar project could be conducted in the United States that builds on the information and results from the European Union project. Design criteria and draft specifications for the use of the new material will be a part of the project results.

Tasks:

1. Identify required properties for thin overlays.
2. Identify existing materials used for thin cementitious overlays.
3. Modify existing materials or develop new materials for thin overlays, if necessary.
4. Develop field trials or accelerated load testing of overlay materials.
5. Develop design criteria, specifications, and construction procedures for use of cementitious overlay materials.

Benefits:	New, more durable overlay material that is less susceptible to rutting and shoving than asphalt and can be placed in thin, flexible layers.
Products:	Specifications, design criteria, and construction procedures for flexible cementitious overlays.
Implementation:	This project will result in draft specifications, design criteria, and construction procedures for flexible cementitious overlays.

Problem Statement AM 1.2. High-Performance, Fiber-Reinforced Concrete Pavements

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$1 M–\$2 M

In recent years, advancements have been made regarding the use of fiber reinforcement for improving concrete pavement performance. The first goal of this project will be to synthesize the information available about this topic. Researchers then could determine the potential of advanced fiber concepts aimed at extending the long life pavement category. Attention should be given to both the benefits and drawbacks of using fiber reinforcement. The end product would include both procedural and analytical guidance for the optimum use of fibers. It is anticipated that this research will explore the field of fracture mechanics and will improve understanding of the impacts that fibers can play on load transfer (as compared to dowels and tie bars).

Tasks:

1. Identify different fiber types and previous use of fibers in concrete pavement.
2. Identify desirable properties for paving concrete with fibers to achieve long life, high-performance pavements.
3. Identify, through lab testing or field tests, optimum fiber types and proportions for different paving applications (including varying climates).
4. Develop design recommendations, specifications, and construction procedures for incorporating fibers into paving concrete mixes.
5. Evaluate design recommendations and construction procedures in pilot projects.

Benefits:	Fiber reinforcement that will result in high-performance concrete pavement that is less susceptible to microcracking from concrete shrinkage than other pavements, resulting in a more durable, long-lasting pavement.
Products:	Design recommendations, construction procedures, and specifications for fiber-reinforced concrete pavement.
Implementation:	This project will result in design recommendations, construction procedures, and specifications for fiber-reinforced, high-performance concrete pavement.

Problem Statement AM 1.3. Pervious Concrete Pavement Program

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

Pervious or porous concrete pavement has several notable advantages over conventional concrete pavement, primarily noise reduction and better drainage. Certain types of pervious pavement can pass 11.4 to 18.9 liters (3 to 5 gallons) of water per minute, which is much greater than most conceivable rain events and very effective in reducing hydroplaning risk. Porous concrete also offers improved filtration and an enormous amount of surface area to catch oils and chemical pollutants, which can reduce skid and environmental damage. Some experts believe that the bacteria living in these spaces breakdown pollutants, preventing much of the runoff pollution that normally occurs with traditional pavements. Most of the pervious pavements constructed thus far, however, have been for parking lots, not highways. This research would investigate the use of pervious concrete in highway pavements, examining the advantages and disadvantages, including the feasibility of large-scale pavement construction. The study should examine long-term maintenance and durability issues, such as permeability, abrasion resistance, and wetting/drying, as well as the effect of the bacteria. Stages of this research would include the development of mix design techniques as well as the field trial phase.

Tasks:

1. Identify previous applications of pervious concrete use for pavements (including bases and subbases).
2. Identify required properties for application of pervious concrete to highway pavements.
3. Identify construction requirements for pervious concrete pavements, including pavement structure (e.g., subgrade, base).
4. Develop design recommendations, specifications, and construction procedures for pervious concrete for highway pavements.
5. Develop pilot projects for testing pervious concrete pavement for highway applications.

Benefits:	Pervious concrete pavements that will drain water from the pavement surface without the need for a cross slope, improving the safety of the pavement surface; promotion of the breakdown of chemical pollutants due to the large surface area within the pavement surface.
Products:	Design recommendations, construction procedures, and specifications for pervious concrete pavement for highway pavements.
Implementation:	This project will result in design recommendations, construction procedures, and specifications for using pervious concrete for highway pavements.

Problem Statement AM 1.4. Carbon Dioxide-Treated Materials

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$100 k–\$250 k

The treatment of cementitious materials with gaseous carbon dioxide to achieve rapid strength development has been studied for many years. Recently, advances have been made in the treatment of cementitious materials that will facilitate the use of supercritical carbon dioxide in achieving a tenfold reduction in permeability, while strength increases by several fold. While the precast concrete industry already uses this technology, further research is needed to apply the technology to pavements. In particular, research is needed to better understand the mechanisms of rapid strength development in concrete with supplementary cementitious materials. With further research, this process likely could lead to the development of new materials from novel waste streams and accelerate the development of new and improved concrete mixtures.

Tasks:

1. Identify previous applications of carbon dioxide treatment to concrete materials.
2. Identify beneficial properties for pavements using carbon dioxide-treated materials.
3. Identify procedures for incorporating carbon dioxide into materials for concrete pavements.
4. Conduct laboratory testing and/or pilot projects to evaluate carbon dioxide-treated materials for concrete pavements.
5. Develop recommendations for using carbon dioxide-treated materials for concrete pavements.

Benefits:	Carbon dioxide-treated materials that will increase strength and the rate of strength development, while significantly decreasing permeability, resulting in more durable pavements that can be opened to traffic faster.
Products:	Recommendations for using carbon dioxide-treated materials for concrete pavements.
Implementation:	This project will result in recommendations for using carbon dioxide-treated materials for concrete pavements.

Problem Statement AM 1.5. Reactive Powder Concretes as Ductile Materials

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

With a technological breakthrough at the beginning of the 1990s, RPC offered compression strengths in excess of 200 megapascals (MPa) (29,000 pounds-force per square inch (psi)), flexural strengths of over 40 MPa (5,800 psi), and ductility. Ductal® and BSI®, two products of the RPC family developed in France, are considered ultrahigh-performance concretes. They are ductile materials capable of resisting substantial flexural loads and do not require passive reinforcement. This allows the overall thickness of structural elements to be reduced. The material is also extremely durable with very low permeability. Thus far, this material has been used predominantly in Europe for concrete structures, but future research should investigate its use in concrete pavements with or without fibers.

Tasks:

1. Identify RPC mixtures that could be used for concrete pavement, the properties of these mixes, and the advantages of these mixes (e.g., elimination of reinforcement).
2. Identify the properties required to use RPC in concrete pavement.
3. Conduct laboratory testing and/or field trials using RPC for concrete pavement construction.
4. Develop pavement design recommendations, specifications, and construction procedures for concrete pavements constructed using RPC.

Benefits:	Ultrahigh-performance concretes using RPC that are very high-strength concretes with ductility and very low permeability; the possibility of thinner pavement sections and a reduction or elimination of reinforcement, resulting in a more durable pavement that is cheaper to construct.
Products:	Design and material recommendations and construction procedures for using RPC for ultrahigh-performance concrete pavements.
Implementation:	This project will result in design and material recommendations, specifications, and construction procedures for using RPC to achieve ultrahigh-performance concrete pavements.

Problem Statement AM 1.6. Chemically Bonded Ceramic

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing
Approximate Phasing:	N/A
Estimated Cost:	\$100 k–\$250 k

Chemically bonded phosphate ceramic (Ceramicrete) is a type of concrete with very low permeability. Ceramicrete is formed when magnesium oxide powder and soluble phosphate powder (both available, low-cost materials) are mixed with water, creating a nonporous material with compressive strength higher than that of concrete. Ceramicrete can be made with commercially available equipment that mixes the powder components into the binder. "The wet material (binder, aggregates, and water mixture) can then be pumped, gunned, or sprayed, also with commercially available equipment."[6] The feasibility (costs and benefits) of using Ceramicrete for concrete paving should be explored.

Tasks:

1. Identify Ceramicrete mixes and their properties (strength, permeability, workability, long-term durability) and cost.
2. Evaluate the feasibility of using Ceramicrete for concrete pavement construction, considering constructability, durability, and cost.
3. Develop recommendations for using Ceramicrete in concrete paving applications, including repairs, overlays, and new construction.

Benefits:	Better corrosion resistance and strength characteristics for concrete pavements, resulting from Ceramicrete's very low permeability and higher compressive strength than normal strength concrete.
Products:	Recommendations for the use of Ceramicrete for concrete paving applications.
Implementation:	This project will result in recommendations for the use of Ceramicrete for concrete paving applications, including repairs, overlays, and new construction.

Problem Statement AM 1.7. Localized High-Quality Concrete at the Joints

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$1 M–$2 M

Many concrete pavement failures occur because of joint damage. Improving the quality of the concrete at these potential weak areas thus would increase the overall pavement life. Therefore, a system should be developed to ensure that the concrete at the joints consists of a higher quality material than the concrete midslab. This process could involve introducing fibers, chemicals, or other additives at the joints.

Tasks:

1. Identify joint failure mechanisms in concrete pavements.
2. Identify possible materials—i.e., high-quality concrete—for improving the toughness and durability of joints.
3. Develop construction techniques for incorporating high-quality material into the paving process at the joints.
4. Conduct field trials/accelerated pavement testing of pavements constructed with high-quality materials at the joints.
5. Develop design recommendations and construction procedures for concrete pavements with high-quality materials at the joints.

Benefits:	High-quality material at the joint regions in concrete pavements that may not be affordable for use in the rest of the slab, ensuring better joint toughness and durability and enhancing pavement life.
Products:	Recommendations for using high-quality materials at the joints in concrete pavements.
Implementation:	This project will result in design construction recommendations for using high-quality materials at the joints in concrete pavements.

Problem Statement AM 1.8. Alternative Reinforcement Material for Continuously Reinforced Concrete Pavements

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 1. Performance-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

Steel reinforcement is a critical component of CRCP. However, factors such as concrete permeability and water infiltration at cracks, the resulting corrosion of steel reinforcement, and the associated tendency of concrete to lose bond action with imbedded reinforcement reduce structural performance over time. Research is needed to develop economical, thermodynamically durable, metallic and nonmetallic corrosion-resistant reinforcements. Widespread use of these technologies, which have been researched for many years, will lead to additional refinements, such as the further development of fiber-reinforced plastic (FRP) bars with a useful form of pseudo-ductility that makes full use of their strength. Another advantage of alternate reinforcing materials for CRCP is reduced placement costs. Lightweight FRP bars require less labor to be installed. Researchers should begin by examining work that has been done previously in this area, including ongoing studies sponsored by FHWA.

Tasks:

1. Identify alternative metallic and nonmetallic reinforcing materials.
2. Evaluate the suitability of these materials for CRCP construction, considering properties such as strength, modulus of elasticity, bond strength, corrosion resistance, ductility, cost, and constructability.
3. Conduct laboratory testing and/or pilot projects to evaluate the viability of these materials for CRCP construction.
4. Develop recommendations for types and usage of alternative reinforcement, including design recommendations based on properties of each specific material.

Benefits:	Alternative reinforcing materials that provide better corrosion resistance, bond strength, and modulus of elasticity; lighter materials that reduce labor costs during placement and dependence upon a volatile steel market.
Products:	Recommendations for alternative reinforcing materials for CRCP.
Implementation:	This project will result in recommendations for the design and use of alternative reinforcing materials for CRCP.

SUBTRACK AM 2. CONSTRUCTION-ENHANCING CONCRETE PAVEMENT MATERIALS

The materials developed under this subtrack address specific constructability issues and provide creative alternatives to conventional concrete. The problem statements in this subtrack will develop special concrete materials for use in various concrete paving applications. Table 60 provides an overview of this subtrack.

Table 60. Subtrack AM 2 overview.

Problem Statement	Estimated Cost	Products	Benefits
AM 2.1. Application of Self-Consolidating Concrete for Concrete Paving	$500 k–$1 M	Recommendations for design and construction of pavements using self-consolidating concrete (SCC).	Better consolidation of concrete around dowels and reinforcement, reducing the need for vibration, resulting in a more durable pavement while reducing labor costs during construction.
AM 2.2. Applying Very High-Strength Concrete to Pavement Operations	$1 M–$2 M	Mix design recommendations, construction procedures, and specifications for very high-strength concrete pavements.	Concrete pavement with a very high tensile strength to permit longer sections of pavement to be constructed, reducing the number of joints, and helping to reduce cracking and improve long-term durability.
AM 2.3. Dry-Laid Concrete	$500 k–$1 M	Design and construction guidelines and recommendations for dry-laid concrete pavement.	Dry-laid concrete pavement that eliminates the need for mixing concrete onsite (batch-plants) and permits thinner, durable pavement slabs, greatly reducing construction and materials costs.
AM 2.4. Energetically Modified Cement	$100 k–$250 k	Recommendations for the use of energetically modified cement (EMC) for concrete paving mixes.	EMC with faster strength development and better long-term strength of blended mixes, resulting in more durable pavements using blended mixes that can be opened to traffic sooner.
AM 2.5. Advanced Curing Materials	$250 k–$500 k	Recommendations for advanced curing materials and the requirements for these materials.	More effective curing materials for concrete paving operations, especially those constructed under short construction windows and in extreme environments; advanced curing materials that better ensure the necessary curing requirements, resulting in a more durable pavement.
AM 2.6. Cold Weather Concreting Advancements	$500 k–$1 M	Recommendations for cold weather paving mixes and construction practices.	Cold weather-tolerant concrete paving mixes and construction techniques that will extend the pavement construction season in colder regions and reduce the labor required to protect pavements during cold weather paving operations.
AM 2.7. Advancements in Internal Curing of Concrete	$250 k–$500k	Mix design recommendations that will promote internal curing (IC) of concrete pavements.	IC that will help reduce autogenous shrinkage and self-desiccation and will ensure more complete hydration of cementitious materials, resulting in a less permeable, stronger, more durable pavement.
AM 2.8. Self-Curing Concrete	$250 k–$500 k	Recommendations on materials and techniques for constructing self-curing concrete pavements.	Self-curing concrete pavements that will reduce dependence on the contractor to apply adequate curing measures to new concrete pavement; more complete hydration of the cementitious materials, resulting in stronger, less permeable, and more durable concrete pavements.

Problem Statement AM 2.1. Application of Self-Consolidating Concrete for Concrete Paving

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

Significant interest in recent years has arisen over the use of SCC for various applications. The most common application is in complex structural work, where the presence of the reinforcing steel has made adequate consolidation using conventional means difficult. Because some concrete paving work faces similar challenges with consolidation (near dowels and reinforcements), using SCC for concrete paving has been suggested. As part of this effort, researchers will evaluate innovative ways to incorporate SCC into PCC pavements that include full sections, overlays, inlays, and patching, for both fixed- and slipform operations. This research will build on work already underway by FHWA and other organizations.

Tasks:

1. Identify previous applications of SCC for pavements or slab on grade.
2. Identify desirable mix properties for using SCC in pavements.
3. Develop mix design recommendations for using SCC for pavements.
4. Develop best practice construction procedures for using SCC for new construction, overlays, inlays, and patching.
5. Conduct lab testing and/or pilot projects to test SCC for pavements, including an evaluation of consolidation around dowels and reinforcements.

Benefits:	Better consolidation of concrete around dowels and reinforcement, reducing the need for vibration, resulting in a more durable pavement while reducing labor costs during construction.
Products:	Recommendations for design and construction of pavements using SCC.
Implementation:	This project will result in design recommendations and best practice construction procedures for using SCC for pavements.

Problem Statement AM 2.2. Applying Very High-Strength Concrete to Pavement Operations

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$1 M–$2 M

High-strength concrete currently is being used in rapid-cure patches. However, the high cement content causes high temperatures that can result in thermal contraction problems. At present, early opening is the only advantage to using high-strength concrete in pavements. Also, such concrete is expensive, and if high-strength pavements are to be competitive, ways to minimize the amount of the expensive concrete must be found. The French have developed a two-layer extruded slipform operation that encapsulates normal concrete within a protective high-strength concrete. Other more economical options also might be considered, such as slabs cast with internal voids, or beam and slab configurations, although data is needed on deflection, water movement, friction, curling, and warping of unusual slab configurations. Jointing technology also would be needed. A vigorous research study would be needed to make using 69 MPa (10,000 psi) concrete more efficient for structural pavements.

Just as continuously welded rails are used, it should be possible to construct a continuous ribbon of concrete that would withstand a temperature range of 55 °C (100 °F). A tensile strength of about 17 MPa (2,500 psi) would be needed, which might be possible with a compressive strength of about 172 MPa (25,000 psi) (plus a factor of safety). This could be accomplished with polymer impregnation if a field process could be developed. For comparison, a laboratory strength of about 731 MPa (106,000 psi) has been attained with PCC. Special concretes currently are being used in the 172 MPa (25,000 psi) range, based on a reactive powder process. The strength must be attained about 18 hours before the concrete begins to cool and contract. Of course, such continuous ribbons of ultrahigh-strength concretes will experience about 50 mm (2 inches) of movement at the ends, making special anchors or joints necessary.

Tasks:

1. Identify high-strength mixes and the properties (i.e., strength, shrinkage, and workability) of these mixes.
2. Determine the suitability of these mixes for paving applications based on these properties.
3. Modify existing mixes or develop new mixes to meet paving requirements.
4. Identify construction requirements (i.e., special curing procedures) for using high-strength mixes for pavements.
5. Identify alternative paving techniques (e.g., voided or hollow slabs) to reduce the quantity and cost of using high-strength mixes.
6. Conduct lab testing and/or field trials of high-strength pavements.
7. Develop mix design recommendations, construction procedures, and specifications for high-strength concrete pavements.

Benefits:	Concrete pavement with a very high tensile strength to permit longer sections of pavement to be constructed, reducing the number of joints, and helping to reduce cracking and improve long-term durability.
Products:	Mix design recommendations, construction procedures, and specifications for very high-strength concrete pavements.
Implementation:	This project will result in mix design recommendations, construction procedures, and specifications for high-strength concrete pavements.

Problem Statement AM 2.3. Dry-Laid Concrete

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

New formulations and procedures have been developed that enable concrete to be placed as a cementitious dry mix that is then watered from above to produce a strong, thin slab or pavement. The need for onsite mixing is eliminated. In the field, the strength of dry-laid slabs only 10 to 50 mm (0.39 to 1.95 inches) thick saves raw materials and excavation costs and may make resurfacing old concrete a practical possibility. Dry-laid materials are also easier to work with than conventional moist or semidry concrete screeds, and should result in a stronger and more durable end product.

Preliminary tests indicate that strong concrete substantially free of shrinkage cracking can be produced by dry-laid methods using premixed materials in which the maximum particle size is limited, typically to 5 mm (0.2 inch) in diameter. The absence of large particles means that thinner slabs of concrete down to 10 mm (0.39 inch) can be laid. Although the mixture has a higher cement and fines content than conventional concrete, the dry-laid process reduces the problem of self-induced cracking due to drying shrinkage that generally is encountered with cement-rich mortars laid as a wet mix. Although the product originally was conceived as an easy-to-use, do-it-yourself surfacing product, there appears to be a major opportunity to apply it to concrete paving. Innovative aspects of dry-laid techniques include:

- Need for mixing onsite eliminated; more easily placed than wet or semidry mixes; factory-mixed precision carried through to final placement; problems of premature setting avoided.
- The strength of concrete and the thinness of mortars or screeds combined; readily compatible with the delivery of dry mixes in silos and mechanized placement.
- Early resistance to traffic.
- Convenient material for patching repairs and extensive resurfacing of old concrete as well as new pavements.
- Attractive surface finishes can be incorporated; economical to produce.

Tasks:

1. Identify dry-laid concrete materials, techniques, and previous applications.
2. Identify required properties for dry-laid concrete for PCC pavements and benefits of using dry-laid concrete over conventional wet construction.
3. Identify materials and techniques for dry-laid concrete that will meet the requirements for PCC pavements.
4. Perform laboratory testing and/or field trials to evaluate the viability of dry-laid concrete for pavements.
5. Develop design recommendations and construction procedures for using dry-laid concrete for overlays, repairs, and new construction.

Benefits:	Dry-laid concrete pavement that eliminates the need for mixing concrete onsite (batch-plants) and permits thinner, durable pavement slabs, greatly reducing construction and materials costs.
Products:	Design and construction guidelines and recommendations for dry-laid concrete pavement.
Implementation:	This project will result in recommendations for using dry-laid concrete for PCC pavements, including design guidelines and construction procedures.

Problem Statement AM 2.4. Energetically Modified Cement

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$100 k–\$250 k

One important constraint of using cement blended with various pozzolanic or cementitious substances (e.g., fly ash, blast furnace slag) is the early strength development requirements included in current standards. Blended cements typically take longer to develop their strength and often do not meet standards without additives. EMC is a patented technology that has overcome this obstacle. By intensively grinding and activating the cement together with the pozzolan, the surfaces of the particles are activated. Investigators believe that the activation creates a network in the cement particles of submicrocracks, microdefects, and dislocations that allows the water to penetrate deeper into the cement particles, which in turn uses a higher percentage of the potential binding capacity of the cement. This process also activates inert fillers, such as fine quartz sand. The EMC technology is based solely on grinding; no additives of any kind are used. Evaluations and tests of concretes and mortars made with EMC have shown EMC to perform significantly better than portland pozzolan-blended cements containing 20–40 percent fly ash. EMC with fly ash, by comparison, allows a 10 percent reduction in water-cement ratio, translating to higher long-term strength. EMC also showed slightly improved sulfate resistance, and the workability of EMC was better than cement.

Tasks:

1. Identify the EMCs and cement-pozzolan blends and their specific properties (e.g., strength, permeability, workability, long-term performance).
2. Identify the benefits of using EMC for concrete pavement mixes and evaluate the suitability of its properties for concrete pavement construction, considering cost and the variable climates in which the pavements are constructed.
3. Develop recommendations for using EMC for concrete paving mixes, considering proprietary specifications.

Benefits:	EMC with faster strength development and better long-term strength of blended mixes, resulting in more durable pavements using blended mixes that can be opened to traffic sooner.
Products:	Recommendations for the use of EMC for concrete paving mixes.
Implementation:	This project will result in recommendations for the use of EMC for concrete paving mixes.

Problem Statement AM 2.5. Advanced Curing Materials

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$250 k–$500 k

Curing methods used for concrete paving have not changed significantly in the past 30 years. Liquid curing compound remains the most commonly used form of protection. However, the demands being placed on concrete paving are evolving. Rapid reconstruction and extreme weather events have challenged traditional curing methods and demand better solutions. This project will investigate new and advanced curing materials for these extreme circumstances. Effectiveness, cost, and proprietary issues should be considered. Ideally, the project will result in a performance or end-result standard for advanced curing materials that would allow adequate competition and provide the user with the desired properties. To further this goal, a functional specification could be developed that establishes critical moisture and temperature conditions required to achieve varying degrees of quality. The ability of the cure to meet these functional thresholds would determine its quality.

Tasks:

1. Identify advanced curing materials that could be used for concrete pavement construction, soliciting ideas for new materials if the number of existing materials is limited.
2. Evaluate the effectiveness of these materials, with consideration given to special circumstances such as rapid reconstruction and extreme climatic conditions.
3. Develop recommendations for required effectiveness of curing materials, considering critical moisture and temperature conditions under which the materials must provide adequate curing conditions.
4. Develop recommendations for advanced curing materials, ensuring that the requirements are such that a sole proprietary product is not the only available material.

Benefits:	More effective curing materials for concrete paving operations, especially those constructed under short construction windows and in extreme environments; advanced curing materials that better ensure the necessary curing requirements, resulting in a more durable pavement.
Products:	Recommendations for advanced curing materials and the requirements for these materials.
Implementation:	This project will result in recommendations for different types of advanced curing materials and requirements for the effectiveness of these materials.

Problem Statement AM 2.6. Cold Weather Concreting Advancements

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$500 k–\$1 M

USACE researchers are experimenting with concrete admixtures that allow for subzero pours as low as –15 °C (5 °F) in the open air. Underwritten by 10 State DOTs, the 3-year, \$750,000 program is paving the way for reduced labor in winter months and a longer construction season. The team is working with combinations of off-the-shelf products to lower the freezing temperature of concrete. These substances, which commonly are available to contractors, include concrete accelerators, corrosion inhibitors, and plasticizers already governed by their own set of standards. One recent study involved a 32-m (104-ft)-long bridge curb in Lebanon, NH. The result of using the laboratory's experimental concrete was a savings of 132 labor hours needed to build an enclosure and \$50 in liquid propane. The total cost was \$700, rather than \$750 plus labor for traditional methods. The next step is to develop a recipe guide for admixture chemicals. Beyond this, research still is needed to demonstrate the benefits of this technology for concrete pavements.

Tasks:

1. Identify materials and concrete mixtures that permit concrete placement in subzero conditions without special measures to protect the concrete.
2. Evaluate the properties of these materials and the viability of their use in concrete pavements.
3. Conduct laboratory or field trials of cold weather concretes for paving projects.
4. Evaluate the cost versus benefits of cold weather concretes, giving consideration to extending the construction season and reducing cold weather construction labor.
5. Develop recommendations for cold weather pavement mixes and construction and curing procedures.

Benefits:	Cold weather-tolerant concrete paving mixes and construction techniques that will extend the pavement construction season in colder regions and reduce the labor required to protect pavements during cold weather paving operations.
Products:	Recommendations for cold weather paving mixes and construction practices.
Implementation:	This project will result in recommendations for cold weather concrete paving mixes and construction practices.

Problem Statement AM 2.7. Advancements in Internal Curing of Concrete

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$250 k–$500 k

In the past few years, IC has evolved into a science. With the advent of lower water-cement ratio mixtures and high-performance concrete, the need for a system to eliminate autogenous shrinkage and self-desiccation has developed, and the use of lightweight fines for the IC of concrete increasingly is being recognized. The paper, "Internal Curing of Concrete Using Lightweight Aggregate" includes a state of the art of practice in this area.[7] In this research, the use of IC for concrete pavement will be explored. The costs and benefits of this technology should be weighed and a recommendation made for proceeding with field trials and other implementation projects.

Tasks:

1. Identify materials and techniques to promote IC of concrete.
2. Evaluate the properties of concrete made with these materials, including workability, durability, strength, and permeability, and the suitability of these materials for concrete pavements.
3. Conduct laboratory testing to evaluate the effectiveness of IC for concrete paving applications.
4. Develop recommendations for materials and concrete mixes that will provide IC for concrete pavement applications.

Benefits:	IC that will help reduce autogenous shrinkage and self-desiccation and will ensure more complete hydration of cementitious materials, resulting in a less permeable, stronger, more durable pavement.
Products:	Mix design recommendations that will promote IC of concrete pavements.
Implementation:	This project will result in material and mix design recommendations that will promote IC of concrete pavements.

Problem Statement AM 2.8. Self-Curing Concrete

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 2. Construction-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$250 k–$500 k

Most paving mixtures contain adequate mixing water to hydrate the cement if the moisture is not allowed to evaporate. It should be possible to develop an oil, polymer, or other compound that would rise to the finished concrete surface and effectively seal the surface against evaporation. R.K. Dhir et al. recently published some test results on self-curing mixtures.(8) This research will explore further the potential of self-curing concrete.

Tasks:

1. Identify materials or techniques for developing self-curing concrete.
2. Evaluate the suitability of these materials for concrete pavement applications, considering workability, strength, permeability, and durability.
3. Conduct laboratory testing or field trials to evaluate the effectiveness of self-curing concrete for paving applications.
4. Develop recommendations on materials and techniques for self-curing concrete pavements.

Benefits:	Self-curing concrete pavements that will reduce dependence on the contractor to apply adequate curing measures to new concrete pavement; more complete hydration of the cementitious materials, resulting in stronger, less permeable, and more durable concrete pavements.
Products:	Recommendations on materials and techniques for constructing self-curing concrete pavements.
Implementation:	This project will result in recommendations on materials and techniques for constructing self-curing concrete pavements.

SUBTRACK AM 3. ENVIRONMENT-ENHANCING CONCRETE PAVEMENT MATERIALS

The problem statements in this subtrack will address environmental concerns in concrete pavement materials, construction, and performance. The materials developed in this research can be used to improve air quality and will enhance recycled concrete pavement materials. Table 61 provides an overview of this subtrack.

Table 61. Subtrack AM 3 overview.

Problem Statement	Estimated Cost	Products	Benefits
AM 3.1. Cement Containing Titanium Dioxide	$100 k–$250 k	Recommendations for the use of cement containing titanium dioxide in concrete paving mixes.	Concrete pavements containing titanium dioxide that potentially can remove certain volatile organic compounds (VOC) from the air, helping to reduce air pollution in urban areas.
AM 3.2. Sulfur Concrete	$100 k–$250 k	Recommendations for the use of sulfur concrete in paving applications.	Sulfur concrete that consists of 100 percent recycled material, made from byproducts of electricity production and petroleum refinement; a dense, acid-resistant material that may have applications for concrete paving.
AM 3.3. Increased Percentages of Reclaimed Asphalt Pavement as an Aggregate for Concrete Paving Mixtures	$1 M–$2 M	Recommendations for using reclaimed asphalt pavement (RAP) as an aggregate for concrete paving mixes.	RAP in concrete paving mixes, reducing the amount of RAP that must be disposed, as well as reducing the demand for virgin aggregate for concrete pavements.
AM 3.4. Mix Design Considerations with Recycled Concrete Aggregate	$1 M–$2 M	Recommendations for using recycled concrete as aggregate in new pavement construction.	Recycled concrete for aggregate in new concrete pavements, reducing the amount of reclaimed concrete pavement that must be disposed, as well as the demand for virgin aggregate in concrete pavements.
AM 3.5. Acceptance Criteria for using Recycled Aggregate	$500 k–$1 M	Recommendations for acceptance criteria and test procedures for recycled aggregate and concrete made with recycled aggregate.	Established acceptance criteria and test procedures for recycled aggregate in new concrete pavements to promote the use of recycled aggregates, thereby reducing the demand for virgin aggregate for new construction.
AM 3.6. Waste Materials in Concrete Mixes	$1 M–2 M	Recommendations (proportions and limits) for the use of waste materials in concrete paving mixes.	Use of waste materials in concrete mixes, reducing the amount of waste materials and the demand for cement (which must be produced), while producing a better concrete mix.
AM 3.7. Ecocement for Concrete Mixes	$100 k–250 k	Recommendations for the production and use of Ecocement in the United States.	Ecocement that is produced during the incineration of solid waste and sewage sludge, reducing the amount of waste, while reducing the amount of cement required for concrete paving mixes, resulting in a faster setting concrete mix.
AM 3.8. Polymer Concrete Made from Recycled Plastic Bottles	$100 k–250 k	Recommendations for using polymer concrete for paving applications.	Polymer concrete that results in a more durable pavement or pavement overlay, making use of recycled plastic bottles and reducing the demand on landfills.

Problem Statement AM 3.1. Cement Containing Titanium Dioxide

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$100 k–$250 k

To help reduce air pollution and prevent the discoloration of urban concrete surfaces, several cement companies have marketed cement containing a photocatalyst (titanium dioxide), which removes polluting VOCs from the atmosphere and converts them to carbon dioxide. If put into widespread use, such cement could potentially improve urban air quality (e.g., reduce smog), since the amount of carbon dioxide produced would be much smaller than the amount of carbon dioxide from combustion sources. The use of cementitious materials containing photocatalysts is thus an innovative and profitable way to eliminate pollutants, particularly in urban areas. Concrete pavement would be an ideal application for such a product, as the pavement could decrease the smog produced by the vehicles traveling over the pavement.

Tasks:

1. Identify concrete mixes containing titanium dioxide that have been shown to remove VOC air pollutants.
2. Identify the properties of these mixes and evaluate their suitability for concrete pavement applications.
3. Conduct laboratory testing or field trials to evaluate the effectiveness of these mixes for reducing pollution.
4. Develop recommendations for using titanium dioxide concrete mixes for concrete paving mixes.

Benefits:	Concrete pavements containing titanium dioxide that can potentially remove certain VOCs from the air, helping reduce air pollution in urban areas.
Products:	Recommendations for the use of cement containing titanium dioxide in concrete paving mixes.
Implementation:	This project will result in recommendations for the use of cement containing titanium dioxide in concrete paving mixes.

Problem Statement AM 3.2. Sulfur Concrete

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$100 k–\$250 k

Sulfur concrete is made from sulfur collected from the petroleum refining process and coal ash from coal burning thermal power stations. The process applies vibration and pressure to a mixture of heated sulfur and coal ash. The resulting concrete is 100 percent recycled. Hardened sulfur concrete is dense and acid-resistant enough to be used where PCC cannot be used. Although most concrete pavements will not need such a high level of resistance, a feasibility study may be warranted to determine whether sulfur concrete could be used for concrete paving.

Tasks:

1. Identify sulfur concrete mixes and their properties, including strength, permeability, and durability.
2. Evaluate the feasibility of sulfur concrete for concrete pavement, specifically constructability, durability, cost, and specific applications where it may be beneficial.
3. Develop recommendations for using sulfur concrete in concrete paving applications.

Benefits:	Sulfur concrete that consists of 100 percent recycled material, made from byproducts of electricity production and petroleum refinement; a dense, acid-resistant material that may have applications for concrete paving.
Products:	Recommendations for the use of sulfur concrete in paving applications.
Implementation:	This project will result in recommendations for the use of sulfur concrete for concrete paving applications.

Problem Statement AM 3.3. Increased Percentages of Reclaimed Asphalt Pavement as an Aggregate for Concrete Paving Mixtures

Track: 12. Advanced Concrete Pavement Materials (AM)
Subtrack: AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing: N/A
Estimated Cost: $1 M–$2 M

One of the main problems with rehabilitating or reconstructing existing asphalt pavement is the question of what to do with the wasted RAP. Much of the time it is recycled back into a new asphalt pavement or used as embankment material. Though it has been recycled back into concrete on occasion (Austria does it regularly), its use and performance has not been widespread or documented in the United States. This research intends to determine whether RAP can be used as an aggregate in concrete pavements. The specific objectives will help determine the expected performance and potential detrimental effects of using RAP for aggregate in concrete.

Tasks:

1. Identify previous applications of RAP used as an aggregate in concrete paving mixtures.
2. Identify the properties of RAP aggregate concrete mixes (e.g., strength, durability, workability) and their suitability for concrete pavement construction.
3. Conduct laboratory testing and/or field trials of RAP aggregate concrete mixes.
4. Develop recommendations for using RAP in concrete mixes, with specific guidance regarding acceptable RAP materials.

Benefits: RAP in concrete paving mixes, reducing the amount of RAP that must be disposed, as well as reducing the demand for virgin aggregate for concrete pavements.

Products: Recommendations for using RAP as an aggregate for concrete paving mixes.

Implementation: This project will result in recommendations, including mix design recommendations and limits for RAP properties, for using RAP as an aggregate in concrete paving mixes.

Problem Statement AM 3.4. Mix Design Considerations with Recycled Concrete Aggregate

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$1 M–$2 M

To determine innovative ways to use recycled concrete in PCC pavements, this research will investigate the boundaries of using recycled materials in bases and two-lift construction; investigate its use in shorter performance life pavements, such as 8-year pavement; and investigate using portions of the product (i.e., fine or coarse fractions). FHWA's program for recycled concrete should be reviewed before executing this effort.

Tasks:

1. Identify previous studies of recycled concrete for concrete aggregate and gaps in the knowledge that still remain.
2. Identify the properties of concrete made with recycled concrete aggregate (strength, permeability, workability, durability) and the limits of recycled concrete in new mixes.
3. Identify applications for concrete made with recycled concrete aggregate, such as two-lift construction and shorter life pavement.
4. Develop recommendations for using recycled concrete as aggregate in new concrete paving mixes, including mix design and pavement design recommendations and construction procedures.

Benefits:	Recycled concrete for aggregate in new concrete pavements, reducing the amount of reclaimed concrete pavement that must be disposed, as well as the demand for virgin aggregate in concrete pavements.
Projects:	Recommendations for using recycled concrete as aggregate in new pavement construction.
Implementation:	This project will result in recommendations for using recycled concrete as aggregate in new paving mixes, including limits for usage.

Problem Statement AM 3.5. Acceptance Criteria for Using Recycled Aggregate

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	$500 k–$1 M

The use of recycled aggregate in concrete pavement is of great interest for reducing waste and reusing materials available at the job site. Using recycled aggregate will also reduce the amount of aggregate hauled to the job site. Research is needed to determine the applicability of standard tests and acceptance criteria for using recycled concrete as aggregate and PCC comprised of recycled concrete as aggregate.

Tasks:

1. Identify typical recycled aggregate materials and mix designs for concrete made with recycled aggregate.
2. Conduct laboratory testing using standard acceptance test procedures on aggregates and concrete mixes made with recycled aggregate.
3. Evaluate the suitability of these test procedures for recycled aggregates and concrete made with recycled aggregates.
4. Modify existing test methods or develop new test methods for acceptance testing of recycled aggregate and concrete made with recycled aggregate.
5. Develop recommendations for acceptance criteria and test procedures for recycled aggregate and concrete made with recycled aggregate.

Benefits:	Established acceptance criteria and test procedures for recycled aggregate in new concrete pavements to promote the use of recycled aggregates, thereby reducing the demand for virgin aggregate for new construction.
Products:	Recommendations for acceptance criteria and test procedures for recycled aggregate and concrete made with recycled aggregate.
Implementation:	This project will result in recommendations for acceptance criteria and acceptance test procedures for recycled aggregate and concrete made with recycled aggregate.

Problem Statement AM 3.6. Waste Materials in Concrete Mixes

Track: 12. Advanced Concrete Pavement Materials (AM)
Subtrack: AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing: N/A
Estimated Cost: $1 M–$2 M

Fly ash, silica fume, and blast furnace slag are three common waste products that can be used to replace or supplement cement in concrete mixtures to produce more durable, workable, higher strength concrete. However, other waste materials, such as rice husk ash, palm oil fuel ash, and other agricultural wastes, also are proving to be effective materials for use in concrete. Sludge from paper mills can be heated to form metakaolin, which can be used as an additive for concrete, producing a very impermeable product. In addition, recent studies show the benefits of using rubber particles from used tires to replace fine aggregate in PCC-based concrete used in roads.

Tasks:

1. Identify alternative waste materials that have been tested in concrete mixes and determine the benefits of these materials.
2. Establish optimal mix design methods (or material optimization) for the waste materials.
3. Conduct laboratory testing to identify the properties of concrete mixes containing these materials, including strength, workability, permeability, and durability.
4. Develop recommendations for using these waste materials in concrete paving mixes, including proportions and limits of their use.

Benefits: Use of waste materials in concrete mixes, reducing the amount of waste materials and the demand for cement (which must be produced), while producing a better concrete mix.

Products: Recommendations (proportions and limits) for the use of waste materials in concrete paving mixes.

Implementation: This project will result in recommendations for the used of waste materials in concrete paving mixes, including proportions and limits.

Problem Statement AM 3.7. Ecocement for Concrete Mixes

Track: 12. Advanced Concrete Pavement Materials (AM)
Subtrack: AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing: N/A
Estimated Cost: $100 k–$250 k

Ecocement replaces half of the traditional cement raw materials with ash generated by the incineration of municipal solid waste and sewage sludge. It has been recognized as type A energy efficient cement by the Japanese Institute of Civil Construction, Ministry of Construction, with the following characteristics:

- Rapid hardening, similar to high-early strength cement.
- Short initial setting time (approximately 20 to 40 minutes).
- Handling time that can be adjusted to suit particular applications by adding retarding admixtures.

During the Ecocement process, chinaware fragments in the incineration ash are used, and metal wastes are extracted and recycled. Research is needed to determine the viability of producing and using this material domestically in concrete pavements.

Tasks:

1. Identify the Ecocement material and its properties.
2. Identify the process for manufacturing Ecocement.
3. Determine the viability of producing Ecocement in the United States and the cost versus benefits of producing it.
4. Develop recommendations for producing and using Ecocement in concrete paving applications.

Benefits: Ecocement that is produced during the incineration of solid waste and sewage sludge, reducing the amount of waste, while reducing the amount of cement required for concrete paving mixes, resulting in a faster setting concrete mix.

Products: Recommendations for the production and use of Ecocement in the United States.

Implementation: This project will result in recommendations for producing and using Ecocement for concrete paving applications in the United States.

Problem Statement AM 3.8. Polymer Concrete Made from Recycled Plastic Bottles

Track:	12. Advanced Concrete Pavement Materials (AM)
Subtrack:	AM 3. Environment-Enhancing Concrete Pavement Materials
Approximate Phasing:	N/A
Estimated Cost:	\$100 k–\$250 k

Polymer concrete consists of organic polymers, typically unsaturated polyesters that bind inorganic aggregates that essentially replace the hydraulic binders in cement with organic polymers. Polymer concrete can be used alone or as an overlay or coating on ordinary PCC to increase its durability and lifetime dramatically. Recently, investigators have studied the use of resin obtained from recycled polyethylene terephthalate (PET) bottles (water and carbonated beverage containers). Recycled PET resin-based polymer concrete is stronger and cheaper than conventional polymer concrete. Recycling PET into polymer concrete also helps dispose of waste. Research is needed to determine the viability of this material for use in concrete pavements.

Tasks:

1. Identify polymer concretes made from recycled plastic and their properties—namely, strength, permeability, workability, durability, and cost.
2. Evaluate the viability and benefits of polymer concrete for concrete paving applications.
3. Develop recommendations for using polymer concrete for concrete paving applications, such as repairs, overlays, and new construction.

Benefits:	Polymer concrete that results in a more durable pavement or pavement overlay, making use of recycled plastic bottles and reducing the demand on landfills.
Products:	Recommendations for using polymer concrete for paving applications.
Implementation:	This project will result in recommendations for using polymer concrete for concrete paving applications.

APPENDIX A. Cross-Reference Tables

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LIST OF TABLES

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OVERVIEW

Conventionally separate concrete pavement topics are integrated across the research tracks in the CP Road Map. Distinct topic areas can be identified easily and pulled out of the tracks into their own table using the CP Road Map database. Three example topic areas are presented here as cross-reference tables:

- Table A. Concrete Pavement Foundations and Drainage.
- Table B. Concrete Pavement Maintenance and Rehabilitation.
- Table C. Environmental Concrete Pavement Advancements.

Table A. Concrete pavement foundations and drainage.

Problem Statement	Estimated Cost	Products	Benefits
DG 1.3. Development of Model for Erosion Related to Material Properties under Dynamic Wheel Loading (see Track 2)	\$800 k–\$1.2 M	A comprehensive base/subgrade erosion test and model capable of predicting vertical as well as horizontal displacement of fine particles as a function of traffic loading and climatic conditions; a more efficiently designed base and subbase course for specific site conditions.	More reliable and cost effective base and subbase course support for specific site conditions.
DG 2.6. Improved Consideration of Foundation and Subdrainage Models (see Track 2)	\$1 M–\$1.5M	An improved and more comprehensive design procedure that more fully considers the base layer, subbase layers, subgrade, and subdrainage of concrete pavements; guidelines that will be implemented into a future version of the pavement design guide.	Improved consideration of the foundation and subdrainage that will be implemented into the pavement design guide to produce more reliable and cost effective designs.
ND 2.5. Concrete Pavement Support Sensing (see Track 3)	\$1 M–\$2 M	Devices for measuring pavement support during construction.	Automatic adjustments to the mix design, slab thickness, and joint spacing during construction, resulting from continuous monitoring of pavement support in front of the paving operation; high-quality pavements constructed precisely for the support over which they are placed.
ND 2.9. Concrete Pavement Smoothness Sensing (see Track 3)	\$1 M–\$2 M	Wet smoothness-sensing equipment.	Pavement smoothness monitored behind the paver, permitting surface deviations to be corrected while the concrete is still plastic and allowing the paver or batching operation to be adjusted to prevent further surface deviations; smoother as-constructed pavements that do not require additional measures (diamond grinding) to meet smoothness specifications.
ND 2.10. Concrete Pavement Texture (Skid Resistance, Splash/Spray) Sensing (see Track 3)	\$500 k–\$1 M	Equipment for predicting skid resistance and splash/spray potential.	Continuously monitored surface texture, permitting real-time prediction of skid resistance and splash/spray potential; automatic adjustments to finishing and texturing processes to achieve the desired skid resistance and splash/spray characteristics, resulting in as-constructed pavements that meet surface texture requirements without the need for additional texturing measures.
EA 4.1. Rapid Subgrade/Subbase Stabilization (see Track 5)	\$1 M–\$2 M	New techniques and equipment for rapid subgrade/subbase stabilization.	Rapid subgrade/subbase stabilization that will allow subgrade/subbase support to be repaired and restored before placing new pavement in a short construction window.
EA 4.2. Automated Subdrain Installation in Concrete Pavement Construction (see Track 5)	\$1 M–\$2 M	New techniques and equipment for automated subdrain installation.	Automated subdrain installation that permits the process to be completed in a single pass immediately in front of the paver, thus expediting construction.

Table B. Concrete pavement maintenance and rehabilitation.

Problem Statement	Estimated Cost	Products	Benefits
DG 3.2. Characterization of Existing PCC or Hot-Mix Asphalt Pavement to Provide an Adequate Rehabilitation Design (see Track 2)	\$3.5 M–\$4.5 M	Improved characterization of existing pavements; improved estimates of remaining life that will be useful for selecting from alternative rehabilitations; identification of solutions for overcoming existing poor design and material situations; improved support for unbonded concrete overlay design.	Proper characterization of the existing pavement critical to reliable and cost effective rehabilitation design; rehabilitation design improvements to the pavement design guide.
DG 3.3. Improvements to Concrete Overlay Design Procedures (see Track 2)	\$4 M–\$4.5 M	Improved guidelines and design procedures for several types of concrete overlays, including concrete overlays of difficult existing pavements, ultrathin slab design that includes improved concrete-to-asphalt bonding procedures, improved layering modeling for unbonded concrete overlays, characterization of underlying PCC slab design and condition for unbonded overlays, and improved bonding between thin PCC overlay and existing PCC slabs.	Concrete overlays of difficult existing pavements; ultrathin slab design, including improved concrete-to-asphalt bonding procedures; improved layering modeling for unbonded concrete overlays; characterization of underlying PCC slab design and condition for unbonded overlays; improved bonding between thin PCC overlay and existing PCC slabs.
DG 3.4. Improvements to Concrete Pavement Restoration/Preservation Procedures (see Track 2)	\$2 M–\$3 M	Improved guidelines and design procedures for several types of concrete overlays that improve their reliability, viability, and cost-effectiveness.	Improved guidelines and design procedures for the several activities involved with restoring and preserving existing concrete pavements, resulting in improved decisionmaking for potential CPR projects in terms of selecting needed treatments (such as DBR), predicting remaining life, and further validating CPR as a reliable alternative.
DG 3.6. Optimizing Procedure for New Design and Future Maintenance and Rehabilitation Capable of Minimizing Total Life Cycle Costs, Lane Closure Time, and Other Design Goals over the Range of Design Life (see Track 2)	\$1 M–\$2 M	A comprehensive system that, for a given design project, analyzes a number of alternative initial designs, future preservation treatments, and rehabilitation options, and determines the optimum combination to minimize life cycle costs, initial construction cost, or lane closure time, and to address other needs of the designer. Such a system could handle varying design lives from 8 to more than 60 years.	New and innovative design options that will improve options for the design to consider and provide more cost effective and reliable concrete pavement designs.
EA 5.1. High-Speed, In Situ PCC Pavement Breakup, Removal, and Processing (see Track 5)	\$2 M–\$5 M	Equipment for high-speed, one-pass, in situ breakup, removal, and processing of PCC pavement.	Equipment that will permit old concrete pavement to be broken up, removed, and processed in place, allowing the concrete material to be recycled into base material or new concrete and significantly reducing or even eliminating waste material.

Table B. Concrete pavement maintenance and rehabilitation, continued.

Problem Statement	Estimated Cost	Products	Benefits
EA 5.2. Recycled Concrete Processing/ Improvement (see Track 5)	$1 M–$2 M	Equipment and recommendations for separating crushed concrete into usable materials.	Equipment that will separate crushed concrete properly into materials that can be used for new concrete, minimizing or eliminating waste from reconstructed concrete pavements.
EA 5.3. High-Speed, In Situ, One-Pass, Full Concrete Pavement Reconstruction (see Track 5)	$2 M–$5 M	New equipment for one-pass pavement reconstruction.	Equipment that permits one-pass concrete pavement reconstruction, including breaking up, removing, and processing the old pavement, and placing the new pavement using recycled materials from the old pavement; expedited pavement reconstruction with no waste generated.
EA 6.2. Automated Concrete Pavement Crack Sensing and Sealing (see Track 5)	$500 k–$1 M	Automated crack sensing and crack sealing equipment/vehicle.	Automated concrete pavement crack sensing and crack sealing equipment that requires less labor, minimal traffic control, and provides a safer working environment for crack sealing.
EA 6.3. Fully Automated Concrete Pavement Restoration Equipment (see Track 5)	$1 M–$2 M	Fully automated one-pass DBR and patching equipment.	Fully automated DBR and patching equipment that will expedite CPR processes, requiring less labor and lowering costs.
IJ 2.2. Development of Innovative Ways for Detecting Joint Deterioration in New and Older Pavements (see Track 6)	$1 M–$1.5 M	Validated and implementable procedures and guidelines for rapidly and reliably evaluating existing concrete pavement joints to determine preservation and repair treatments as well as structural and functional condition.	Procedures to evaluate and recommend preservation and repair actions for existing joints.
RC 2.2. Precast Concrete Pavements for Slab Replacement (see Track 7)	$500 k–$1 M	Design standards, specifications, and best practice guidelines for using precast concrete in full-depth slab replacement.	Best practice guidelines for using precast panels in full-depth slab replacement.
RC 2.4. Precast Joints for Joint Replacement (see Track 7)	$500k–$1 M	Design standards, specifications, and best practice guidelines for using precast panels for joint replacements.	Best practice guidelines for using precast concrete panels for joint replacement.
RC 3.4. Accelerated Concrete Pavement Restoration Techniques (see Track 7)	$500 k–$1 M	Best practice guidelines for accelerated CPR techniques.	Best practice guidelines for accelerated CPR techniques.

Table B. Concrete pavement maintenance and rehabilitation, continued.

Problem Statement	Estimated Cost	Products	Benefits
LL 1.3. Strategic Application of Preservation Treatments to Preserve Long Life Concrete Pavement (see Track 8)	\$500 k–\$700 k	Recommendations on the type, design, construction, and optimum application timing of restoration or rehabilitation treatments for extending pavements service life or indefinitely preserving the original pavement structure.	Recommendations on the optimum application timing of restoration or rehabilitation treatments that will extend pavement service life or indefinitely preserve the original pavement structure; a tool for practicing engineers to use in designing long life, cost effective concrete pavements with minimal restoration.
PP 2.1. Guidelines for a Supplemental Pavement Management System and Feedback Loop for Continuous Concrete Pavement Improvements (see Track 10)	\$500 k–\$750 k	Guidelines for developing a supplemental PMS that includes design, construction, materials, and rehabilitation data in a format conducive to engineering decisionmaking.	PMS that provide sufficient information for improving design, construction, materials, and rehabilitation; guidelines that produce information sufficient for key engineering decisions.
PP 2.2. Advancements in Forensic Analysis of Concrete Pavements (see Track 10)	\$500 k–\$750 k	A state-of-the-art forensic study manual.	Forensic analysis that could be tied with the determination of remaining life to develop criteria for selecting appropriate rehabilitation and pavement strengthening actions to extend the existing pavement performance life.
BE 2.2. The Economic and Systemic Impacts of Concrete Pavement Mix-of-Fixes Strategies (see Track 11)	\$250 k–\$500 k	Advanced mix-of-fixes strategies that address a variety of performance and budget requirements; demonstration of the need to develop additional concrete pavement products that meet price and performance criteria.	Quantifications of a reasonable percentage of concrete pavement work with service life needs anywhere from 10 to 60 years.
AM 1.1. Flexible Cementitious Overlay Materials (see Track 12)	\$500 k–\$1 M	Specifications, design criteria, and construction procedures for flexible cementitious overlays.	New, more durable overlay material that is not as susceptible to rutting and shoving as asphalt and can be placed in thin, flexible layers.

Table C. Environmental concrete pavement advancements.

Problem Statement	Estimated Cost	Products	Benefits
MD 3.5. Functional PCC Pavement Models Adaptation (see Track 1)	\$250 k–\$500 k	Thoroughly documented models, also in computerized form, that can be used to predict the functional performance (e.g., smoothness) of a concrete pavement as a function of mix properties.	Functional models predicting the linkage between concrete pavement function (e.g., smoothness, safety, noise) and mix properties in the mix design system; supplements for other ongoing efforts to develop these models.
ND 2.11. Tire-Pavement Noise Sensing (see Track 3)	\$500 k–\$1 M	Equipment for predicting pavement noise characteristics during construction.	Prediction of tire-pavement noise potential during construction, allowing surface textures to be corrected while the concrete is still plastic and automatic adjustments to the surface texturing process to meet the tire-pavement noise restrictions; as-constructed pavements that meet stringent tire-pavement noise restrictions without the need for additional noise mitigation.
EA 5.1. High-Speed, In Situ PCC Pavement Breakup, Removal, and Processing (see Track 5)	\$2 M–\$5 M	Equipment for high-speed, one-pass, in situ breakup, removal, and processing of PCC pavement.	Equipment that will permit old concrete pavement to be broken up, removed, and processed in place, allowing the concrete material to be recycled into base material or new concrete and significantly reducing or even eliminating waste material.
EA 5.2. Recycled Concrete Processing/ Improvement (see Track 5)	\$1 M–\$2 M	Equipment and recommendations for separating crushed concrete into usable materials.	Equipment that will separate crushed concrete properly into materials that can be used for new concrete, minimizing or eliminating waste from reconstructed concrete pavements.
RC 2.5. Precast Quiet Pavement Surfaces (see Track 7)	\$500 k–\$1 M	Recommendations for noise-reducing techniques for precast concrete pavement surfaces.	Exploration of noise-reducing techniques that may not be viable for conventional concrete pavements but that can be incorporated into precast concrete pavements.
LL 1.1. Identifying Long Life Concrete Pavement Types, Design Features, Foundations, and Rehabilitation/ Maintenance Strategies (see Track 8)	\$800 k–\$1.2 M	Feasible pavement strategies and promising features for providing long life for each type of concrete pavement selected; case studies of past long life concrete pavements.	Feasible pavement strategies for providing long life that will provide input throughout track 8 (Long Life Concrete Pavements).
BE 2.1. Achieving Sustainability with Concrete Pavements (see Track 11)	\$500 k–\$750 k	Macroanalysis of whole-life factors related to concrete pavements.	A study of the broader issues associated with cement, aggregate, construction, rehabilitation, and concrete pavement salvaging that allows policymakers and engineers to examine the full societal value of concrete pavements and recommend improvements.

Table C. Environmental concrete pavement advancements, continued.

Problem Statement	Estimated Cost	Products	Benefits
BE 5.1. The Impact of Concrete Pavement Reflectance, Absorption, and Emittance on the Urban Heat Island Effect (see Track 11)	\$250 k–\$500 k	A report detailing the impact of the reflectance of various concrete pavement types on the heat island effect.	An examination of existing efforts to understand and reduce the heat island effect to determine their applicability to concrete pavements and help determine the impact of concrete pavements on the heat island effect, as well as the costs associated with reducing the effect.
AM 3.1. Cement Containing Titanium Dioxide (see Track 12)	\$100 k–\$250 k	Recommendations for the use of cement containing titanium dioxide in concrete paving mixes.	Concrete pavements containing titanium dioxide that potentially can remove certain VOCs from the air, helping to reduce air pollution in urban areas.
AM 3.2. Sulfur Concrete (see Track 12)	\$100 k–\$250 k	Recommendations for using sulfur concrete in paving applications.	Sulfur concrete that consists of 100 percent recycled material, made from byproducts of electricity production and petroleum refinement; a dense, acid-resistant material that may have applications for concrete paving.
AM 3.3. Increased Percentages of Reclaimed Asphalt Pavement as an Aggregate for Concrete Paving Mixtures (see Track 12)	\$1 M–\$2 M	Recommendations for using RAP as an aggregate for concrete paving mixes.	RAP in concrete paving mixes, reducing the amount of RAP that must be disposed, as well as reducing the demand for virgin aggregate for concrete pavements.
AM 3.4. Mix Design Considerations with Recycled Concrete Aggregate (see Track 12)	\$1 M–\$2 M	Recommendations for using recycled concrete as aggregate in new pavement construction.	Recycled concrete for aggregate in new concrete pavements, reducing the amount of reclaimed concrete pavement that must be disposed, as well as the demand for virgin aggregate in concrete pavements.
AM 3.5. Acceptance Criteria for Using Recycled Aggregate (see Track 12)	\$500 k–\$1 M	Recommendations for acceptance criteria and test procedures for recycled aggregate and concrete made with recycled aggregate.	Established acceptance criteria and test procedures for recycled aggregate in new concrete pavements to promote the use of recycled aggregates, thereby reducing the demand for virgin aggregate for new construction.
AM 3.6. Waste Materials in Concrete Mixes (see Track 12)	\$1 M–2 M	Recommendations (proportions and limits) for the use of waste materials in concrete paving mixes.	Use of waste materials in concrete mixes, reducing the amount of waste materials and the demand for cement (which must be produced), while producing a better concrete mix.
AM 3.7. Ecocement for Concrete Mixes (see Track 12)	\$100 k–250 k	Recommendations for the production and use of Ecocement in the United States.	Ecocement that is produced during the incineration of solid waste and sewage sludge, reducing the amount of waste, while reducing the amount of cement required for concrete paving mixes, resulting in a faster setting concrete mix.
AM 3.8. Polymer Concrete Made from Recycled Plastic Bottles (see Track 12)	\$100 k–250 k	Recommendations for using polymer concrete for paving applications.	Polymer concrete that results in a more durable pavement or pavement overlay, making use of recycled plastic bottles and reducing the demand on landfills.

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