

Strategic Highway Research Program

Research Plans

Sponsored by
AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS
FEDERAL HIGHWAY ADMINISTRATION—U.S. Department of Transportation

TRANSPORTATION RESEARCH BOARD—National Research Council
National Cooperative Highway Research Program
Washington, D.C.
May 1986

NCHRP Project 20-20, FY '83
ISBN 0-309-04017-5

L.C. Catalog Card No. 86-50371

Price: $15.00

NOTICE The studies on which this report is based were carried out under separate contracts with seven agencies. The study on long-term pavement performance was sponsored by the Federal Highway Administration of the U.S. Department of Transportation. The remaining six studies were part of the National Cooperative Highway Research Program, which is administered by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The National Cooperative Highway Research Program is sponsored by the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration. Members of the SHRP Task Force selected to monitor these studies and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the studies.

This report has been reviewed and accepted for publication by the SHRP Task Force and by a series of technical advisory committees specially established to monitor and advise the individual studies. The opinions and conclusions expressed or implied are those of the research agencies that performed the studies, and while they have been accepted as appropriate by the Task Force, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration.

This report is available from:

Transportation Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

Contents

	Page
FOREWORD	iv
STRATEGIC HIGHWAY RESEARCH PROGRAM ORGANIZATION	v
STRATEGIC HIGHWAY RESEARCH PROGRAM TASK FORCE AND ADVISORY COMMITTEES	vi
LIST OF ABBREVIATIONS	x
OVERVIEW AND INTEGRATION REPORT	1

	Technical Research Area
Detailed Planning for Research on Asphalt Properties	1
Detailed Planning for Research on Long-Term Pavement Performance	2
Detailed Planning for Research on Maintenance Effectiveness	3
Detailed Planning for Research on Bridge Component Protection	4
Detailed Planning for Research on Cement and Concrete	5
Detailed Planning for Research on Snow and Ice Control on Highways and Bridges	6

Foreword

The Strategic Highway Research Program was originally proposed in *TRB Special Report 202,* "America's Highways: Accelerating the Search for Innovation," published in June 1984. The report contained the findings of the Strategic Transportation Research Study sponsored by the Federal Highway Administration and conducted by the Transportation Research Board. It documented the need for a concerted research effort to produce major innovations for increasing the productivity and safety of the nation's highway system, and it recommended a $150 million, five-year program of research focused on six high-priority areas where the nation spends most of the $50 billion used for roads each year.

Both the American Association of State Highway and Transportation Officials and the Federal Highway Administration enthusiastically accepted the recommendations and initiated steps to have 0.25 percent of federal-aid highway funds earmarked for support of the program in fiscal years 1987 through 1991. Over a period of about 12 months starting in March 1985, a major effort, directed by the SHRP Task Force, has been focused on the development of detailed plans for the research program. This report documents the results of that effort.

The Report represents an important milepost on the path of progress for the Strategic Highway Research Program. Seven contract agencies, each supported by an advisory committee of representatives from the highway community, have worked intensively for almost one year to develop well-defined plans for the performance of research in the six technical areas that constitute the Strategic Highway Research Program. This document represents a compilation of the reports prepared by the seven contract agencies and constitutes in total a workplan for carrying out a program that will provide the greatest surge in highway research that this nation has ever witnessed.

There is great intrinsic value in the program. It responds to some long-neglected needs for improvements in basic technologies and materials serving our national street and highway system. It is a new, additional, supplemental program not intended to supplant any ongoing research activities under state highway agencies, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, the Transportation Research Board, the National Science Foundation, or elsewhere. As a new program, with an accelerated, highly focused, results-oriented thrust, it can demonstrate the payoffs from research and serve as an example to encourage other new research investments.

The planning process for the Strategic Highway Research Program will not end with this final report. The report provides a clear definition of the goals and objectives of the program and a sound plan on which to begin the research effort. However, technical, environmental, economic, social and political changes will continue to affect the plan, and it must be reassessed and reevaluated throughout the program. The early results of parts of the research will influence the later stages of the plan. To be successful, the management of the Strategic Highway Research Program must be a dynamic process, with a clear and steady vision of the program goals but an open, responsive approach to finding a path to those goals.

This research plan was developed under National Cooperative Highway Research Program contracts for the overview study and for five of the technical areas and under a Federal Highway Administration contract for the sixth technical area, Long-Term Pavement Performance, all working in close cooperation with the office of the Strategic Highway Research Program, established by the American Association of State Highway and Transportation Officials.

STRATEGIC HIGHWAY RESEARCH PROGRAM ORGANIZATION

THOMAS D. LARSON
Chairman, SHRP Task Force

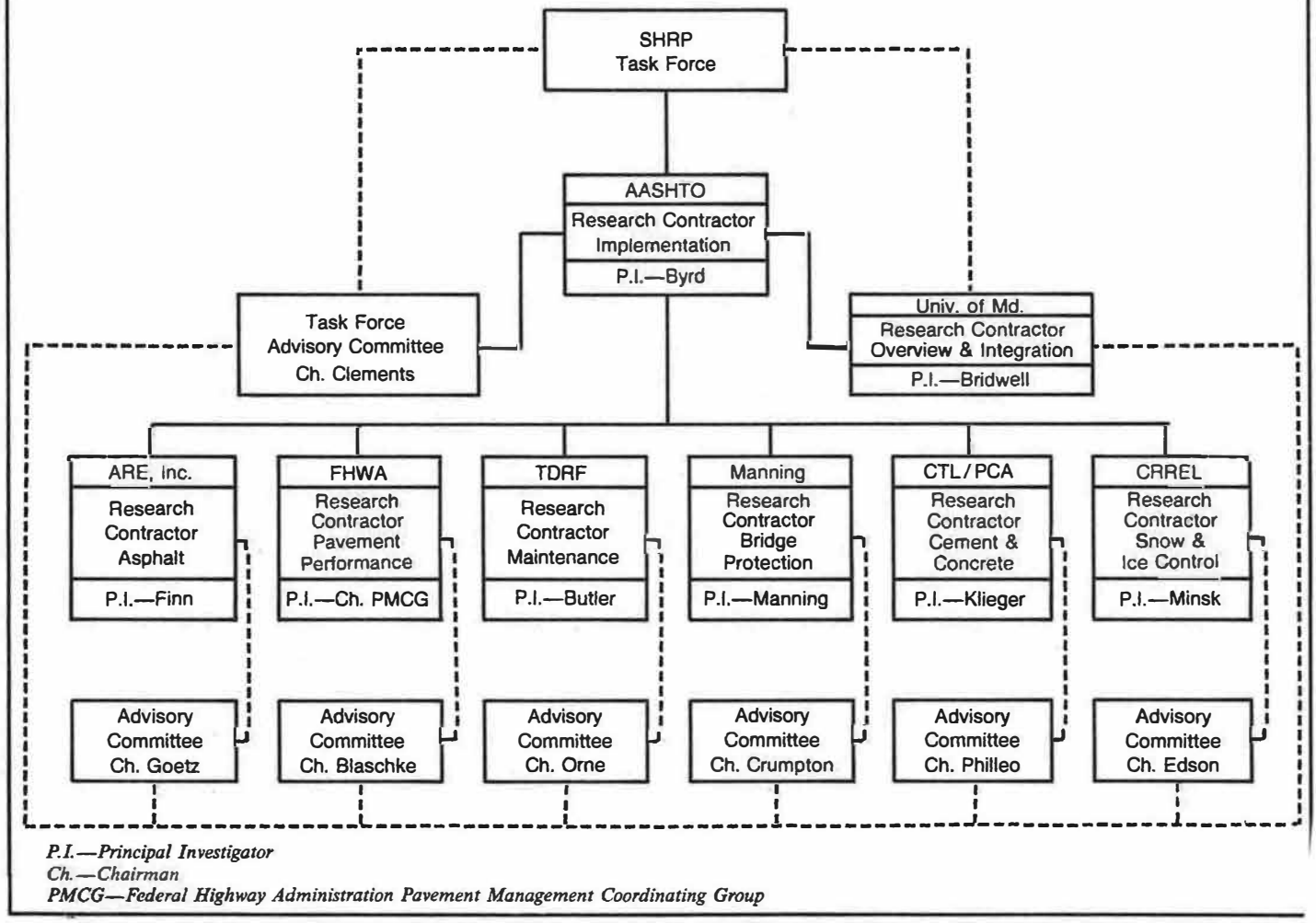
L. GARY BYRD
Interim Director

RICHARD A. MCCOMB
Special Assistant to Interim Director

JUDITH A. ROSENTHAL
Administrative Assistant

Strategic Highway Research Program
444 North Capitol Street, N.W.
Suite 343
Washington, D.C. 20001
202/624-5808

SHRP PRE-IMPLEMENTATION STUDY ORGANIZATION



P.I.—Principal Investigator
Ch.—Chairman
PMCG—Federal Highway Administration Pavement Management Coordinating Group

STRATEGIC HIGHWAY RESEARCH PROGRAM
TASK FORCE

Thomas D. Larson, Chairman
Secretary of Transportation
Pennsylvania Department of Transportation

Ray A. Barnhart
Federal Highway Administrator
Federal Highway Administration

Duane Berentson
Secretary of Transportation
Washington Department of Transportation

Thomas B. Deen
Executive Director
Transportation Research Board

Francis B. Francois
Executive Director
AASHTO

Mark G. Goode
Engineer-Director
Texas State Department of Highways

David J. Hensing*
Deputy Executive Director
AASHTO

Boris Hryhorczuk**
Deputy Minister
Manitoba Department of Highways

Robert N. Hunter
(Retired) Chief Engineer
Missouri Highway Department

Lester P. Lamm
President
Highway Users Federation

Harold W. Monroney
Director, Division of Highways
Illinois Department of Transportation

Thomas D. Moreland
Commissioner
Georgia Department of Transportation

David K. Phillips*
Associate Administrator for RD&T
Federal Highway Administration

Robert J. Reilly*
Director, NCHRP
Transportation Research Board

Charley V. Wootan
Director
Texas Transportation Institute

* Liaison
** Ex-Officio Member

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
OVERVIEW AND INTEGRATION STUDY

John A. Clements, Chairman
President
New England Fuel Institute

Lester A. Hoel, Vice Chairman
Chairman, Department of Civil Engineering
University of Virginia

Richard E. Barnes
President
American Concrete Pipe Assoc.

Byron Blaschke
Assistant Engineer-Director, Operations
Texas State Department of Highways

Thomas W. Bradshaw, Jr.
Vice President, Public Finance
The First Boston Corporation

Richard P. Braun
Commissioner
Minnesota Department of Transportation

William A. Bulley
Senior Vice President
H.W. Lochner, Inc.

Roger Carrier
Chambers Deval Corporation

James Choromokos, Jr.
Director, Research & Development
U.S. Army Corps of Engineers

Carl F. Crumpton
Engineer of Research
Kansas Department of Transportation

Howard Dugoff (Former) Science Advisor
to the Secretary of Transportation
U.S. Department of Transportation

Charles Edson
Chief Engineer, Const. & Maint.
New Jersey Department of Transportation

M. Baron T. George
Vice President, Planning
AVCO Everett Research Laboratory

Robert H. Given
Executive Vice President
Iowa Concrete Paving Association

William Goetz, (Retired) Professor
School of Civil Engineering
Purdue University

John Gray, President
National Asphalt Pavement
Association

Calvin G. Grayson, Director
Kentucky Transportation Center
University of Kentucky

B. J. Hamm
Deputy Minister
Nova Scotia Department of Transportation

Daniel J. Hanson, Sr., President
American Road and Transportation
Builders Association

Thomas F. Humphrey
Lecturer & Research Associate
Massachusetts Institute of Technology

K. B. Johns
Assistant Director
Transportation Research Board

Peter G. Koltnow
Consultant

Richard D. Morgan
Executive Director
Federal Highway Administration

George Nesterczuk, Science Advisor
to the Secretary of Transportation
U.S. Department of Transportation

Howard Newlon, Jr., Research Director
Virginia Highway and Transportation
Research Council

William A. Ordway
Consultant

Donald Orne, Asst. Deputy Director,
Highway Technical Services
Michigan Department of Transportation

Robert G. Packard, Manager
Paving and Transportation Department
Portland Cement Association

Vince Paul, Chief
Division of Engineering Services
California Department of Transportation

Robert E. Philleo
Consulting Engineer

Anil K. Rastogi, Director
Corporate Diversification Portfolio
Owens Corning Fiberglas Corporation

William M. Spreitzer
GM Research Laboratories
General Motors Corporation

Gerald S. Triplett
President
The Asphalt Institute

Richard N. Wright, Director
Center for Building Technology
National Bureau of Standards

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
ASPHALT STUDY

William H. Goetz, Chairman
(Retired) School of Civil Engineering
Purdue University

Don M. Harriott, Vice Chairman
Administrator, Engineering Division
Montana Department of Highways

David A. Anderson
Pennsylvania Transportation Institute
The Pennsylvania State University

Ernest J. Barenberg, Professor
Department of Civil Engineering
University of Illinois

Herbert W. Busching, Professor
Department of Civil Engineering
Clemson University

Ronald J. Cominsky
Chief, Materials and Testing Division
Pennsylvania Department of Transportation

Clara D. Craver
President
Chemir Laboratories

Campbell Crawford
Director of Engineering
National Asphalt Pavement Association

Joseph E. Crowe
Deputy Director of Highways
Illinois Department of Transportation

James V. Evans
Amoco Oil Company

William G. Gunderman
Engineer of Materials and Construction
Transportation Research Board

Kenneth A. Gutschick
Technical Director
National Lime Association

Douglas I. Hanson, Chief
Materials Lab Bureau
New Mexico State Highway Department

Richard E. Hay, Director
Engineering & Highway Operations R&D
Federal Highway Administration

Charles L. Huisman (Deceased)
Materials Engineer
Iowa Department of Transportation

P. W. Jennings, Professor
Department of Chemistry
Montana State University

William J. Kari
Consultant

Glenn R. Kemp
California Department of Transportation

K. C. Kresge, Manager
Industrial Lubricants,
Mobil Research & Development Corporation

Richard Langlois
Laboratoire Central
Ministere des Transports du Quebec

Philip E. McIntyre
Materials & Research Engineer
New Hampshire Department of Highways

Robert B. McKeagney
Manager, Business Development
Vulcan Materials Company

Roderick W. Monroe
Bituminous Engineer
Iowa Department of Transportation

Harold W. Muncy
Director, R&D
Bituminous Materials Co., Inc.

Gale C. Page
Bituminous Materials Engineer
Florida Department of Transportation

George E. Paul
Street Maintenance Engineer
City of Albuquerque

R. D. Pavlovich
Senior Research Engineer
New Mexico Engineering Research Institute

V. P. Puzinauskas
Principal Engineer
The Asphalt Institute

Tom Stapler
State Materials & Research Engineer
Georgia Department of Transportation

Garland W. Steele
Engineering and Special Studies Advisor
West Virginia Department of Highways

Donald O. Swing
Materials & Tests Engineer
Nebraska Department of Roads

J. D. Telford
Materials Engineer
Oklahoma Department of Transportation

Robert G. Warburton
State Materials Engineer
Wyoming State Highway Department

Harold H. Weber
Director of Industrial Research
The Sulphur Institute

James E. Wilson, Jr.
Asst. Materials Engineer
Oregon Department of Transportation

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
PAVEMENT PERFORMANCE

Byron Blaschke, Chairman
Assistant Engineer-Director, Operations
Texas State Department of Highways

Brooks Nichols, Vice Chairman
Assistant Chief Engineer, Design
Arkansas State Highway Department

Richard D. Barksdale, Professor
School of Civil Engineering
Georgia Institute of Technology

Tom Christison
Senior Research Engineer
Alberta Research Council

Leland Fletcher
Asst. to Chief Engineer-
Missouri Transportation Department

Raymond A. Forsyth
Chief, Transportation Laboratory
California Department of Transportation

Dave Gendell
Director, Office of Highway Operations
Federal Highway Administration

Wade Gramling
Chief, Roadway Technology Division
Pennsylvania Department of Transportation

Kevin Heanue
Director, Office of Highway Planning
Federal Highway Administration

R. G. Hicks, Professor
Department of Civil Engineering
Oregon State University

Ronald W. Houska
Deputy Director
Illinois Department of Transportation

W. Ronald Hudson, Professor
Department of Civil Engineering
University of Texas at Austin

Paul E. Irick
Consultant

Mike Jaskaniec
Chief, Construction Engineer
Wisconsin Department of Transportation

W. H. Jorgenrud
Iowa County Engineer

Robert Joubert
The Asphalt Institute

Roger LeClerc
Consultant

Richard A. Lill
American Trucking Associations Inc.

William N. Lofroos
State Pavement Design Engineer
Florida Department of Transportation

Joel Marcuson
Transportation Manager
City of Tampa

Frank P. Nichols, Jr.
National Stone Association

Charles A. Pagen
Director of R&D
National Asphalt Pavement Association

Art Peters
Materials Engineer
Washington Department of Transportation

Dale Peterson
Consultant

Roger Petzold
Federal Highway Administration

Randell Riley
American Concrete Pavement Assoc.

Harry A. Smith
NCHRP- Transportation Research Board

Dick Sullivan
Assistant Division Director
Minnesota Department of Transportation

Shiraz D. Tayabji
Transportation Development Department
Construction Technology Lab., PCA

Harry H. Ulery Jr.
Waterways Experiment Station
Corps of Engineers

Fred Van Kirk
West Virginia State Highway Engineer

George B. Way
Pavement Management Engineer
Arizona Department of Transportation

Thomas D. White, Professor
Department of Civil Engineering
Purdue University

Matthew W. Witczak, Professor
Department of Civil Engineering
University of Maryland

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
MAINTENANCE STUDY

Donald E. Orne, Chairman
Asst. Deputy Director
Michigan Department of Transportation

A. D. Andreas, Vice Chairman
Deputy Secretary of Transportation
Washington State Department of Transportation

Don Adams
Maintenance Engineer
Oregon Department of Transportation

Carlos L. Alvarez
Vice President & Division Mgr.
DeLeuw Cather & Company

Stanley S. Ather
Chief, Street Maintenance Division
D.C. Department of Public Works

Joseph A. Bruno, Jr.
Director of Research
Steel Structures Painting Council

Adrian G. Clary
Engineer of Maintenance
Transportation Research Board

James J. Connor
Bayou Ash, Inc.

Jack Cropper
Chief, Division of Highway Maintenance
California Department of Transportation

Paul E. Cunningham (Retired)
Chief, Construction & Maintenance Division
Federal Highway Administration

Ken Davis
District Engineer
Nevada Department of Transportation

William Gartner, Jr.
Senior District Engineer
The Asphalt Institute

Wilbur M. Haas
Professor of Civil Engineering
Michigan Technological University

Louis J. Haff
King County Maintenance Engineer

David J. Halpenny
Paving and Transportation Department
Portland Cement Association

Edwin W. Hauser
Director, Institute for Transportation
Research and Education

Paul E. Heise
Assistant District Engineer, District 3-0
Pennsylvania Department of Transportation

Christine M. Johnson
Project Coordinator
Port Authority of NY & NJ

Jimmy Lee
Head of Bridge Maintenance
North Carolina Department of Transportation

David C. Mahone
Senior Research Scientist
Virginia Transportation Research Council

Michael J. Markow, Research Associate
Department of Civil Engineering
Massachusetts Institute of Technology

George E. Moberly
Engineer of Maintenance
Illinois Department of Transportation

Bob Myers
Chief, Construction & Maintenance Division
Federal Highway Administration

Andrew D. Nielsen
Maintenance Supervisor
Idaho Department of Transportation

Bernhard H. Ortgies
Maintenance Engineer
Iowa Department of Transportation

Gerald Ray
Maintenance Systems Engineer
Louisiana Department of Transportation

Martin C. Rissel
Senior Associate
Byrd, Tallamy, MacDonald and Lewis

Eugene L. Rowen
Consultant

John G. Schoon, Professor
Department of Civil Engineering
Northeastern University

Paul Schwarting
Sac County Iowa Engineer

Kumares C. Sinha, Professor
School of Civil Engineering
Purdue University

Lyle W. Smith
Assistant Deputy Minister
New Brunswick Department of Transportation

Ralph Speer, Jr.
Director of Public Works
City of Rockford, Illinois

Hugh Tyner
District Engineer
Georgia Department of Transportation

Ronald L. Zook
Engineer of Maintenance
Ohio Department of Transportation

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
BRIDGE PROTECTION STUDY

Carl F. Crumpton, Chairman
Engineer of Research
Kansas Department of Transportation

Philip D. Cady, Vice Chairman
Professor of Civil Engineering
The Pennsylvania State University

Gordon Beecroft
Research Engineer
Oregon Department of Transportation

Neal S. Berke
Research Engineer Associate
W. R. Grace & Company

Nicholas A. Bittenbinder
Senior Staff Consultant
GAI Consultants, Inc.

William Chamberlin
Civil Engineer
New York Department of Transportation

A. M. Digioia
President
GAI Consultants, Inc.

L. Edwin Dunn
Structure Const. Field Super.
California Department of Transportation

Ed Escalante
Corrosion Group
National Bureau of Standards

Anthony E. Fiorato, Director
Construction Technology Laboratory
Portalnd Cement Association

Ron I. Frascoia
Research & Development Supervisor
Vermont Agency of Transportation

William M. Gere
Director of Operations
South Dakota Department of Transportation

C. S. Gloyd
Bridge & Structures Engineer
Washington State Department of Transportation

Gary L. Hoffman, Director
Bureau of Bridge and Roadway Technology
Pennsylvania Department of Transportation

Theodore H. Karasopoulos
Engineer of Materials and Research
Maine Department of Transportation

Richard J. Kessler
Structural Concrete Engineer
Florida Department of Transportation

Louis A. Kuhlmann
Research Leader
DOW Chemical Company

Andrew J. Lane
Bridge Engineer
New Hampshire Department of Highways

Orris J. Lane, Jr.
Portland Cement Concrete Engineer
Iowa Department of Transportation

Carl E. Locke, Professor
College of Engineering
University of Oklahoma

Wallace T. McKeel Jr.
Research Scientist
Virginia Transportation Research Council

Dave Marett
Chief Structural Engineer
Municipality of Ottawa-Carleton

Garrett Morrison
Dragon Products Company

Robert J. Reilly
Director,Cooperative Research Programs
Transportation Research Board

W. Eugene Sampley
Skagit Co., Public Works Director

Arunprakash M. Shirole
Engineer - Structures & Bridges
City of Minneapolis - PWD

L. F. Spaine
Consultant

Robert T. Stafford
Director
Concrete Reinforcing Steel Institute

Yash Paul Virmani
Office of Research
Federal Highway Administration 1,

David Whiting
Senior Research Engineer
Construction Technology Lab., PCA

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
CEMENT & CONCRETE STUDY

Robert E. Philleo, Chairman
Consulting Engineer

T. J. Pasko, Vice Chairman
Chief, Pavements Division
Federal Highway Administration

E. J. Breckwoldt
Support Services Engineer
Louisiana Department of Transportation

A. D. Donofrio
Chief, Materials & Research
Delaware Department of Transportation

Geoffrey J. Frohnsdorff, Chief
Building Materials Division
National Bureau of Standards

Richard D. Gaynor
Executive Vice President
National Ready Mix Concrete Association

J. G. Gehler
Engr Materials & Physical Research
Illinois Department of Transportation

Gene R. Hardy
Dallas County, Iowa Engineer

Eugene D. Hill, Jr.
Openaka Corporation, Inc.

Thomas A. Holm
Northeast Solite Corporation

Frank L. Holman
Research Engineer
Alabama Highway Department

Richard H. Howe
Concrete and Aggregate Engineer
Pennsylvania Department of Transportation

Crawford E. Jencks
Projects Engineer, NCHRP
Transportation Research Board

Truman R. Jones Jr.
Technical Director-Constr. Material
Vulcan Materials Company

Cyrus S. Layson
Asst. State Highway Engr.
Kentucky Department of Transportation

Bryant Mather
Chief Structures Laboratory
US Army Corps of Engineers

P. K. Mehta
Professor of Civil Engineering
University of California, Berkeley

Jim Murphy
Director, Materials Bureau
New York Department of Transportation

William G. Prince
Asst. Research & Mat'ls Engineer
South Carolina Department of Highways

Charles F. Scholer, Professor
School of Civil Engineering
Purdue University

Surendra P. Shan
Professor of Civil Engineering
Northwestern University

Jan P. Skalny
Associate Director
Martin Marietta Laboratories

Peter Smith
Director, Research & Development
Ontario Ministry of Transp. & Comm.

Bufford D. Stroud
State Testing Engineer
Mississippi State Highway Department

Heber Vlam
Engineer of Materials and Research
Utah Department of Transportation

Frank T. Wagner
Head of Materials & Tests
North Carolina Department of Transportation

James Woodstrom
Supervising Materials & Research Engr.
California Department of Transportation

William Yrjanson
Director of Engineering
American Concrete Pavement Assoc.

STRATEGIC HIGHWAY RESEARCH PROGRAM
ADVISORY COMMITTEE
SNOW AND ICE STUDY

Charles T. Edson, Chairman
Chief Engineer, Const. & Maint.
New Jersey Department of Transportation

Herbert O. Klossner, Vice Chairman
Director of Transportation
Hennepin County, Minnesota

Phillip W. Amos
Director, Bureau of Maint. and Operations
Pennsylvania Department of Transportation

T. W. Beaulieu
District Engineer
Maryland State Highway Administration

Walter B. Bienert
President
Dynatherm Corp.

Paul R. Camp Professor
Department of Physics & Astronomy
University of Maine

William E. Dickinson
President
Salt Institute

Joseph Di Fabio
Associate Civil Engineer
New York State Department of Transportation

Charles E. Dougan
Director of Research
Connecticut Department of Transportation

Jerome D. Franklin
Director of Public Works
City of Madison, Wisconsin

J. E. Gruspier
Research Engineer
Ontario Ministry of Transp. & Comm.

Stanley Haas
Maintenance Engineer
North Dakota State Highway Department

Richard C. Ingberg
Physical Research Engineer
Minnesota Department of Transportation

R. Ian Kingham, Manager
Transportation Planning & Research
Greenhorne and O'Mara, Inc.

Byron N. Lord
Research Environmental Engineer
Federal Highway Administration

Kenneth M. Mellinger
Chief, Division of Maintenance
Indiana Department of Highways

Jim Norris
Director of Maintenance
Tennessee Department of Transportation

Kynric M. Pell, Professor
College of Engineering
University of Wyoming

Robert L. Sandvig, Professor
Department of Chemical Engineering
South Dakota School of Mines and Technology

Douglas L. Shaffer
Staff Maintenance Supt.
Colorado Department of Highways

Max I. Sheeler
Chemical Engineer
Iowa Department of Transportation

Leo C. Stevens Jr.
Chief of Laboratory
Massachusetts Department of Public Works

Larry R. Sweet
Research Manager
Alaska Department of Transportation

Ronald Tabler
Hydrologist & Project Leader
U.S. Forest Service

David C. Vegh
Director, Technical & Marketing Service
Ziebart Corporation

Leslie Vipond
Federal Aviation Administration

Abbreviations

AADT	Annual Average Daily Traffic
AAMAS	Asphalt-Aggregate Mixture Analysis System
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACI	American Concrete Institute
ALF	Accelerated Loading Facility
APT	Accelerated Pavement Testing
ASTM	American Society for Testing & Materials
AVC	Automatic Vehicle Classification
CMA	Calcium Magnesium Acetate
COPES	Concrete Pavement Evaluation System
CRCP	Continuously Reinforced Concrete Pavement
CRREL	Cold Regions Research and Engineering Laboratory (U.S. Army)
CTL	Construction Technology Laboratories
DOT	Department of Transportation
ESAL	Equivalent Single Axle Load
FCP	Federally Coordinated Program (Highway Research and Development)
FHWA	Federal Highway Administration
FRC	Fiber Reinforced Concrete
G&A	General and Administrative Costs
GBFS	Ground Blast-Furnace Slag
GPS	General Pavement Studies
HRWR	High-Range Water Reducer
IPS	Inservice Pavement Studies
JCP	Jointed Concrete Pavement
JPCP	Jointed Plain Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
LEF	Load Equivalence Factor
LTM	Long-Term Pavement Monitoring
LTPP	Long-Term Pavement Performance
MOE	Measures of Effectiveness
MUTCD	Manual on Uniform Traffic Control Devices
NAS	National Academy of Sciences
NCHRP	National Cooperative Highway Research Program
NDT	Nondestructive Testing Technique
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
PCC	Portland Cement Concrete
PSR	Pavement Serviceability Rating
RFP	Request for Proposal
SHA	State Highway Agency
SHRP	Strategic Highway Research Program
SPS	Special Pavement Studies
STRS	Strategic Transportation Research Study
TRA	Technical Research Area
TRB	Transportation Research Board
TRIP	Road Information Program
WIM	Weigh-In-Motion

SHRP
OVERVIEW AND INTEGRATION REPORT

PREPARED FOR:

NCHRP PROJECT NUMBER 20-20(2)
PRE-IMPLEMENTATION ACTIVITIES FOR THE
STRATEGIC HIGHWAY RESEARCH PROGRAM

MAY 1986

PREPARED BY

TRANSPORTATION STUDIES CENTER
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MARYLAND
COLLEGE PARK, MARYLAND 20742

TABLE OF CONTENTS

		Page
	LIST OF FIGURES	i
	LIST OF TABLES	ii
	ABSTRACT	iii
	ACKNOWLEDGEMENTS	iv
Section 1.	OVERVIEW.....	1
Section 2.	RESEARCH DESIGN SUMMARY.....	8
Section 3.	SHRP ORGANIZATION AND MANAGEMENT	21
Section 4.	MAJOR PROGRAM CONSIDERATIONS	28
Section 5.	ANALYSIS OF RESEARCH PLANS	35
APPENDIX A	SHRP STATISTICS.....	A-1

LIST OF FIGURES

Figure		Page
3.1	CONCEPTUAL ORGANIZATIONAL PLAN FOR TECHNICAL RESEARCH	24
5.1	DISTRIBUTION OF ANNUAL RESEARCH EXPENDITURES	41
5.2	CUMULATIVE TECHNICAL RESEARCH AREA EXPENDITURES DURING SHRP FIVE-YEAR PERIOD	42
5.3	DISTRIBUTION OF TECHNICAL RESEARCH AREA CONTRACT WORTH AWARDED BY YEAR (EXCLUSIVE OF TRA-2)	45
5.4	CUMULATIVE YEARLY CONTRACT AWARDS AND ESTIMATED NUMBER OF CONTRACTS (EXCLUSIVE OF TRA-2)	46
A.1	RESEARCH PROJECT SCHEDULE (TRA-1)	A-15
A.2	RESEARCH PROJECT SCHEDULE (TRA-2)	A-16
A.3	RESEARCH PROJECT SCHEDULE (TRA-3)	A-17
A.4	RESEARCH PROJECT SCHEDULE (TRA-4)	A-18
A.5	RESEARCH PROJECT SCHEDULE (TRA-5)	A-19
A.6	RESEARCH PROJECT SCHEDULE (TRA-6)	A-20
A.7	ANNUAL DISTRIBUTION OF RESEARCH TASKS STARTING AND FINISHING (EXCLUSIVE OF TRA-2)	A-21
A.8	DISTRIBUTION OF TECHNICAL RESEARCH AREA CONTRACTS FINISHED AND AWARDED BY YEAR (EXCLUSIVE OF TRA-2)	A-22

LIST OF TABLES

Table		Page
1.1	OVERVIEW OF PROPOSED STRATEGIC HIGHWAY RESEARCH STUDY	2
5.1	ANNUAL SHRP EXPENDITURES BY PROJECT	40
5.2	SUMMARY OF RESEARCH PROJECT-TASK DURATION	44
5.3	RESEARCH STUDY TYPE SUMMARY STATISTICS	48
5.4	END PRODUCT TYPE SUMMARY STATISTICS	49
5.5	SUMMARY OF POTENTIAL TRA-2 INTERACTION	56
5.6	SUMMARY OF SHRP RESEARCH PROJECT INTERACTION AND COORDINATION (EXCLUSIVE OF TRA-2).	57
A.1	ANNUAL BUDGET EXPENDITURES (TRA-1)	A-2
A.2	ANNUAL BUDGET EXPENDITURES (TRA-2)	A-3
A.3	ANNUAL BUDGET EXPENDITURES (TRA-3)	A-4
A.4	ANNUAL BUDGET EXPENDITURES (TRA-4)	A-5
A.5	ANNUAL BUDGET EXPENDITURES (TRA-5)	A-6
A.6	ANNUAL BUDGET EXPENDITURES (TRA-6)	A-7
A.7	FREQUENCY DISTRIBUTION OF PROJECT-TASK BUDGETS (EXCLUSIVE OF TRA-2)	A-8
A.8	SUMMARY OF PROJECT-TASK COSTS BY TRA	A-9
A.9	SUMMARY OF RESEARCH STUDY TYPES	A-10
A.10	SUMMARY OF END PROJECT TYPES	A-11
A.11	RESEARCH TOPICS NOT INCLUDED IN SHRP	A-13

ABSTRACT

The five-year STRATEGIC HIGHWAY RESEARCH PROGRAM (SHRP) is to be one of the most comprehensive highway research programs undertaken in the United States. SHRP is a highly focused, specially funded program that concentrates on six critical areas within pavements and bridges: asphalt, long-term pavement performance, maintenance effectiveness, protection of bridge components, cement and concrete, and snow and ice control.

The primary function of SHRP is to concentrate highly innovative research approaches to achieve significant gains in a few specific areas of highway technology rather than incremental research advances in many areas.

This report provides a general overview of the all-inclusive SHRP research plan that was completed early in 1986 under the general guidance of the American Association of State Highway and Transportation Officials and the Federal Highway Administration. It provides information relative to the details of the technical research plans developed for each of the six areas, management and organizational considerations of a central SHRP organization under the National Research Council, and comments on several major program issues critical to the eventual success of SHRP.

ACKNOWLEDGEMENTS

This report was performed under NCHRP Project 20-20 by the University of Maryland Transportation Studies Center. The principal investigator of this study was Mr. L. K. Bridwell, Director, at the University of Maryland's Transportation Studies Center. The co-principal investigator was Dr. M. W. Witczak, Professor, Civil Engineering, also of the University of Maryland. Both investigators were assisted by, and are grateful to, Dr. G. Rada of the University staff.

Above all, the principal investigators gratefully acknowledge the assistance provided by the Strategic Highway Research Program (SHRP) staff (Mr. L. G. Byrd and Mr. R.A. McComb), the SHRP Task Force (chaired by Mr. T.D. Larson), and the Overview and Integration Advisory Committee (chaired by Mr. J. Clements). In this connection, special thanks are also due to the timely efforts and cooperation of the six technical research contractors, their advisory groups, and all other individuals whose contributions have directly shaped and led to the development of the national SHRP plan. The overall guidance, encouragement, and planning assistance provided by members of the Transportation Research Board, the National Cooperative Highway Research Program, the American Association of State Highway and Transportation Officials, and the Federal Highway Administration staffs should not be overlooked in this effort. Finally, special mention needs to be made of the liberal use of numerous documents within this report that were generated by the several individuals, committees, and agencies involved in the SHRP effort. Sincere appreciation is expressed to these individuals for their development of the information used in this report.

SECTION 1
OVERVIEW

BACKGROUND

The deterioration of the nation's highway and bridge infrastructure has received intensive public and private attention and concern in recent years, and significant action has been taken at the Federal and State levels of government to address the problems through increased financial and other resources.

The Transportation Research Board (TRB) of the National Research Council, under sponsorship of the Federal Highway Administration and with the cooperation of the American Association of State Highway and Transportation Officials (AASHTO) undertook a thorough and probing study of the extent to which expanded research and development could make major contributions to improving highway transportation.

The study recommended that a Strategic Highway Research Program (SHRP) be initiated to focus on this problem. The SHRP concept was originally proposed in a TRB report, "America's Highways: Accelerating the Search for Innovation," published in 1984. The report recommended a $150 million, five-year program of research focused on six high priority areas where the United States expends most of the $50 billion that are spent on highways each year.

TRB Special Report 202 proposed that six technical research areas be given emphasis within the SHRP study. The technical research areas (TRA) were:

TRA 1. Asphalt Characteristics

TRA 2. Long-Term Pavement Performance

TRA 3. Maintenance Cost Effectiveness

TRA 4. Concrete Bridge Component Protection

TRA 5. Cement and Concrete

TRA 6. Snow and Ice Control

Table 1.1 (originally published in TRB Special Report 202) presents an overview of the proposed SHRP study by research area in terms of the major area objective, preliminary 5-year budget, and potential results of the effort.

PROGRAM DEVELOPMENT

The final development of the SHRP research and management plan was accomplished by an efficient and timely process. The recommendations provided in TRB Special Report 202 to initiate a Strategic Highway Research Program were approved by the Policy Committee of the American Association of State Highway and Transportation Officials (AASHTO) in July 1984. The office of the SHRP Interim Director was established in October 1984, and plans were also set in motion to implement SHRP under the guidance of a special Task Force.

TABLE 1.1

OVERVIEW OF PROPOSED STRATEGIC HIGHWAY RESEARCH STUDY

Research Area	Objective	Projected 5-Year Costs ($ million)	Potential Results
Asphaltic materials	Define Chemical and physical characteristics of asphalt and their relationship to performance in pavement systems.	50	Better quality control and better materials; and improved design capability and performance predictions. Potential saving of $100 million per year.
Pavement performance	Assess long-term performance of various pavements under various loading and environmental conditions. (Studies would continue for three additional 5-year terms of data collection and analysis.)	50	New capability to assess and select alternative pavement maintenance and rehabilitation strategies; and improved design and construction techniques. Potential saving of $10 billion.
Maintenance cost-effectiveness	Develop improved procedures for administering and controlling maintenance programs; develop new processes, equipment, and materials; and improve productivity of maintenance program.	20	New management systems and increased maintenance productivity. Potential saving of $150 million per year.
Concrete bridge component protection systems	Develop new methods to stop further deterioration of existing chloride-contaminated bridge decks and other components.	10	More effective techniques for removing chloride from concrete or protecting concrete from chloride contamination. Potential saving of $400 million per year.
Cement and concrete	Understand chemical and physical phenomenon of hydration; evaluate new options such as recycled concrete and energy saving components; and develop nondestructive testing methods.	12	Ability to produce a better quality and more durable concrete. Potential saving of $50 million per year.
Chemical control of snow and ice	Reduce the use of salt through management techniques and optimum use of mechanical or thermal removal plus alternative chemicals.	8	Reduction in corrosion and environmental problems without a reduction in the level of service of snow and ice control programs. For example, potential savings from a decrease in automobile corrosion could be $45 million per year.

Under the auspices of the National Cooperative Highway Research Program (NCHRP), six separate SHRP contractors were selected by the SHRP Task Force in early 1985 to develop the specific research plans in the technical areas of asphalt, maintenance, bridge component protection, cement and concrete, and snow and ice control; and a contractor was selected to provide overview and integration. The detailed design of the pavement performance research was already underway by the Federal Highway Administration prior to the onset of SHRP activity. This technical area was directly integrated into the overall program.

In addition, an Advisory Committee appointed by the Task Force was created to assist each of the seven contractors (overview plus six TRAs). Each committee was composed of approximately 30 people, and represented a broad range of research organizations, including public and private institutions, academia, and industry. The front section of this report contains information regarding the contractors.

During the development of the detailed research program,in each TRA several advisory group meetings were held to assist the research contractor. In addition, a National SHRP Workshop was held in Dallas during September 1985 to provide a preview of the preliminary research plans that were developing within each TRA. Both U.S. and foreign professionals were invited to the workshop. The second broad introduction of the developing SHRP effort occurred at the January 1986 Annual Meeting of the Transportation Research Board in Washington, D.C. At this meeting, detailed presentations and discussions were held along with a specially developed program to increase the foreign technical community's awareness of the SHRP study.

The individual TRA research plans were finalized by February 1986 and presented to the SHRP Task Force for approval.

Paralleling the efforts of the individual research contractors, and their advisory groups, the SHRP Task Force and the national workshops and meetings, several subcommittee groups were formed by SHRP to address key topics affecting the overall SHRP planning effort. The major subcommittees formed were: Data Management, Innovation, Instrumentation, and SHRP Organization and Management.

As can be observed, the planning and development of SHRP was based on the involvement of hundreds of interested and knowledgeable highway professionals. Because of this aspect, the program has a true national input and reflects the critical review and support of the highway community.

UNIQUENESS OF SHRP

One very important concept of SHRP is that it possesses a unique role within the overall research efforts historically and currently underway in the United States. As a cohesive research program, it is unparalleled in that:

- SHRP is a specially funded program focused on a few critical, high-payoff technical areas of innovation.

- SHRP has a well defined time period of 5 years for research to be accomplished.

- SHRP is intended to supplement existing programs and must not be viewed as a competing research program.

- SHRP is primarily accomplishment-oriented and intended to develop significant gains in a few specific areas of highway technology rather than incremental research advances in many areas.

SPECIAL CHALLENGES OF SHRP

Because of the uniqueness of the proposed SHRP effort, the program carries with it a complex set of special challenges that must be continuously stressed during the program. Among the most important of these elements are:

- The research must be product-oriented.

- Implementation of the research findings must occur in a rapid manner by the professional highway community.

- The technical and administrative management of SHRP will be a complex endeavor requiring the most effective management and communication tools available.

- Innovation, and its accompanying high risk potential, must become an integral part of the SHRP effort, if the program is to be successful.

- The professional highway community must be receptive to the use of new materials, methods, equipment, and concepts developed within the SHRP effort. While risks are an inherent part of any research implementation program, the potential benefits associated with cost savings must become the salient decision criteria for use of the SHRP research results.

- Finally, the key challenge of SHRP lies in its goal to develop significant technology advances in six unique technical areas.

SUMMARY OF PROGRAM CHARACTERISTICS

Major characteristics of the overall program are summarized to highlight the salient aspects deemed important to the eventual success of SHRP.

Program Overview

- The Strategic Highway Research Program is a highly focused, specially funded 5-year research effort investigating six critical areas of pavement research: Asphalt, Long-Term Pavement Performance, Maintenance Effectiveness, Concrete Bridge Component Protection, Cement and Concrete, and Snow and Ice Control.

- The Strategic Highway Research Program is a high payoff, goal-oriented program that is expected to result in sizeable economic benefits and savings to the highway industry.

Research Plan

- The total SHRP budget (research plus administration and management) is estimated to be in the range of $160 to $170 million over a 6-year time frame (includes one additional year for program phase out).

- The overall program will require an estimated 700 professional (research) man-years of effort to complete the research plan developed.

- The program is comprised of 34 major research projects within the 6 technical research areas, having an average cost of about $4 million and an average research duration of about 4 years.

- SHRP research projects are subdivided into 122 separate research tasks, having an average cost of about $1 million with an average duration of about 2.5 years.

- The majority of SHRP research studies are directed toward evaluation, testing (laboratory and field) or equipment and instrumentation development. A smaller number of research efforts deal with state-of-the-art reviews and theoretical (analytical) studies, while planning and implementation are generally absent. The SHRP study plan developed is very consistent with the original goals and objectives established by TRB Special Report 202.

- The SHRP research activities can be categorized as having as end products the development of a new or improved methodology, the development of new or improved equipment and instrumentation, developments in new or improved materials, and advances in communication-computer systems.

Administration and Management

- An analysis of the comprehensive SHRP research plan indicates that the 50th percentile levels of total number of tasks started and total worth of tasks started will occur within the first 10 to 11 months of SHRP. Because of this, the full complement of SHRP administrative and management staff should be in place on or as near as possible to the onset of the SHRP study if the program is to be successfully completed within the proposed 5-year time period.

- Final decisions regarding contract size and scope can only be determined by a detailed examination of individual TRA plans by the program managers and staff. However, it is recommended

that a major criterion of contract size be based on the ability of a contract to have a specific end product or deliverable rather than by an arbitrary contract dollar value.

- The area of contract administration and project management of SHRP is of major importance. Because of the unique characteristics of SHRP (technical focus, time, number, and size of typical contracts), the following groups (units) should work closely together to achieve efficient management: (a) expert advisory teams; (b) TRA division program managers, and (c) contractor research project management teams.

- Even though a well-planned 5-year research plan has been developed, SHRP management must be prepared to provide a flexible and dynamic approach to the research program. Periodic reviews and continuous monitoring of research studies must be done to determine whether or not various studies should be continued, terminated, or modified.

- SHRP management must ensure that the contract award and selection process allow for the response to RFPs by all possible qualified researchers and research organizations. In order for SHRP to develop a quality program, input and response from private industry, individuals, private and federal research institutes, transportation study centers, university researchers, and consulting engineering companies must be mobilized.

- Detailed planning, coordination, and interaction must continue to better define the potential use of LTPP pavement sections by all other TRA study areas (particularly TRA-1, TRA-3, and TRA-5). This can be accomplished by TRA division program managers in SHRP with coordination between contract agencies doing research work.

- It is clearly recognized that not all SHRP field testing studies can, nor should, be conducted using LTPP pavement sections. This is primarily due to potential scheduling-time conflicts within TRA research plans or the need to identify pavements or materials having characteristics and attributes not common to LTPP objectives. Nonetheless, wherever possible, all non-TRA-2 groups conducting or contemplating field studies should try to interact and use LTPP sections. This will ensure maximum interaction, the greatest potential for research success, and optimum benefits at minimum cost.

Key Considerations

- SHRP has been developed to produce highly implementable highway research results such as new or improved methodologies, equipment, materials or tests.

- Implementation of research findings can best be accomplished by top level management commitment and communications, demonstration projects, private sector involvement, development of standard documents and manuals, technology transfer programs, SHRP publications, and national SHRP conferences. The FHWA Office of Implementation and the technology transfer (T^2) program of that agency offer valuable experience and qualifications to assist in implementation of SHRP research findings.

- International involvement in SHRP should be encouraged to the fullest extent possible. Some ways in which this can be accomplished are to: (1) seek international staff on a loaned basis, to work with SHRP management; (2) have international representation on various advisory groups and teams that will be developed in SHRP; (3) ascertain the willingness to place some LTPP sections within other countries; (4) actively promote the idea of developing satellite SHRP studies; (5) encourage countries having their own major field performance studies to consider the use of SHRP standardized data collection guidelines so that a broader geographical and technological data base can be developed (this would be helpful to extend pavement performance prediction result); and (6) actively encourage international participation at SHRP meetings and conferences and request cooperation in reviews and evaluations of SHRP research results as they are developed and become available.

- Innovation is a key element in the eventual success of SHRP and must be encouraged by management throughout the program. While innovative ideas and approaches may have high associated risk, the potential for high benefits and payoffs is consistent with the SHRP philosophy.

- The SHRP Executive Committee should consider the possibility of creating special earmarked funds (of nominal proportions) from the program specifically geared to fostering innovative research studies.

- Though the SHRP research program has been developed within the framework of individual TRA research plans, several of the research studies proposed will be of significant interest and assistance to the researchers in other SHRP TRAs. SHRP management should develop a dynamic data management plan to provide for technology coordination and interaction as quickly as it is developed in the program.

- All data management capabilities for all SHRP activities should be centrally controlled within the SHRP organizational unit.

SECTION 2
RESEARCH DESIGN SUMMARY

RESEARCH OVERVIEW

The following sections present an overview of the SHRP research plan. Each major SHRP research project is described along with the specific study objective associated with each of the six technical areas.

TRA 1. Asphalt Characteristics

The Problem. A fundamental and widely used material in highway construction and maintenance is asphalt, a product derived from crude oil. Highway agencies spend $10 billion per year on asphalt pavements. Recent years have also witnessed increasing numbers of larger and heavier trucks operating on the highways. There have been growing demands on pavement durability, and more premature or unexpected pavement failures involving asphalt materials have been occurring. Furthermore, some of the physical specifications and tests to classify asphalt and ensure the quality control are more than 70 years old and require reassessment in terms of today's needs and current technology.

Objectives. The goal of the research area is to improve pavement performance through increased understanding of the chemical and physical properties of asphalt cements and asphaltic concretes. The research results would be used to develop specifications, tests, and construction procedures needed to achieve and control pavement performance.

SHRP proposes to achieve major breakthroughs in the understanding of how the chemical and physical properties of asphalt relate to performance, and ultimately to develop performance-based specifications for significantly improved asphalt and asphalt-aggregate mixtures.

The asphalt program proposes that work be done under five major research tasks.

Project 1-1 Asphalt Properties: This project will address the fundamental aspects of chemical and physical properties, their interrelationships, and the interaction between asphalt and aggregate. The information will create an extensive data base needed to (1) relate asphalt chemical compositions and physical properties and pavement performance; (2) develop new test methods relevant to asphalt properties; (3) improve asphalt quality; (4) provide information for preparing performance-based specifications; and (5) provide tools for diagnosing the role of asphalt in pavement performance.

There are up to 200 crude sources of asphalt used in the United States, produced to comply with a variety of regional and agency specifications. SHRP will conduct an industry-wide survey to identify asphalt refining processes and obtain samples representing key refining practices and major sources of crude oil.

SHRP will perform a broad variety of tests on a large set of asphalt samples to develop a data base that describes the physical and chemical

properties. Many of the tests will use procedures involving state-of-the-art methods of quantitative chemical analysis.

In addition, considerable attention will be given to improving methods for testing asphalt, from tests of asphaltic binder properties through every other stage of the paving process, including nondestructive tests of completed pavements. Special emphasis will be placed on improving testing methods to measure fracture properties; to determine how long-term aging, both oxidative and steric hardening, affect physical properties; to devise for field use new methods to measure and calculate the physical properties of asphalt in a pavement through nondestructive testing; and to develop tests to characterize the significant performance properties of recycled asphalt when combined with soft asphalts, recycling agents, or emulsions as in cold mix recycling.

Part of this research will be devoted to developing asphalt additives or modifiers that produce more cost-effective asphalt-aggregate mixtures that have desirable properties for use in pavements. Important properties to be achieved from the use of additives or modifiers are durability, adhesion, temperature sensitivity, resistance to permanent deformation, flexibility, and resistance to cracking due to temperature, weather, and traffic. This project will investigate such asphalt additives or modifiers as minerals, elastomers, plastics, oxidants, antioxidants, hydrocarbons, surface active agents, and recycled crumb rubber. The desired end products are dense-graded asphaltic concrete for surface and for base courses.

Project 1-2 Performance-Based Testing and Measuring Systems: This project will identify and develop standardized testing and measuring systems to define the chemical and physical properties of asphalts. Tests that correlate well with pavement performance and are useful for acceptance specifications will be identified.

Project 1-3 Models to Predict Pavement Performance: The primary objectives of this research project will be to develop asphalt pavement performance prediction models. Empirical models or mechanistic-empirical models will be calibrated to field performance, and evaluated through additional field observations. Interrelationships between asphalt properties and asphaltic concrete mixture properties will be established. For example, measures of asphalt stress, strain, or deformation will be compared to performance of pavements subject to traffic and environmental stress and other factors. A typical model might relate the number of load repetitions before a specified amount of cracking occurred to various material properties or observed strains. Such models will be recalibrated, as necessary, to reflect the results of the long-term pavement performance study and the testing of asphalt samples, collected from around the country. Models will be developed for three types of distress: (1) rutting, (2) fatigue cracking, and (3) low temperature cracking. Also sought is a model of permanent deformation. Prediction models will be required to reflect the influence of the physiochemical properties of asphalt as well as the properties of the asphalt-aggregate system. The research will include preparation of guidelines for state highway agencies to maintain and update performance prediction models and to modify specification requirements.

Project 1-4 Preparation of Performance-Based Specifications and an Asphalt-Aggregate Mixture Analysis System: The asphalt research program will culminate in the preparation of performance-based specifications for asphalt and recommendations for an asphalt-aggregate mixture analysis system using modified or unmodified asphalts.

Project 1-5 Coordination: Because of the magnitude of the asphalt research project, a separate project is planned to coordinate the different tasks; establish and operate a materials reference library; coordinate the statistical design of each research activity and the selection and distribution of testing materials; evaluate the economic consequences of the research findings; and assemble implementation packages suitable for user agencies in employing the research findings.

TRA 2. Long-Term Pavement Performance

The Problem. Our nation will spend about $400 billion replacing and rehabilitating pavements before the end of the century. Despite these immense projected expenditures, no comprehensive research on long-term pavement performance has been conducted since the accelerated AASHO Road Test a quarter of a century ago.

The Long-Term Pavement Performance (LTPP) program embraces the total range of pavement information needs. It draws on technical knowledge of pavements presently available and seeks to develop models that will better explain how pavements perform. It also seeks to gain knowledge of the specific effects on pavement performance of various design features, traffic and environment, use of various materials, construction quality, and maintenance practices.

In years to come, as sufficient data become available, "Analysis" is expected to be conducted by numerous interested agencies. The LTPP products are expected to include better predictive models for use in design and pavement management, much better understanding of the effects of many variables on pavement performance, and new techniques for design and construction. These improved "tools" are then expected to result in Improved Pavement Management.

Objectives. The specific objectives developed for the LTPP program are:

1. Evaluate existing design methods.
2. Develop improved design methodologies and strategies for the rehabilitation of existing pavements.
3. Develop improved design equations for new and reconstructed pavements.
4. Determine the effects of (a) loading, (b) environment, (c) material properties and variability, (d) construction quality, and (e) maintenance levels on pavement distress and performance.
5. Determine the effects of specific design features on pavement performance.

6. Establish a national long-term pavement data base to support SHRP objectives and future needs.

The LTPP Study Program. The LTPP study program has three potential types of studies. These include General Pavement Studies (GPS), Specific Pavement Studies (SPS), and Accelerated Pavement Testing (APT). The General Pavement Studies involve a very large experiment that embraces an array of site selection factors expected to produce a broad range of products and results. The Specific Pavement Studies will have their own set of more limited goals, construction needs, and experimental approaches; and are generally aimed at more intensive studies of a few independent variables for each of a number of study topics. The other category of studies, which is to be considered for future adoption, is the Accelerated Pavement Testing Program. The APT could include either road tests (not under consideration) or an accelerated loading facility (ALF).

General Pavement Studies (GPS): The primary goal of the GPS is to structure an experiment, using primarily existing inservice pavement sections that have a suitable range of characteristics to develop a national data base needed to meet the objectives of LTPP. This is done by identifying major factors of known significance (such as environment, pavement type, traffic) and suitable levels (or magnitudes), and combining them into a factorial experiment. These factors are used in selecting test sections so that suitable representation of the significant characteristics and their effects on performance are attained.

The first and most obvious factor considered is type of pavement. For practical reasons, it is necessary to develop and analyze separate factorial experiments for each type of pavement considered. For budgetary reasons, the number of pavement types is limited to five "original pavement types" (pavements in their first performance period) and four rehabilitation techniques. Each of the nine types of pavements is considered to be an individual experiment, and a detailed experimental design was developed for each one.

The experimental design approach adopted is a tiered factorial approach. For each pavement type, the key factors of traffic, climate (moisture and temperature), and subgrade soil were selected in common for the primary tier factorial. Traffic was divided into medium and high levels. Climate was divided into "freeze" and "non-freeze" temperature levels and "wet" and "dry" moisture levels. Subgrade soil was divided into "coarse" and "fine-grained" soils. Thus, pavements located in any one of these 16 primary tier cells have approximately the same traffic, climate, and subgrade soil. These four factors basically describe the forces that act on a pavement structure in a given geographic location.

A secondary tier factorial experimental design is then set up in each primary tier cell by selecting the factors that are of greatest concern for that particular pavement type and selecting factor levels that are most relevant to it. The tiered approach was selected because it provides maximum flexibility for analyzing all or portions of the data, and thus will be responsive to the specific needs and resources available in a given geographic area.

It is important to remember that the major factors described above are those for which characteristics are to be enforced during site selection. The actual data collected for test sections selected and implemented in the study will include dozens of data elements for each test section, including all of those believed to significantly affect performance.

Specific Pavement Studies (SPS): The specific pavement studies are generally limited factorials for very intensive studies of the effects of a few factors. The highway sections will be specifically designed and constructed through a cooperative effort with interested State Highway Agencies (SHAs), frequently with the test sections collocated to ensure the same subgrade, climate, and traffic. However, some studies may use existing pavements. The factorial experiments for these topics have been developed.

Accelerated Load Testing: The Accelerated Loading Facility (ALF) at the FHWA is a mobile test facility that may be used on existing or specially constructed pavements. It applies dual truck tire wheel loads ranging from 9,000 to 22,500 lb at a rate of approximately 8,500 load applications per day over a test pavement length of 30 ft in one direction. An individual testing sequence or experiment will last from 4 to 6 months.

Data Collection and Management: The data items recommended for collection are considered in two broad categories. The first is basic inventory data, which include those items that remain constant over the monitoring period. The second is monitoring data, which include those items that will change with time and will require periodic measurements or updating during the monitoring period.

The basic inventory data include that data necessary to: (1) identify the test section, (2) describe the geometric details of its construction and the material properties of its structural constituents, (3) describe the environment in which the pavement test section exists, (4) identify the accumulated traffic and axle-load data prior to the long-term monitoring effort, (5) identify previous maintenance activities, (6) identify previous resurfacing or rehabilitation, and (7) identify construction costs and costs of maintenance and repair prior to the long-term monitoring effort. All of this data should remain constant throughout the monitoring period unless the pavement is resurfaced or rehabilitated.

The monitoring data include: (1) distress, serviceability, and skid measurements; (2) traffic and axle load data; (3) skid testing results; (4) deflection testing results; (5) identification of pavement maintenance and its costs; and (6) identification of restoration and rehabilitation and their costs during the monitoring year. These data are to be collected on a periodic basis (expected to vary from continuous collection of traffic data to perhaps once every year for deflections) to provide a historical data base for developing relationships between distress, performance, traffic and axle loads, age, maintenance, and costs.

One of the strong points of the conclusions emanating from the pilot studies and meetings in the past 4 years relative to long-term monitoring of pavements has been the necessity for uniformity and consistency in data

collection. This means careful training of data collection personnel nationwide, use of essentially identical procedures and equipment, and close quality control on data collection activities.

State-of-the-art automated data collection equipment will be used. This is expected to include the following:

- Automated photographic collection of distress data with simultaneous direct measurement of rutting.
- Use of some type of profilometer rather than a response-type roughness meter.
- Deflection measurements made with the falling weight deflectometer.
- Use of new equipment at greatly reduced costs being developed for traffic counting, vehicle classification, and weighing axles in motion.

It is expected that numerous permanently-installed induction loop systems with telemetry tied to central data control will be used for vehicle classification and counting. Promising and economical weigh-in-motion (WIM) systems using piezoelectric cables or capacitance strips are expected by 1988, and will be installed when available. Their installation will provide both automatic vehicle classification (AVC) and axle weight measurements for each GPS test section and each SPS location. The AVC/WIM equipment purchase may be shared between SHRP and the state highway agencies, but this equipment will be operated by the state highway agencies as part of their traffic monitoring activities.

Coring and boring of all test sections will be performed by SHRP contractors. The material testing on these samples will include relatively sophisticated tests to measure resilient moduli of pavement layers. Both the material sampling and testing will be accomplished by SHRP regional contractors, while the SHAs will be requested to provide traffic control during coring and boring operations. As a portion of a structured experiment, some coring and testing of materials will be conducted periodically.

Data Analysis. The usual products or results gained from analysis of any data base are equations that describe the relationships among various data elements in the data base. In this case, dependent variables in the equation will generally be major distress or performance measures, and the independent variables will be the data elements whose variations have significant effects on the dependent variables. These independent variables will include material characteristics, environmental data, traffic data, pavement structure data, and so on. Such equations may be used in pavement management systems to predict the deterioration of pavements and to select rehabilitation or repair strategies. They may be modified to design equations or transformed into nomographs for design of original pavements or overlays.

Other information of importance may be obtained somewhat more directly to indicate which rehabilitation techniques perform best and are more cost-effective in terms of performance and relative cost. Similar information

may be gained pertinent to performance versus maintenance levels or versus quality control during construction.

The overall expectation from the improved predictive equations, improved design procedures, and additional insight gained with respect to pavement performance is anticipated to be better pavement performance at a lesser cost.

TRA 3. Maintenance Cost Effectiveness

The Problem. State and local highway maintenance expenditures throughout the country total approximately $18 billion in 1985. In addition, there are other maintenance costs that have not been quantified in dollars, including the approximately 500 maintenance workers killed each year in work-related accidents and a considerable number of environmental impacts.

Objectives. The objectives of this study are to develop elements of pavement maintenance management systems, which establish budgets, administer programs, and allocate resources more efficiently. In addition, the development of equipment, materials, and processes that will increase productivity and reduce service life costs of pavement maintenance are also sought.

Project 3-1 Quantifying Pavement Maintenance Effectiveness: This project concerns the need to understand maintenance treatment effectiveness in terms of pavement condition improvement and extended life. The study will parallel and be coordinated with the long-term pavement performance study over 5 years. This scientifically designed study will create a data base to evaluate the effectiveness of four flexible pavement maintenance treatments and two rigid pavement treatments. The project will generate a data base that includes environmental, traffic, extensive pavement characterization, and performance data. The end product will be an understanding of the maintenance effectiveness of six specific pavement treatments, plus a study guide to be used by highway agencies in evaluating other maintenance treatments.

Project 3-2 Measuring Systems and Instrumentation for Evaluating Pavement Maintenance Effectiveness: This project was created to help highway agencies evaluate pavement maintenance effectiveness. Maintenance practices vary widely from one agency to another. The six specific treatments being studied in Project 3-1 cover only a few of the many variations in treatments, conditions, and environments. There remains a need to understand the effectiveness of pavement treatments not studied.

Focus on this problem is made by outlining a study program to develop measuring methods and instrumentation to quantify pavement conditions and the factors that influence pavement conditions. The study will define measurement needs and identify existing equipment, instrumentation, or methods that can be used in the measurement process. When existing technology is deficient, new instruments and processes will be developed. The study will produce specifications for measurement instruments plus standard measurement and data reduction procedures.

Project 3-3 Improved Materials and Equipment for Pavement Surface Repairs and Crack Filling: This project will study the materials, equipment, and procedures used in two prevalent pavement maintenance activities: localized pavement surface repairs (essentially patching), and pavement joint and crack sealing. These activities will be studied for flexible and rigid pavements, urban and rural situations, both low and high traffic volumes, and all climatic conditions. The study is expected to identify a number of new and innovative applications for existing materials and material combinations. Also sought will be existing and new equipment to handle materials more efficiently and, finally, more productive procedures for executing the two pavement maintenance activities.

Project 3-4 Pavement Maintenance Work Zone Systems to Improve Worker and Motorist Safety: This project recognizes that major improvements in pavement maintenance productivity must be complemented with faster and more efficient procedures to install and remove traffic controls. This project will create objective procedures to evaluate both existing and newly developed devices and equipment. Emphasis is placed on developing better barriers, impact attenuators, and warning systems to improve motorist and worker safety. The end products will include specifications on the new materials and devices, plus training guides on improved traffic control installation and removal procedures.

Project 3-5 Media Evaluation and Implementation Research in Highway Maintenance: This project addresses a fundamental concern of the maintenance community, i.e., getting research results used. New and innovative ways to implement research results are wanted. Contemporary communications technology will be examined in depth, and specialists in this technology will interact with the maintenance research consultants for Projects 3-1 through 3-4. Together, they will produce a series of implementation training packages that will have been tested, evaluated, and modified to ensure their effectiveness in reaching the maintenance field organization.

TRA 4. Concrete Bridge Component Protection

The Problem. This $10 million research plan for protection of concrete bridge components comprises four projects that address the needs of protecting in-service reinforced concrete components against damage resulting from corrosion of the steel reinforcement and the need for rehabilitating components already suffering from corrosion-induced distress.

The principal cause of the rapid and premature deterioration of bridge decks is the use of salt in winter maintenance operations. The salt penetrates the concrete and causes corrosion of the embedded reinforcement. Once initiated, corrosion is extremely difficult to arrest. As the steel corrodes, stresses induced by the expanding corrosion product cause spalling of the concrete and result in the potholes familiar to the road user. It is not only bridge decks that have experienced the ravages of corrosion-induced distress, but, in those parts of the country where deicing chemicals are used, chloride ions have penetrated beams, piers, and abutments that are exposed to surface runoff or spray from passing vehicles. Many concrete components in

bridges located in a marine environment have also been penetrated by chloride ions and are exhibiting serious corrosion problems.

Objectives. The overall objectives are to provide methods to protect existing chloride-contaminated concrete components against deterioration and to rehabilitate and protect those components that are already exhibiting corrosion-induced distress.

The key question which must be answered by bridge owners is how and when to protect existing bridges against corrosion to minimize life-cycle costs. Consequently, the final goal will be the development of a decision model that is applicable at the project level and will lead to the most appropriate protective treatment for any structure under an agency's jurisdiction.

Project 4-1 Inspection and Assessment of the Physical Condition of Concrete Structures: This project will develop economic and reliable methods for the inspection and assessment of the existing condition and for predicting the future condition of concrete bridge components. In addition to developing products that can be used by bridge owners to obtain more reliable information on the condition of bridges, the products are also required for the successful completion of the other three projects. In particular, the measurement of the rate of corrosion of embedded reinforcement is required to evaluate materials and procedures developed in both Projects 4-2 and 4-3.

Other procedures such as the detection of delamination in substructure components, and the measurement of chloride content and concrete permeability, also have application with Projects 4-2 and 4-3. Developments such as determining the condition of asphalt-covered deck slabs, the effectiveness of sealers, and the integrity of membranes will be used in Project 4-3, especially in evaluating the service life of existing methods of protection. Project 4-1 will also generate the information for determining the existing condition and predicting the future condition of concrete components that will be required as part of the development of the Time-Deterioration Model in Project 4-4.

Project 4-2 Protection and Rehabilitation by Electrochemical Methods: This project will explore two categories of electrochemical treatment for protecting existing concrete bridge components against corrosion. The first is electrochemical removal or displacement of chloride ions. Currently, no practical method exists to remove chloride ions from contaminated concrete or to ensure that the ions separated from reinforcing steel will not migrate back.

The second part of this project will improve cathodic protection so that it can be applied more easily by highway practitioners in state and local governments. Accordingly, the research on cathodic protection will be heavily field-oriented, concentrating on developing procedures that will gain wider acceptance and use.

Project 4-3 Protection and Rehabilitation by Other than Electrochemical Methods: Conventional, nonelectrochemical methods of protecting contaminated bridge components have unknown life, high cost, long construction times, few options for components other than decks, and no

methods for protecting prestressed concrete components. In addition they are weather-dependent and do not stop corrosion. The principal method used in the past is concrete removal and replacement. This project will pursue research to improve concrete removal, surface preparation techniques, and protection of concrete components once partial or complete removal has occurred; to evaluate the feasibility of altogether new approaches; to develop and evaluate rapid techniques for deck rehabilitation and replacement; and to improve deck joints.

Project 4-4 Methodology for the Protection and Rehabilitation of Existing Bridge Components: This project is designed to bring together the products of Projects 4-1, 4-2, and 4-3 in a single usable form. It will develop a decision model that will be applicable at the project level as opposed to the network level. In other words, it will lead to the selection of the protection strategy that will result in the lowest anticipated life-cycle costs for a specified bridge based on its existing condition and consideration of options for protecting its various components against damage. Project 4-4 has been conceived as a study that will be conducted largely in an office environment and will rely heavily on the products of the other three projects.

TRA 5. Cement and Concrete

The Problem. The highway industry consumes 16 percent of the portland cement used for construction in the United States, and its capital outlay for portland cement runs more than $1 billion annually. The nation's principal arterials, particularly the Interstate system, frequently have a portland cement concrete riding surface. Two-thirds of the short span bridges in the country are built of concrete, and portland cement is also the most commonly used material for curbs, sidewalks, and median dividers.

Despite its long and widespread use, the nature of this material and the process for reproducing it needs further study to enhance performance. Some important aspects of the hydration process remain enigmas. The extent to which residual moisture plays a role in deteriorating processes and weakens the structure of hardened cement paste is not adequately understood. The gains in durability from additives such as fly ash, ground granulated blast-furnace slag, and silica fume have only begun to be examined.

Objectives. The primary goal of the research plan for cement and concrete is to increase service life through an improved understanding of the chemistry of cement hydration, the properties of concrete, and the performance of concrete in the highway environment. Particular attention will be given to improving the understanding of the mechanisms of setting and strength development, and the chemical processes during hydration of the cementitious component. Attention will also concentrate on improving the production, placement, quality control, nondestructive testing, and durability of concrete.

Project 5-1 Chemistry and Physics of Cement and Concrete: Better knowledge of how to control the microstructure and hydration of cement and concrete could help extend the service life of concrete. This project focuses on how the microstructure of fresh cement pastes, the chemistry of hydration of cements and pozzolanic reactions, and the chemistry of deterioration processes each affects the microstructure and properties of hardened cements and concrete.

The research relies on both analytical and empirical approaches. Improved test methods will be sought by replacing empirical relationships, when feasible, with mechanistic mathematical models derived from a correct understanding of the physical process involved. These models will provide testable hypotheses for experimental work and identify the most important characteristic of materials required to control concrete properties. Attention is focused on the effects of hydration and pore structure and the distribution of the hydration reaction rather than the individual hydrated phases.

By increasing the ability to exploit the microstructure of concrete for improved performance, and by determining the mechanisms of chemical deterioration processes and their control, this project will contribute to the development of superior concretes for highways.

Project 5-2 Durability of Concrete: This project will develop means to increase significantly the durability and service life of concrete. Particular attention will be given to minimizing deterioration in pavements due to freezing and thawing, D-cracking, and alkali-silica reactivity, and to determining the moisture gradient in field concrete. It will also explore the mechanism of freeze-thaw damage and develop more definitive information on aggregates and entrained air-void criteria for enhancing durability when using water reducers and supplementary cementitious materials and admixtures. Part of the project will result in improved techniques for guarding against alkali-aggregate reactivity which leads to deleterious expansion and cracking, with a clearer understanding of the role of moisture condition of the concrete as influenced by environmental conditions. If feasible, it will also entail developing a computerized expert system to provide diagnostic capability and solutions to durability problems.

Project 5-3 Quality Control and Condition Analysis Through Nondestructive Testing: Nondestructive testing can play a significant role in improving quality control during construction. Such techniques can also be useful in evaluating the condition of existing structures, thus enabling necessary remedial measures to be taken. This project will develop a quality assurance system for acceptance, form stripping, and placing in service based on existing and newly developed nondestructive tests. It will also develop an in-place permeability test for hardened concrete, and a test method apparatus to determine the characteristics of the entrained air void system in freshly mixed concrete to facilitate acceptance or rejection before placement. In addition, it will develop a means for determining the residual functional capability of a pavement.

Project 5-4 Mechanical Behavior of Concrete: The mechanical behavior of concrete during its exposure to traffic loads plays an important role in the performance of the pavement system. While much is known regarding the mechanical behavior of most present-day concretes, relatively new developments in concrete technology may be of significance in improving the function and durability of pavement systems. Finely divided materials, such as fly ash, ground granulated blast-furnace slag, silica fume, and other cementing materials, play an increasingly important role in enhancing durability. Fiber reinforcement assists in mitigating cracking problems, and high strength concrete allows for longer span bridges. To use these materials

properly requires more information on the mechanical properties of such concretes. This project will explore the fatigue resistance and strain capacity of high-strength concrete subjected to repetitive loading. It will evaluate the properties of quickly setting high-strength concrete and the influence of fly ash, ground granulated blast-furnace slag, silica fume, and other cementing materials on the structural properties. It will also assess the effect of random fiber reinforcement, including combinations of different fibers, on structural properties.

TRA 6. Snow and Ice Control

The Problem. While elimination of snow and ice makes roads safer for motorists, the widespread use of salt has aggravated the deterioration of highways and bridges, especially those containing steel support. It causes motor vehicles to rust and poses an environmental hazard, particularly near some roadsides where concentrations are exceptionally high. Snow and ice removal is also expensive; equipment and labor costs of winter maintenance programs exceed $1 billion each year.

Objectives. The objective of this study area is to provide more cost-effective ways to remove the buildup of snow and ice on highways and streets during winter conditions; reduce deterioration of bridges, pavements, and vehicles; and mitigate adverse environmental consequences of snow and ice control.

Project 6-1 Prevention of Ice-Pavement Bond: Ice and refrozen compacted snow form an exceedingly tenacious bond to asphalt and portland cement concrete pavements. The nature of this bond and the mechanisms by which it develops are not clearly understood.

Research on the fundamental chemical and physical structure and mechanics of bond formation may provide a basis for developing techniques and devices for interfering with or preventing bond formation without adversely affecting pavement properties such as friction. This project will explore chemical modification of the surface by incorporating chemicals into the pavement itself and through physical methods of surface modification, such as icephobic material.

Project 6-2 Destruction of Ice-Pavement Bond: Most present techniques depend on destroying the bond once it has formed. By pursuing approaches of bond destruction as opposed to the prevention of bonding, there appears to be greater probability of success in developing new techniques, materials, and equipment to make significant improvements in ice removal. Key research tasks include fundamental studies of ice-substrate bond; physical surface modification (such as deformable or sacrificial surfaces); noncontact disbonding (e.g., microwave and laser radiation); contact disbonding (e.g., mechanical cutting, breaking, lifting); evaluation methodologies for deicing chemicals; and improvements of sodium chloride as a deicer.

Project 6-3 Development of Improved Displacement Plows: Plows have evolved empirically with scant attention paid to the physical properties of the material being handled and with little consideration given to the aerodynamic and hydrodynamic principles involved in the flow of fluidized snow. As a consequence, the energy expended in displacing snow is

disproportionate to the work performed. The cast distance requires unnecessary rehandling of snow, and the lack of standardization increases the costs highway agencies incur.

This project will establish design criteria and prepare design details and specifications for displacement plow systems based on aerodynamic and hydrodynamic principles, material handling characteristics of snow, and ice cutting mechanics. The project will lead to standard designs for plows for different types of snow and climatic conditions.

Project 6-4 Improved Methods of Controlling Blowing Snow: Snow fences and other means of reducing the amount of snow reaching a roadway help cut the costs of snow clearance, reduce the potential for formation of compacted snow, and reduce the need for chemicals. The study will develop criteria for properly designed snow fences and their proper location, and control wind-blown snow.

Considerable progress has been made in the engineering design of snow fences over the last few years; yet, more remains to be done to increase their effectiveness in a diversity of conditions. It may be possible to improve the effectiveness of snow fences through research on free-turbulent mixing in the vicinity of barriers to allow prediction of surface shear stress. Improper design of roads, overpasses, guardrails, and vegetation creates many severe drifting situations that could be avoided if information on better design were available.

Project 6-5 Management of Snow and Ice Control Operations: Snow and ice control is the single most costly maintenance function performed by many northern states and cities. Staffing levels and equipment specifications are very often based on winter maintenance functions and affect all other seasonal activities. Many maintenance management activities have been improved by research, but winter maintenance has not received adequate attention. This study will develop management guidelines to assist maintenance managers in finding efficient techniques to use in their snow and ice control operations.

SECTION 3
SHRP ORGANIZATION AND MANAGEMENT

INTRODUCTION

One vital factor in the success of SHRP is the organization and management structure developed to monitor and administer the overall research effort. The basic mission of this organization is clear in that it must ensure that usable products and processes are the ultimate result of SHRP.

The following sections of this report deal with recommendations for SHRP management. Although specifics are noted for this plan, it is important to recognize that the final plan will (and should) be dynamic in nature. Management must be alert to the need for future changes, stay flexible, and be ready to respond when required in a timely fashion.

From a planning viewpoint, the Strategic Highway Research Program should be viewed as being comprised of two distinct phases of management. They are:

1. Pre-Implementation Phase
2. Operational Phase

The Pre-Implementation Phase is completed with this overview report and the technical research area reports that provide the specifics of the research plan. The generalities associated with the planning and organizational make-up for this phase have been briefly described in Section 1 of the overview report.

Phase 2, the Operational Phase, begins with the processes leading to research contracts.

OPERATIONAL PHASE

Conceptual Organization

It is envisioned that there will be 9 major organizational units in the SHRP management structure. These are:

- National Research Council
- SHRP Executive Committee
- SHRP Executive Management Staff
- Technical Research Area Staff
- Loaned Professionals
- Data Management Staff
- Information Transfer Staff

- Expert Advisory Teams
- Contractor Project Managers

In general, the first three units will be responsible for setting policy and guidelines, and for enforcing the success of SHRP.

The suggested functions of each of the units are described in more detail.

Functions

National Research Council. The Strategic Highway Research Program will be administered as a new operating unit of the National Research Council.

SHRP Executive Committee. The SHRP Executive Committee will be comprised of approximately 15 executives or professionals from industry, government and the academic community. AASHTO, FHWA, and TRB will be represented in an ex-officio capacity. Several major functions of this Executive Committee will be to:

- Provide major policy guidance for the entire program.
- Provide oversight guidance to the technical program as it evolves.
- Provide recommendations to the NRC concerning approval of all contract research agencies and SHRP management subcontractors selected.
- Provide recommendations concerning whether or not research contracts should be continued, modified, or terminated during the progress of SHRP.

SHRP Executive Management Personnel. The SHRP executive headquarters will have the responsibility for the day-to-day SHRP technical and contract management and monitoring. It should include an Executive Director with two Deputy Directors (or Managers): one for technical operations and the other for administrative matters. Sufficient clerical and secretarial support should be provided for each of the three SHRP officers noted. The specific functions of this unit should be to:

- Operate under established policies and directives of the NRC and SHRP Executive Committee.
- Be responsible for administrative matters and technical oversight of the program.
- Ensure that the SHRP technical research objectives are accomplished in a timely manner.
- Be responsible for overviewing and operating the SHRP data management process.

- Ensure the early dissemination of research findings. Optimize the technology transfer and implementation process to the greatest degree possible.

- Provide an environment for innovation throughout the program.

- Ensure maximum research coordination with all other major national highway research programs in process.

Technical Research Area Staff. This organizational unit represents the basic technical research operating arm of SHRP management. Figure 3.1 shows a conceptual breakdown of this area into suggested technical subdivisions. As noted, 4 separate units are recommended for technical and contract monitoring purposes: (a) Long-Term Pavement Performance (TRA-2), (b) Asphalt (TRA-1), (c) Concrete (TRA-4 and TRA-5), and (d) Operations (TRA-3 and TRA-6). This organizational structure can permit technical interaction and minimize overlaps.

The specific functions of the technical research area staff will be to:

- Be responsible for the contract administration and monitoring process to include:

  - Preparation of proposal requests and work statements.

  - Negotiation of contracts.

  - Monitoring of contract technical and budget progress.

  - Review of contract agency activities and reports.

- Be responsible for the direct technical oversight of the program.

- Interact with expert advisory personnel and contract project managers concerning project progress.

- Formulate recommendations to information transfer personnel regarding technology transfer, information dissemination, and implementation.

- Provide technical engineering analyses and support to the overall program.

- Ensure that key substantive decision points in the research program are objectively identified, evaluated, and acted upon.

- Anticipate problems in the feasibility or economic viability of implementation, and recommend or make adjustments so that the research program adequately adjusts for such issues.

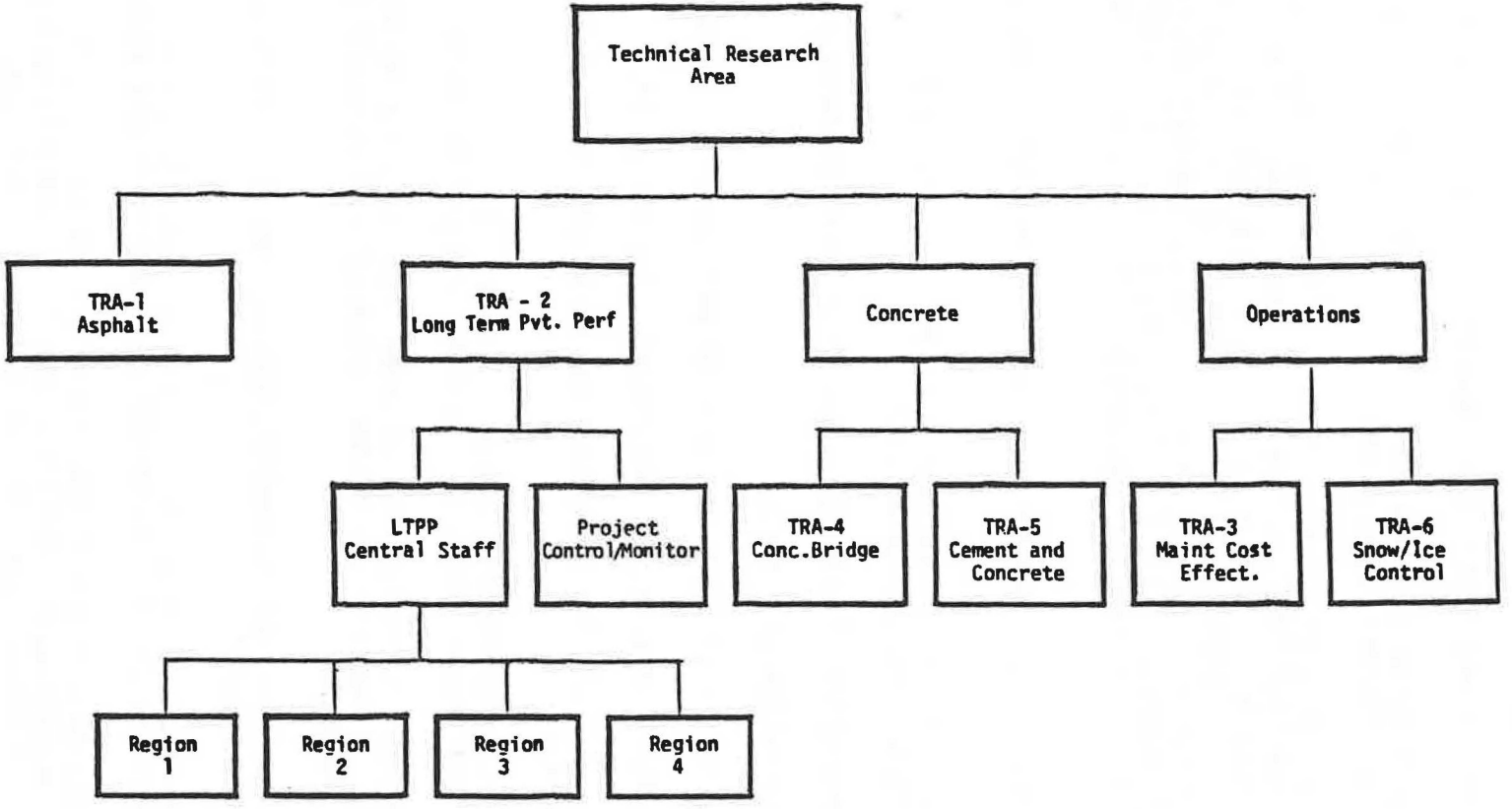


FIGURE 3.1 CONCEPTUAL PLAN FOR TECHNICAL RESEARCH

- Revise working plans as required for the remainder of the program to reflect what has been learned on each area, what unforeseen advances or barriers have emerged, and the progress made in each area.

Loaned Professionals. SHRP offers an opportunity to have "loaned" professional staff become an integral part of the research effort. The main function of these individuals would be to work within the technical research areas.

The use of such professionals has distinct benefits and advantages, not only to SHRP, but to the loaning agencies. Specifically, some of these key benefits are:

- SHRP Benefits

  - Loaned professionals will bring into the program a level of technical expertise that may not be readily available as employed staff.

  - The views and perspectives of the ultimate users of SHRP, represented by loaned staff should strengthen the program.

  - The potential for international and private industry experience, through loaned staff, should add to the program.

  - A potential reduction in program management costs should result from the availability of staff members without salary costs.

- Loaning Agency Benefits

  - The experience and knowledge gained by the loaned professionals from their SHRP efforts should strengthen the programs of lending agencies.

  - Loaned professionals returning to their agencies should provide "seeds of implementation" of the SHRP research results within the agency.

Data Management. Within the overall program, it is anticipated that a wealth of technical data will be generated along with the need to develop and maintain centralized computer data systems for the pavement test sections. Data management personnel must be experienced in data base systems to meet specific requests for information and to access and manipulate all of the technical data that will be assembled. Section 4 of this report provides further details concerning the data management operation. The role of this staff will be to:

- Manage the LTPP data base.

- Manage all other forms of SHRP research data collected within the program.

- Ensure that the system developed can provide:
  - Complete and rapid access to data for all SHRP researchers during the program period.
  - Permanent data bank for all highway researchers after SHRP is concluded.
  - Flexibility in operation to allow continuing use during the 15-year LTPP, post-SHRP period, currently planned for the pavement monitoring scheme.

Information Transfer. The ultimate success of the SHRP effort will depend not only on the research results generated in the program but also on the ability of SHRP management to quickly and effectively communicate major findings to the professional community. In order to accomplish this, the information transfer staff should:

- Be responsible for the rapid transfer of technological advances made through the program.
- Be responsible for the publication and distribution of all reports concerning the program.

Expert Advisors. It is anticipated that the detailed contract development and monitoring phases of SHRP will be a major function of the technical research area. The expert advisory groups should assist SHRP project engineers in this important function. Expert advisory groups should be comprised of a small number of key professionals. Advisors should not be involved in SHRP contract research projects to avoid a conflict of interest. Every effort should be made to select advisory team members, in part, from the original Advisory Committees used in the SHRP Pre-Implementation Phase to maintain the continuity in knowledge gained in the detailed development of the research program. The specific role of expert advisors should be to:

- Assist SHRP technical project monitors in developing RFPs.
- Assist SHRP technical project monitors in formulating recommendations for the selection of the research agency/teams.
- Assist in the periodic review of the technical progress being made on projects.
- Review and recommend disposition of project reports.
- Provide advice and recommendations regarding whether a particular project should be continued, terminated, or modified.
- Provide expert technical assistance to SHRP staff members.

Contractor Project Managers. It is anticipated that, as a general rule, the following conditions will prevail:

- Typical research contracts will be large, multitask technical efforts.
- The research groups will be teams comprised of several organizations.
- Typical contract budget values will be generally in excess of $1 million.

Thus, each agency selected for a contract should be required to develop a project management team to directly interact with the SHRP organization. The specific functions of this team would be to:

- Be responsible for the immediate monitoring of technical and financial management of all subcontractor agencies comprising the research "team" on any given SHRP research contract.
- Report and interact on a regular, frequent basis, with Expert Advisory personnel and SHRP Technical Research Area staff.

SECTION 4
MAJOR PROGRAM CONSIDERATIONS

GENERAL

Sections 2 and 3 of this report have discussed the major elements of the overall research program and SHRP organization and management issues. While these items represent the real operating aspects of SHRP as a viable program, there are several other major considerations that will materially add to the success of the program. These considerations deal with:

- Contract Size and Administration
- Coordination with Non-SHRP Research Program
- User Involvement
- Innovation
- Data Management
- Implementation of Results

CONTRACT SIZE AND ADMINISTRATION

It is not the intent nor within the scope of the overview report to provide recommendations for the specific set of research contracts that should be let by SHRP. This can only be accomplished by a more detailed evaluation of the SHRP plan by SHRP management. Nonetheless, the selection of the relative size of individual contracts as well as the scope of the research contract efforts to be undertaken is a very important decision relative to the success of SHRP as it directly impacts on the level of project management coordination and overview that should be conducted by program managers.

Perhaps the best guideline that can be provided for this topic is to let the contract size be dictated by the need for a unique and specific end product. Although size and budget are important, it is ill-advised to set limits on contract dollar magnitudes as the primary criteria for decisions regarding combining tasks under one contract.

About one-half of the entire SHRP contract administration process (number of contracts and total contract award worth) will have to be accomplished within the first 10 to 11 months of SHRP. Strong consideration should be given to the use of the contractors on the management team to assist SHRP staff.

The final point that should be kept in mind in the contracting process is to ensure that all research organizations and individuals have an opportunity to be considered for participation in this massive research study. In order for SHRP to develop a quality program, input from private industry, individual consultants, federal and private research institutes, university researchers and research centers, and consulting engineering companies must be mobilized.

COORDINATION WITH NON-SHRP RESEARCH

SHRP is a one-time, 5-year program with well-defined goals and objectives. Its development as a unique highway research program is clearly intended to supplement existing research efforts in the six defined technical areas. If SHRP is to successfully achieve technical advances, it is important that on-going research efforts, in similar technical areas, be maintained at their current spending levels rather than reduced over the 5-year operational phase of SHRP. Additionally, there is a need for continuing a strong effort in "soft" research areas that will indirectly strengthen the ultimate objective of SHRP.

Current levels of annual highway research expenditures in the United States are approximately $100 million. The majority of this research stems from on-going programs sponsored by the Federal Highway Administration, and the states using Highway Planning and Research funds and the National Cooperative Highway Research Program.

In addition to ensuring that SHRP research funds are added to the current levels of non-SHRP research, SHRP should interact with research efforts that may have a direct consequence on SHRP projects.

USER INVOLVEMENT

SHRP should provide the opportunity for involvement by a variety of interest groups including state highway and transportation units, the international community, and industry.

State transportation agencies will share a large role with the research contractors particularly in the LTPP (TRA-2) study area. They will furnish pavement inventory data; maintenance, rehabilitation, and reconstruction data; periodic traffic counts and traffic control during field operations; skid resistance measurements; and special pavement sections (SPS).

Strong participation by state personnel within SHRP advisory groups, committees, and the Task Force contributed to the success of SHRP planning efforts. This type of involvement during the operational phase of SHRP should continue.

Every effort should be made by SHRP to encourage and foster international involvement. There are a variety of ways in which this can be accomplished. International engineers should be encouraged to participate as loaned staff within the SHRP management, to serve as observer teams as well as to be active members on various advisory groups and committees.

It may be possible to obtain international cooperation and assistance in the Long-Term Pavement Performance studies. Countries having or planning performance studies should be encouraged to follow the standardized data collection guidelines of SHRP so that performance results can be compared. If economically feasible, a limited number of LTPP sections could be located within another country. If SHRP data collection guidelines are

followed, such information can be entered into the central technical data base. Also, other countries should be encouraged to actively conduct satellite-type SHRP studies.

Private industry can also be a significant contributor to SHRP, through loaned staff or membership on SHRP advisory committees.

INNOVATION

The title of TRB Special Report 202, "America's Highways: Accelerating the Search for Innovation," underscores the projected role of research innovation within SHRP. It is important that SHRP seek innovative solutions to the research tasks defined by the program.

Fostering Innovation

Several factors that may contribute to a more innovative program should be considered.

Qualified researchers for SHRP should not be limited to those who have demonstrated previous extensive research backgrounds in the particular research area. Innovation and technological advances may result from a fresh look at an old problem.

The probability for innovation to take place will be enhanced by the use of multidisciplinary teams. Researchers from a variety of disciplines will tend to complement each other and provide a broader perspective of the whole problem. Likewise, balance within a research group should create an atmosphere conducive to developing new and creative solutions to problems. Thus, a team comprised of a theoretician and practitioner, or people with vastly different technical philosophies on the same subject, may be better able to reach an innovative solution to a problem.

Approaches to Innovation

Several potential ways in which innovation may be encouraged are:

- Allocate special funds for innovative ideas.
- Contracts with incentives.
- Encourage private industry participation.

Consideration should be given to dedicating a modest amount ($2 to $3 million) of SHRP funds for innovative unsolicited proposals that are geared specifically to unique problem solutions. Small initial (pilot) awards could be given to allow researchers to develop more detailed research plans.

The second approach to innovation, contract with incentives, should rely on solicited, but unstructured research proposals. Contractors could propose their own methodology to achieve the objectives. Provisions could be included in contracts promising incentives for successful achievements. This approach could also be used in combination with standard

proposals and would provide a way in which two or more approaches could be compared for the same research task. Such duplication of research may have significant benefits and should be considered in the program.

Encouraging private industry participation may be significant where new instrumentation, equipment, and materials are anticipated. Consideration should be given to the use of SHRP and private funds (perhaps matching funds) to encourage private industry innovation. However, before this approach is used, careful consideration must be given to policies regarding patents, proprietary products, and equipment development and manufacturing licenses.

DATA MANAGEMENT

The development of an effective data management system will be the keystone in expanding, expediting, and assuring the application and use of the knowledge and information developed in SHRP. Necessary communications between research tasks, interactions with external activities, and effective dissemination of program results require proper data management.

Types of Data Considered

To help meet the overall objectives of SHRP, the data base should include the following:

- Technical data from all research areas including LTPP.
- Literature and textual data.
- Business management data.

The above types of data are shown in priority ranking, and they need not all be operational at the start of the program. The data management system will evolve and expand as SHRP progresses. In dealing with business management data, the SHRP staff will have the support of the established offices and program assistance capabilities of the National Research Council.

Technical Data Characteristics

The technical data system must have the following attributes:

- Be comprehensive.
- Be available.
- Be permanent.
- Be reliable.
- Be serviceable.

All technical data that support major findings and conclusions must be preserved so that they can be validated, referenced, and expanded upon by subsequent research. Researchers and other users of the system must have easy

and affordable access to the technical data. In addition, the data must be preserved beyond the 5-year SHRP life and beyond the 20-year LTPP life.

Format and Organization

Organization and data format must provide efficient input, storage, manipulation, and access; flexible expansion, revision, and upgrading of hardware; and simple cost control.

While this suggests some type of relational data base format, the final recommendations will depend on decisions regarding the possible use of existing agency capability, private sector participation, or stand-alone arrangements.

Accessibility and Security

The technical data and literature and textual information should be easily accessible to all interested and qualified users. User fees can offset data system operating costs (access and use) and some portion of the set-up and overhead costs. It will be particularly important to have master files that are protected and security measures provided for both access and for file revision.

IMPLEMENTATION OF RESULTS

SHRP represents a major effort on the part of the entire highway industry to bring the best minds, experience, and expertise available to focus on six critical areas of research. All of this effort, however, is of little to no consequence unless implementable results can be integrated into practice in a timely manner. SHRP was planned to produce highly implementable highway research results. Each major SHRP project has, as its goal, a new or improved methodology, equipment or material. Implementable findings should be a natural consequence of the program.

All SHRP research efforts should devote some portion of project activity to providing recommendations as to how best to implement the findings.

FHWA Office of Implementation

SHRP should place heavy reliance on the expertise of the FHWA Implementation Office to assist in timely implementation of SHRP findings within the highway community.

Commitment and Communications

Implementation is never possible without the commitment and conviction of top level management. Executive summary-type reports and publications, furnished at periodic intervals, are useful tools. Periodic "briefings" on the progress of SHRP, should stress the implementation elements that are of direct value and concern to management.

Good communications during the entire 5-year SHRP period (and beyond) should be an integral element of the program to maintain enthusiasm for SHRP across the country.

Demonstration Projects

Demonstration projects, such as will evolve from the LTPP program, are a vital part of the implementation and technology transfer process.

Private Sector Involvement

SHRP should seek the involvement of the private sector in developing new materials and equipment. Involvement by the private sector has two distinct benefits.

- New technology can best be translated into new products in the private sector.
- Private development can continue beyond the SHRP research and and encourage competition in the marketplace.

Standard Documents

A major source of standard documents will be the new methods of testing developed in SHRP (particularly TRA-1 and TRA-5). Wherever possible, these results should be written in a form suitable for adoption by such agencies as ASTM and AASHTO.

Publications and Meetings

The Transportation Research Board can disseminate SHRP findings to the research community and operating agencies through its regular publications, special publications, workshops, and conferences. During the SHRP pre-implementation phase, TRB served as a major source of information through these types of activities. The state field visit program conducted by TRB is another excellent candidate for coordination and dissemination of information.

Technology Transfer Programs

The national network of Technology Transfer Centers for local transportation agencies that have been established throughout the United States provide a useful means of SHRP implementation. In particular, the emphasis of these centers on getting information disseminated close to an employee's work place is especially germane to the SHRP effort.

SHRP Publications

A responsibility of the information transfer staff of SHRP will be the printing and distribution of all SHRP publications. Reports emanating from the SHRP effort can be expected to be of at least three basic types:

- Research contractor technical reports: These reports should be reproduced in limited quantities and should not serve as a basis for officially distributing SHRP results.

- SHRP-approved technical reports: These reports would normally be only of intermediate value to researchers or other technicians.

- Official SHRP reports: These reports should describe the final products, specifications, tests, guidelines and procedures that constitute the output of the research.

While the first two report types are important, the last category noted should be the one that is widely distributed, its contents providing the basis for the eventual transfer of technology to the profession.

National SHRP Conference

Several national SHRP conferences should be held during the program period. These conferences should focus on implementable results obtained in the program.

SECTION 5
ANALYSIS OF RESEARCH PLANS

INTRODUCTION

This section of the report provides an overview of the final recommended Strategic Highway Research Program developed by the pre-implementation study. The detailed research plans for each of the six technical research areas investigated are presented in following parts of this report. They represent the final plans developed by each of the contractors and are as follows:

Technical Research Area

- TRA-1 Asphalt Properties
- TRA-2 Long-Term Pavement Performance
- TRA-3 Maintenance Effectiveness
- TRA-4 Bridge Component Protection
- TRA-5 Cement and Concrete
- TRA-6 Snow and Ice Control

Guidelines for a uniform report organizational style were used in the preparation of each TRA research plan. Thus, the topical headings (main report sections) are uniform for all six TRA research reports. For example, Section 4 "Recommended Research Plan" is consistent for all six individual TRA reports. The reader should become familiar with the report organization style shown in TRA reports for ease of reference relative to the specific details associated with any particular TRA.

Uniformity in the research activity nomenclature was also obtained by use of the following hierarchal descriptions. The overall program is called the Strategic Highway Research Program and designated as SHRP. The technical research areas, designated by TRA, have previously been noted by the terminology; TRA-1 to TRA-6 for each of the six areas. Following the TRA number, the research is divided into projects, tasks, and subtasks (as appropriate). The alpha-numeric system used to delineate a particular research study unit is as follows:

4-2.1, b

This code would identify subtask "b" of task 1, research project 2 of technical research area 4.* Reference to the research plan for TRA-4 indicates that the title of this research effort is "Electrochemical Removal." Where numbers in parentheses are provided after the task number (e.g. 4-2.1(2), b), the number refers to the year of the overall program (SHRP) that the research unit is scheduled to start (i.e., Year 2).

* It is noted that the reader will find in the individual TRA contractor reports some variation in the nomenclature used to designate subtasks. However, context will preclude confusion.

OVERVIEW MODIFICATIONS TO INDIVIDUAL TRA PLANS

One primary function of the overview activity was to assimilate all of the six individual TRA plans into an integrated, comprehensive, national Strategic Highway Research Program. While every attempt was made to use the precise technical and project scheduling and budget estimates developed by each technical research contractor, some alterations to the recommendations provided in these reports were made to develop the overall program.

The modifications made to the technical areas are minimal in nature and associated with one of the following three categories:

- Transfer of a research unit from a TRA to direct control of SHRP Management.
- Transfer of research funds from a TRA to the SHRP Management.
- Change in the recommended project time.

The latter changes were accomplished by an examination of contractor-recommended "float" times in project schedules. Several project periods were changed to obtain as uniform as possible annual research expenditures over the 5-year SHRP period.

The changes made to each of the TRA plans are as follows:

TRA-1 Asphalt

A review of the research plan for TRA-1 led to the transfer of two specific tasks to be placed under the direct control of the SHRP Management groups. These two tasks were:

1-5.1 Research Project Coordination
1-5.5 Implementation Packages

This was accomplished because it was concluded that research functions dealing with coordination and implementation clearly were in keeping with the purpose and objectives of staff within the SHRP management groups. Budget funds totalling $1.4 million ($1.0 million for 1-5.1 and $0.4 million for 1-5.5) were likewise shifted to the SHRP management groups along with the full responsibility for accomplishing these two tasks. The option to perform these tasks through SHRP staff or contract research was retained.

Because all projects and tasks have a fixed start and end time (i.e.,no "float" time), final research unit scheduling was not changed.

TRA-2 Long-Term Pavement Performance

Two modifications were made. The first change was the scheduling of $7.184 million in LTPP contingency funds to be placed within the sixth (or wind-down) year of SHRP. However, where contingency requirements arise, they will be met in the year needed, to the extent that available funds permit.

The second modification involved moving the recommended LTPP central organization (to coordinate, manage, and review the four field regional units) into the SHRP management section (see Section 3). The budgeted funds for this project were $6.876 million for staff, overhead, and equipment. In transferring these funds to SHRP management, the complete responsibility for accomplishing the objective of the project remains intact. Thus, the funds either can be used by SHRP staff directly working on this activity, or they can be used in a contract for the central LTPP organization, or they can be used in a combination of both.

No other modifications to proposed funds, research projects, or scheduling were made for this TRA.

TRA-3 Maintenance Effectiveness

The research schedule used was that corresponding to the proposed yearly budgeting schedule shown in the research plan.

TRA-4 Bridge Component Protection

For TRA-4, the following minor changes were made: For tasks 4-1.9, 4-3.7, 4-4.2, and 4-4.3, start times were changed to all start in the first year.

The duration of these tasks was not changed, and the changes made in scheduling are consistent with the "float time" (earliest possible start time) offered by the TRA contractor. No modifications were made to the proposed budget or to the research schedule recommended in the contractor-developed plan.

TRA-5 Cement and Concrete

The only recommended modification to the research plan proposed for TRA-5 was the shift in scheduling for Task 5-4.2 "Properties of High Early Strength." The task was moved to the first year of the program to reduce SHRP expenditures in years 2,3, and 4 by $50,000 and increase year 1 expenditures by $150,000.

No changes in budget or project transfers were made for this TRA.

TRA-6 Snow and Ice Control

For the Snow and Ice Control TRA, several minor schedule changes in task start time were made to develop a uniform annual research expenditure for SHRP. Tasks 6-1.2, 6-1.3, 6-2.2, 6-2.3, and 6-2.4 were changed from a start time during the middle of year 2 to the beginning of year 3. Task 6-2.7 was modified to have a project start time in year one. All of these changes were within the contractor-recommended "float" times. No other changes in budget or project scheduling were made.

Summary of Modifications

The previously noted changes resulted in a combined transfer of research funds from the TRAs to the SHRP management of $8.276 million, summarized below:

TRA	Research Unit	Funds Transferred to SHRP Management
1	1-5.1, 1-5.5	$ 1.4 million
2	Central Organization	$ 6.876
		$ 8.276 million

The final TRA funds, after modification, are as follows:

TRA	Final Budget
1	$ 48.6 million
2	43.124
3	20.050
4	10.00
5	12.00
6	8.00
	$141.774 million
Total:	$150.00 million

A summary of project schedule changes (in the time for study initiation) are:

Task	New Start Year
4-1.9	1*
4-3.7	1
4-4.2	1
4-4.3	1
5-4.2	1
6-1.2	3
6-1.3	3
6-2.2	3
6-2.3	3
6-2.4	3
6-2.7	1

* Beginning of SHRP year shown

RECOMMENDED OVERALL PROGRAM

Based on the noted modifications to the individual TRA contractor plans, the final SHRP scheduling and budgetary tables were developed.

Tables A.1 to A.6 (Appendix A) summarize the annual research expenditures ($x1,000) for each of the five SHRP years for each project-task within a given TRA. Figures A.1 to A.6 show the project-task work schedules for each of the TRA plans. Table 5.1 summarizes the annual SHRP research

expenditures by project for each of the six TRAs. The overall summary of the SHRP annual expenditures is given on the bottom of Table 5.1 and graphically plotted in Figure 5.1. Figure 5.2 shows the cumulative yearly SHRP research expenditures.

PROGRAM OVERVIEW

Estimated Expenditure Breakdown

As noted, the projected research expenditure for the six SHRP technical research areas is near $142 million over the 5-year period. Based on the TRA reports, the estimated expenditure for new research equipment purchases within each of the areas is:

TRA-1	$2.5 million
TRA-2	7.9
TRA-3	1.0 (estimated)
TRA-4	1.0 (estimated)
TRA-5	0.6
TRA-6	1.6
	$14.6 million

If it is assumed that about $25 million will be required for other direct project costs, the overall program available for research personnel would be in the $95 to $100 million range.

Although estimates of professional person-year costs are highly variable, it can be seen that the overall SHRP activity will result in the need for 600 to 800 professional research person-years of effort over the 5-year SHRP period. This would average to 120 to 160 person-years per year of SHRP activity and would be exclusive of SHRP management and advisory personnel time.

The total program cost will consist of research project expenditures combined with the general and administrative costs necessary to manage the program. The general and administrative costs, to include research overhead, are estimated to be in the 10 to 15 percent range of the research program. As a result, the total cost of the overall program is estimated to be in the $160 to $170 million range.

Research Unit Cost and Duration

Important management considerations are the cost of a typical unit of research and time for activities within the SHRP period. This impacts on the eventual selection of typical contracts to be awarded, managed, and monitored in the program.

Table A.7 is a summary of cost distributions at the project and task level for all TRA study areas except TRA-2 (Long-Term Pavement Performance). Table A.8 is a similar summary of research cost parameters. As can be seen, there is a high level of variability associated with either typical project level or task level research units. Exclusive of TRA-2, 23 research projects are identified. The overall average project cost is $4.3 million (without

TABLE 5.1

ANNUAL SHRP EXPENDITURES BY PROJECT

TRA	Project	Expenditures ($x1,000) by SHRP Year 1	2	3	4	5	Totals
1	1-1	2,300	5,100	5,620	4,720	4,260	22,000
	1-2	2,100	4,050	4,050	4,050	750	15,000
	1-3	550	850	1,080	1,080	940	4,500
	1-4	-	-	1,670	1,670	1,660	5,000
	1-5	420	420	420	420	420	2,100
	TRA Subtotals	5,370	10,420	12,840	11,940	8,030	48,600
2	TRA Subtotals	10,120	6,604	7,248	6,920	5,048	43,124*
3	3-1	1,050	1,500	1,100	1,150	1,250	6,050
	3-2	100	400	1,000	1,000	1,000	3,500
	3-3	900	1,300	1,160	1,520	1,420	6,300
	3-4	325	350	800	970	455	2,900
	3-5	-	-	200	500	600	1,300
	TRA Subtotals	2,375	3,550	4,260	5,140	4,725	20,050
4	4-1	950	950	375	75	-	2,350
	4-2	675	925	850	625	450	3,525
	4-3	650	900	875	700	425	3,550
	4-4	175	-	25	225	150	575
	TRA Subtotals	2,450	2,775	2,125	1,625	1,025	10,000
5	5-1	865	1,025	865	575	290	3,620
	5-2	745	1,015	815	1,160	880	4,615
	5-3	330	565	425	250	150	1,720
	5-4	290	530	500	380	345	2,045
	TRA Subtotals	2,230	3,135	2,605	2,365	1,665	12,000
6	6-1	425	325	375	500	475	2,100
	6-2	775	675	650	600	550	3,250
	6-3	600	300	300	-	-	1,200
	6-4	-	-	-	150	100	250
	6-5	600	300	300	-	-	1,200
	TRA Subtotals	2,400	1,600	1,625	1,250	1,125	8,000
	SHRP Totals	$24,945	$28,084	$30,703	$29,240	$21,618	$141,774*

* This total cost includes the $7.184 million contingency cost in year 6 for TRA-2 (see Table A.2)

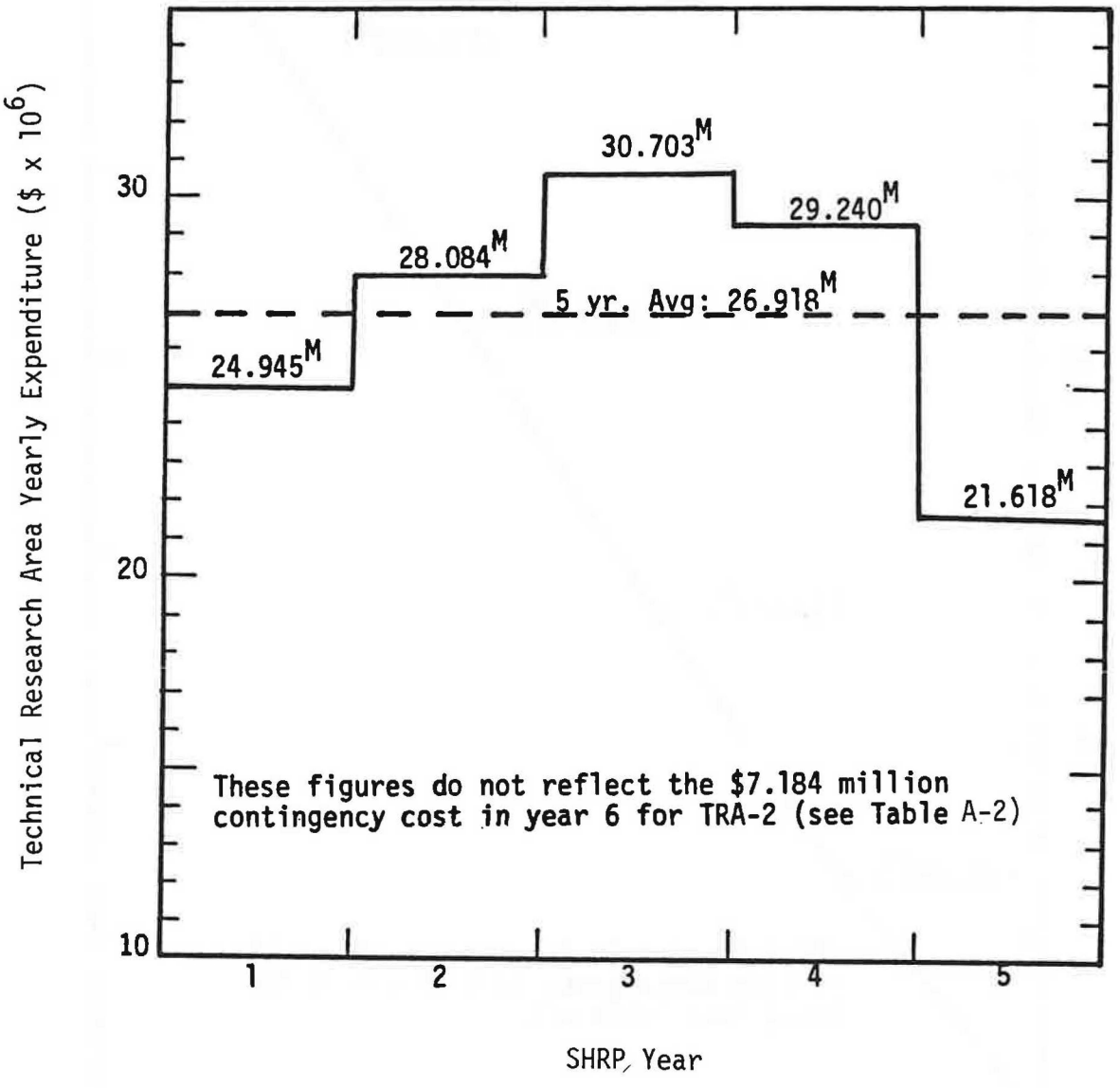


FIGURE 5.1 DISTRIBUTION OF ANNUAL RESEARCH EXPENDITURES

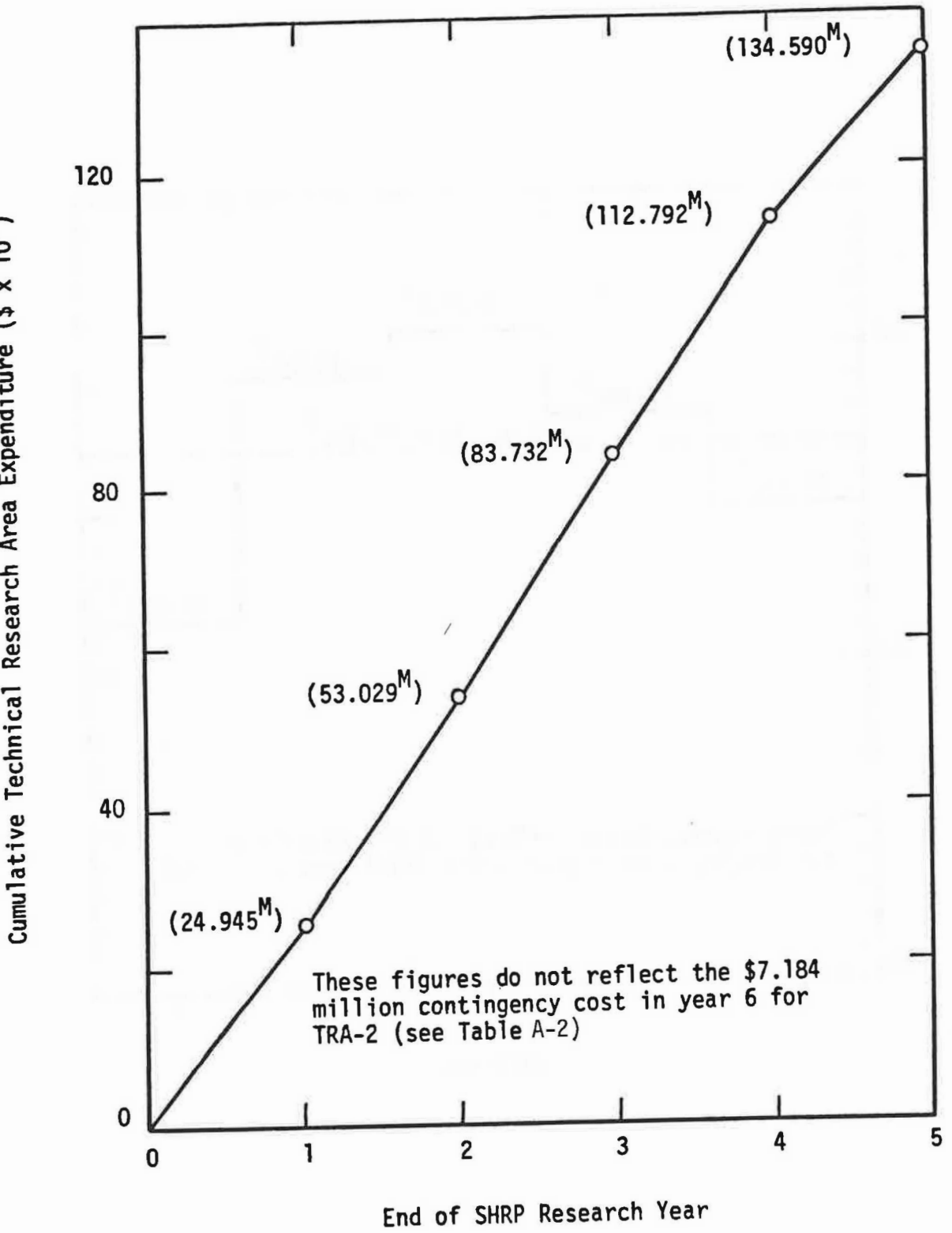


FIGURE 5.2 CUMULATIVE TECHNICAL RESEARCH AREA EXPENDITURES DURING SHRP FIVE-YEAR PERIOD

TRA-2) with a low average for TRA-6 of $1.60 million and a high average of $9.72 million for TRA-1.

When viewed at the research task level, 93 tasks are identified, exclusive of TRA-2 activities. The average research cost per task is $1.06 million, with the low average of $0.37 million for TRA-4 and the high average of $2.7 million for TRA-1.

Table 5.2 summarizes appropriate information concerning research unit duration. Like costs, time durations by units are variable. However, at the project level, the average time (without TRA-2) is about 4 1/2 years and, for all practical purposes, a typical project level activity can be assumed to last for the whole SHRP period.

Duration times for research tasks are highly variable, averaging 2 to 2 1/2 years. Reference to Table 5.2 shows that task durations range from 3 to 60 months.

Figure 5.3 shows the distribution of the number of research tasks starting and finishing by year for all TRA study areas except TRA-2. Figure A.8 shows similar information for the combined task totals of the five SHRP technical research areas presented. As observed, 50 separate tasks would be initiated the first year (exclusive of TRA-2). The number of tasks initiated per year quickly diminishes with time. A mirror image occurs for tasks that are expected to finish within a particular year. It is noted that 50 tasks are scheduled to be completed during the last SHRP year.

If it is assumed, for general planning purposes only, that a research task would be equivalent to a typical research contract award, annual worth of research contract awards can be obtained. Figure 5.3 shows the distribution of TRA contract worth awarded each year of the SHRP study (exclusive of TRA-2). The figure reveals the necessity to enter into contracts that initiate nearly $54 million in contract activities during the first SHRP year and nearly 98 percent of SHRP research by the end of the third year. It should be noted, however, that while this magnitude of research represents the total contract worth that would be "initiated," these figures differ from the annual research "expenditures" previously shown in Figure 5.1. Average annual research expenditures for SHRP are about $27 million (exclusive of general administration and overhead). Figure 5.4 is a dual plot of both research contract award magnitude and number of contract awards, on a cumulative yearly basis. As noted, the time to reach the 50th percentile contract worth and number of contracts is within the first 10 to 11 months of the program.

Summary of Research Study Types

In order to provide a general profile of the broad types of studies within SHRP, a subjective list of the major types found in the review was developed and each task categorized accordingly. The codes and study type descriptions used were as follows:

TABLE 5.2

SUMMARY OF RESEARCH PROJECT-TASK DURATION

Time Interval (Months)	Number of Occurrences			
	Project		Task	
	With TRA-2	Without TRA-2	With TRA-2	Without TRA-2
0-6	1	-	5	-
6-12	2	-	17	11
12-18	3	-	13	6
18-24	-	-	8	6
24-30	2	1	21	20
30-36	2	1	5	2
36-42	3	3	24	22
42-48	1	1	2	-
48-54	3	1	10	9
54-60	17	16	17	17
Average: (months)	44	53	28	30

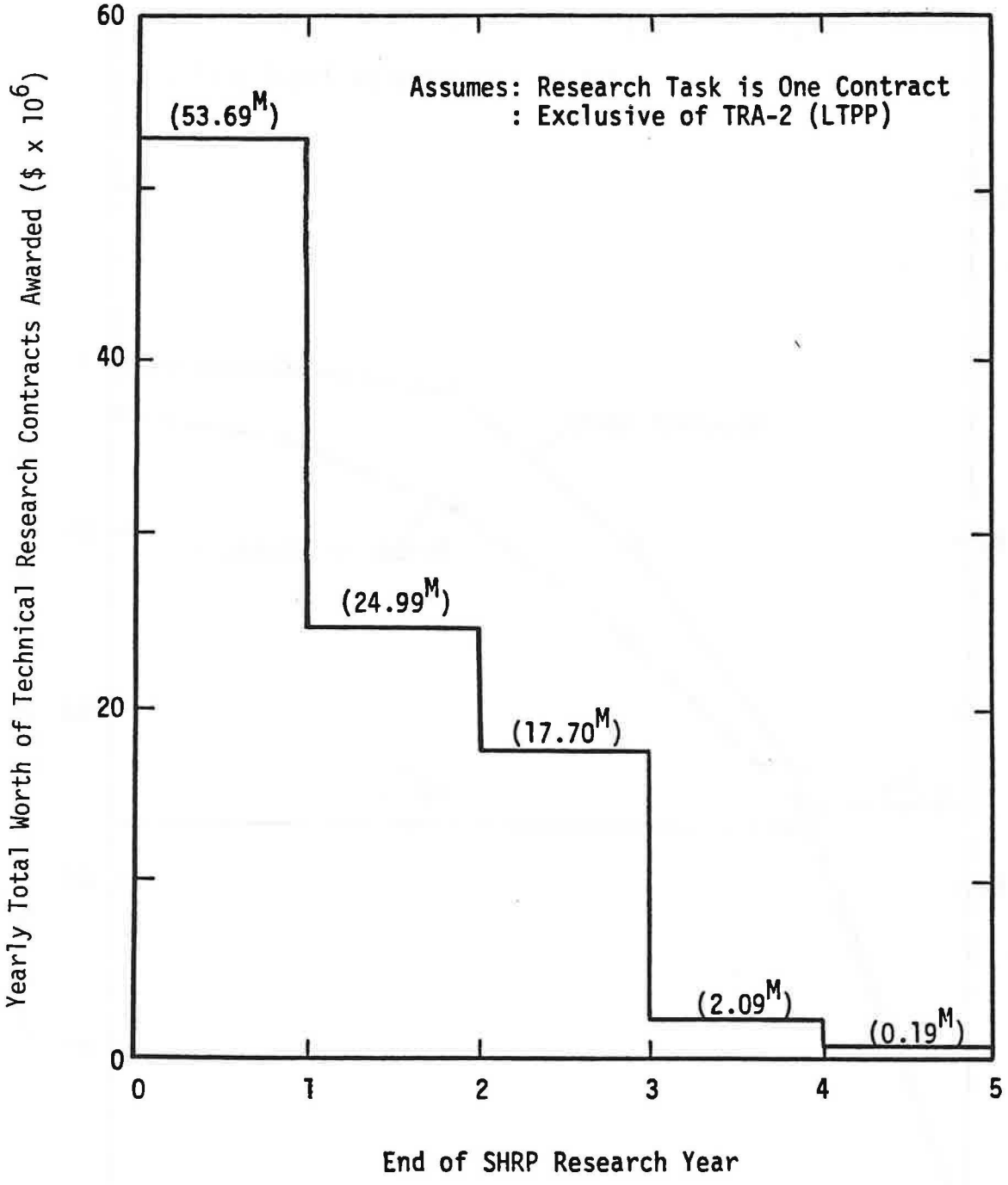


FIGURE 5.3 DISTRIBUTION OF TECHNICAL RESEARCH AREA CONTRACT WORTH AWARDED BY YEAR (Exclusive of TRA-2)

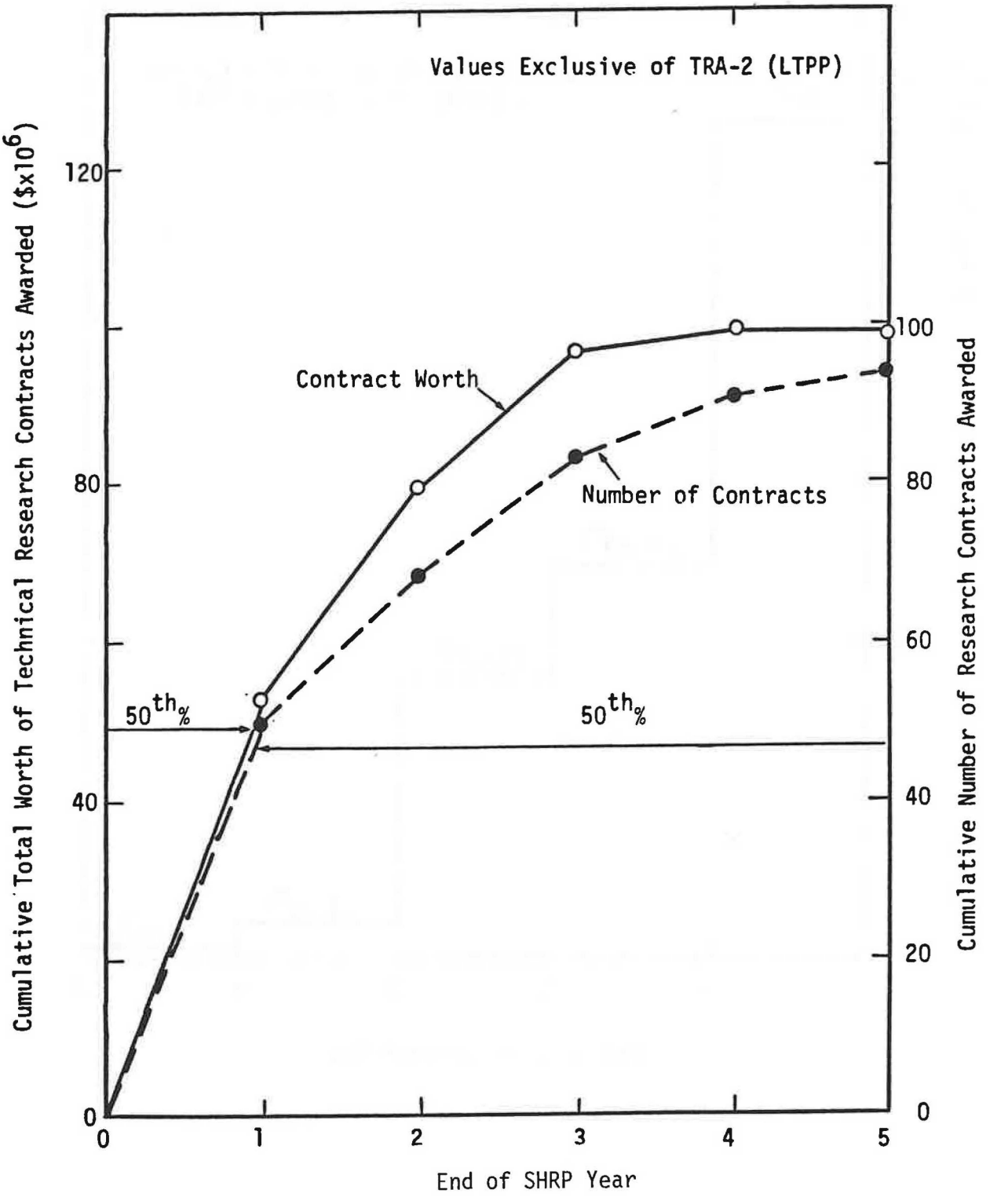


FIGURE 5.4 CUMULATIVE YEARLY CONTRACT AWARDS AND ESTIMATED NUMBER OF CONTRACTS (EXCLUSIVE OF TRA-2)

Study Code	Description	Study Code	Description
1	Planning	6	Implementation
2	Field Test/Data Collection	7	Literature Review
3	Experimental (Lab)	8	Prototype/ Instrumentation
4	Evaluation	9	Equip. Procurement/ Check
5	Analysis	10	Other

The summary was conducted on a task research level basis and study codes were qualitatively assigned to each task. In many instances, multiple codes had to be assigned to a particular task in order to provide as accurate an assessment as possible.

Table A.9 summarizes, by task, the various types of research planned for all six TRAs. Table 5.3 represents the summary statistics of the study type (number of occurrences within tasks, percentage based on the number of tasks, and priority ranking). Because of the rather unique nature of TRA-2, the summary analysis is presented with and without SHRP tasks for the Long-Term Pavement Performance area. It can be observed from this table that the major thrusts of SHRP research activities are: evaluation, experiment, prototype and instrumentation development, and field tests and data collection. Approximately 30 percent or more of all SHRP tasks have these elements of research. Research studies addressing planning and implementation techniques are few in number. (The reader should not infer that implementation is not considered within SHRP. Section 4 contains a more detailed discussion of SHRP implementation.)

Summary of End Product Categories

One of the key considerations of SHRP lies in the fact that it is a research program uniquely devoted to developing highly usable, high payoff end products or deliverables in six major areas. The types of "deliverables" fall into five distinct classifications:

End Product Code	Description
1	New/Improved Materials
2	New/Improved Equipment and/or Instrumentation
3	New/Improved Methodologies, Tests, or Specifications
4	New/Improved Communication/Computer Systems
5	Other

Table A.10 presents the types of end products associated with each of the six TRA study areas, and Table 5.4 presents an analysis of the data in Table A.10. Separate statistics are shown for both project level and task level end products.

TABLE 5.3

RESEARCH STUDY TYPE SUMMARY STATISTICS

Study Code/Description	Exclusive of TRA-2			With TRA-2		
	Number of Occurrences	% (By Task)	Priority Ranking	Number of Occurrences	% (By Task)	Priority Ranking
1. Planning	4	4.3	8	15	12.3	7
2. Field Test/Data Collection	30	32.3	4	36	29.5	3
3. Experimental Lab	39	41.9	2	39	32.0	2
4. Evaluation	42	45.2	1	44	36.1	1
5. Analytical	22	23.7	6	23	18.9	6
6. Implementation Technique	2	2.2	9	4	3.3	10
7. Literature	26	28.0	5	26	2.1	5
8. Prototype Instrumentation	31	33.3	3	35	2.9	4
9. Equipment Procurement/Check	0	0.0	10	6	4.9	9
10. Other	13	14.0	7	13	10.7	8

Notes: Number of Tasks Exclusive of TRA-2: 93
Number of Tasks with TRA-2: 122
Priority Ranking: (1) Highest (10) Lowest

TABLE 5.4

END PRODUCT TYPE SUMMARY STATISTICS

End Product Description	Project Level					
	Exclusive of TRA-2			With TRA-2		
	Number of Occurrences	% (By Proj)	Priority Ranking	Number of Occurrences	% (By Proj)	Priority Ranking
1. New/Improved Materials	4	17.4	3	4	9.8	5
2. New/Improved Equip/Instrument	6	26.1	2	10	24.4	2
3. New/Improved Methodologies	19	82.6	1	22	53.7	1
4. New/Improved Communication/Comp	3	13.0	4	5	12.2	3-4
5. Other	1	4.3	5	5	12.2	3-4

Number of Projects: 23 (without TRA-2); 41 (with TRA-2)

End Product Description	Task Level					
	Exclusive of TRA-2			With TRA-2		
	Number of Occurrences	% (By Proj)	Priority Ranking	Number of Occurrences	% (By Proj)	Priority Ranking
1. New/Improved Materials	5	5.4	5	5	4.1	5
2. New/Improved Equip/Instrument	16	17.2	3	25	20.5	3
3. New/Improved Methodologies	70	75.3	1	73	59.8	1
4. New/Improved Communication/Comp	7	7.5	4	14	11.5	4
5. Other	25	26.9	2	35	28.7	2

Number of Tasks: 93 (without TRA-2); 122 (with TRA-2)

When viewed at the research project level, the most significant end products of SHRP are the development of new or improved methodologies, tests, or specifications. If TRA-2 project objectives are excluded, over 85 percent of the remaining SHRP projects relate to these major program deliverables. New or improved equipment, instrumentation, and materials are second to the methodologies, tests, or specifications.

RESEARCH INTERACTION AND COORDINATION

Long-Term Pavement Performance

General. The overall program presented reveals the need for interaction and coordination between all of the technical research areas. The cornerstone of SHRP rests with TRA-2, Long-Term Pavement Performance. While the degree of interaction between other TRAs and TRA-2 varies widely, coordination of field testing and evaluation is mandatory for the successful outcome of SHRP.

In the delineation of research tasks having potential for TRA-2 interaction, several criteria were used. Although several research tasks were clearly identified in the contractor reports as having direct LTPP involvement, any research tasks involving field testing on in-service pavements or laboratory tests on field samples were identified as possible candidates for LTPP interaction. Further detailed studies should be made when research work statements are developed within the SHRP management unit in order to fully use any sections within the GPS and SPS study portions of the LTPP program. Such decisions can only be made after the characteristics of the LTPP sections are better defined.

Finally, although budget values are shown for each potentially interactive LTPP (non-TRA-2) research task, it should be recognized that not all of this amount may be available for direct transfer to the LTPP program.

TRA-1 Interaction. The TRA on Asphalt Properties possesses a significant potential for direct interaction with the LTPP area. Careful planning must prevail to ensure that field testing and evaluation requirements in TRA-1 are meshed with pavement sections used in TRA-2.

A brief overview of potentially interactive research tasks within TRA-1 is presented. Further details regarding the tasks may be found in the respective TRA research plan presented.

Task 1-1.3: Relationships Between Asphalt Chemical and Physical Properties ($3.5 Million)
Although this task is laboratory test oriented, one specific requirement will be to measure performance-related chemical and physical properties of asphalt cement used in the LTPP program.

Task 1-2.2,d: Aging of Asphalt-Aggregate Systems ($1.0 Million)

This is one of five subtasks within Task 1-2.2 dealing with the development of laboratory testing techniques, procedures, and results on asphalt-aggregate systems. In the "aging" subtask,

test methods developed will be evaluated by comparison to in-service pavements using both short-term and long-term periods.

Task 1-2.3: Relationship of Asphalt Chemical and Physical Properties to Asphalt-Aggregate Mixture Properties ($3.0 Million)

In this task, testing procedures developed for fatigue permanent deformation and low temperature cracking will be used to define the characteristics of the material used in the LTPP study.

Task 1-3.2: Asphalt Performance Studies ($3.0 Million)

This task objective is to obtain documented performance information on cracking, deformation, and thermal effects for projects with long-term performance records and for which samples of the original asphalt and aggregates are available for testing.

Task 1-3.3: Evaluation Procedures for Prediction Models ($1.0 Million)

This task includes the development of methods for interpreting information from the LTPP research area as it applies to the TRA-1 objective and to develop a comprehensive satellite SHRP.

Task 1-5.2: Operate Materials Reference Library ($1.5 Million)

This task will develop and maintain a library of asphalts, aggregates, and modifiers for use by all interested organizations to support research and long-term requirements for TRA-1.

Task 1-5.3: Experiment Design ($0.5 Million)

The task objective is to develop a statistically sound experimental design for each research activity in TRA-1. Of specific consequence to the LTPP are the requirements to provide assistance in furnishing data to the central data bank as well as coordinating plans for TRA-1 with requirements for the LTPP study area.

The seven individual research tasks delineated above have a combined budget value of $13.5 million.

TRA-3 Interaction. The TRA on Maintenance Effectiveness provides a high potential for LTPP interaction. Of the projects noted, 3-1, "Quantifying Pavement Maintenance Effectiveness," is a direct interaction within the LTPP study area. Project 3-3, dealing with "Improved Materials and Equipment for Pavement Surface Repair and Crack Filling", affords interaction in several research tasks requiring field testing of improved maintenance materials. Other projects having a minor potential for interaction with in-service pavements are 3-2 and 3-4.

A brief overview of potentially interactive research tasks within TRA-3 is presented. Further details concerning these tasks may be found in the TRA-3 research plan.

Task 3-1.1: Develop a Detailed Experimental Plan ($0.04 Million)

This task objective is to develop an experimental plan for a detailed study to quantify pavement maintenance effectiveness. A critical examination of the LTPP factors for pavement maintenance is to be conducted with respect to maintenance data collected and establishing sections not included in the LTPP study.

Task 3-1.2: Develop Implementation Plan ($0.04 Million)

This task is to develop a plan for implementing Task 3-1.1.

Task 3-1.3: Implement Maintenance Effectiveness Study ($5.57 Million)

This task is the major TRA-3 activity interacting with the LTPP area. It involves the collection of pertinent pavement maintenance data from the four regional LTPP field locations in accordance with plans developed in 3-1.1.

Task 3-1.4: Evaluate the Effectiveness of Maintenance Treatments ($0.36 Million)

This task is the data evaluation process of the LTPP maintenance factorial.

Task 3-2.1: Evaluate Existing Measuring Systems and Instrumentation ($0.1 Million)

Although the main objective of this task is not directly related to field testing, one requirement is the development of a test plan for evaluating measurement devices of pavement maintenance effectiveness and to identify criteria used to select the field test sites.

Task 3-2.3,d: Test Prototype (Field) ($1.0 Million)

This task is identical to Task 3-2.1 except field testing and evaluation of a new prototype(s) equipment will be made. Field sections used should be the same as for 3-2.1 and, if possible, should be sections included within the LTPP program.

Task 3-3.3: Laboratory and Field Testing of Select Materials ($0.7 Million)

This task has direct field tests required on improved maintenance materials. These short-term tests should not extend for more than one year.

Task 3-3.5: Long-Term Material Field Tests ($0.9 Million)

This task is similar to 3-3.3 except the duration of field material tests will be approximately 3 years.

Task 3-4.1: Evaluate Existing Devices and Procedures ($0.35 Million)

Project 3-4 specifically deals with research intended to improve maintenance work zone-worker and motorist safety. In Task 3-4.1 existing safety devices and procedures will be evaluated. One requirement of this study will be to conduct field studies where gaps in existing knowledge exist. Such field studies should be coordinated, if at all possible, with LTPP sections (Maintenance subsystem) to minimize costs and maximize benefits.

Task 3-4.3,c: Develop and Test New Traffic Controls ($0.815 Million)

In this subtask, both field and laboratory tests of barrier attenuation systems and new detection alert systems for motorists are contemplated. Interaction with LTPP field sections may be minor or of little consequence.

The ten tasks identified having potential LTPP interaction have a total combined budget of $9.88 million.

TRA-4 Interaction. TRA-4 deals with research tasks concerning the protection of concrete bridge components. Although there is a significant amount of field testing validation and evaluation research planned, potential interaction with the LTPP study area is virtually nonexistent. Nonetheless, because it is noted that field performance models are to be developed, some consideration should be given to locating field bridge sites as near as possible (if at all) to selected LTPP sites. If this can be accomplished, some overlap of benefits may be gained from the detailed records of traffic and environmental data that are to be collected in the LTPP study. This information may be of assistance to researchers in TRA-4.

TRA-5 Interaction. The research plan developed for TRA-5, Cement and Concrete, requires a small degree of interaction with LTPP efforts. Major reasons why a stronger interaction is not required are because much of the proposed research is laboratory test-oriented; field testing will be required on portland cement concrete pavements exhibiting certain types of durability problems that would preclude their selection as LTPP candidates (i.e., D-cracking, alkali aggregate reaction, and so forth); and many of the field tests are to be conducted on freshly mixed (plastic) concrete. The latter factor may imply cooperation and coordination with state agencies at construction sites, but does not require the mandatory selection of LTPP pavement sections for long-term performance evaluation.

Research tasks having the potential for LTPP interaction are described in the following sections. The funding levels shown are based on estimates of the portion of each task that might entail field testing. Further details regarding each task (subtask) may be found in the TRA-5 research plan.

Task 5-2.2: Characterize Moisture and Relative Humidity Gradients in Field Concrete ($0.42 Million)

Subtask b of this study requires a field demonstration of the equipment and test procedure developed. It would be useful to

use LTPP sections that afford well-characterized concrete so that testing could be done in different climatic regions and in different seasons.

Task 5-2.3: Freeze-Thaw Durability and Air Voids Criteria ($0.05 Million)

Subtask f requires field trials on at least two highway bridge decks and two pavements using admixtures and aggregates similar to those used in the laboratory subtask work. New construction would be required for field work, but LTPP evaluation is desirable.

TasK 5-3.4: Residual Functional Capability ($0.20 Million)

Subtask c of this reseach effort requires the field evaluation of equipment and techniques of at least five field trial locations. While not specifically stated in the research plan, it is recommended that LTPP sections be used, if at all possible, for this study.

Task 5-4.2: Properties of High Early Strength Concrete ($0.09 Million)

Subtask c requires a field demonstration of several (3) systems developed for quality performance of high early strength concrete. Performance monitoring of these sections is recommended for at least 3 years and should be interacted and coordinated with LTPP studies (maintenance).

Task 5-4.3: Structural Properties of Concrete Containing Cementing Materials in Addition to Portland Cement ($0.16 Million)

Subtask c recommends that this research study be directly integrated into the LTPP area. A total of 8 special concrete mixtures, placed in 4 geographical areas, is recommended for the field trials. New pavement test sections will be required along with a comprehensive pavement performance monitoring study.

The five tasks (subtasks) listed as having a potential for LTPP interaction involve a combined budget of $0.92 million. This total represents only that part of the task budgets allocated for field work.

TRA-6 Interaction. Although not immediately apparent from the proposed research plan, the LTPP interaction requirements with TRA-6, Snow and Ice Control, are felt to be significant and mandatory. All of this potential for interaction occurs within Projects 6-1 and 6-2, which are aimed at the prevention and destruction of the ice-pavement bond, through chemicals, pavement material additives, or new pavement materials. Although the specific objectives of these studies are related to the success of inhibiting or destroying the ice-pavement bond, a more global or systems approach to assessing ice-snow control measures on the long-term pavement performance and friction characteristics of the pavement are also important parameters that must be integrated into any final decisions.

The specific tasks having potential interaction with LTPP are presented and further details may be found in the TRA-6 research plan.

Task 6-1.2: Chemical Surface Modification--Prevention ($0.25 Million)

This task deals with the chemical modification of pavement surfaces to prevent the formation of the ice-pavement bond. One subtask will require the evaluation of effects on this pavement modification on the long-term pavement performance and in recyclability.

Task 6-1.3: Physical Surface Modification--Prevention ($0.05 Million)

This task deals with the development of a physical approach (i.e., icephobic pavement coating) for prevention of the ice-pavement bond. This task, like 6-1.2, will require LTPP monitoring.

Task 6-2.2: Physical Surface Modification--Destruction ($0.05 Million)

This task is parallel to Task 6-1.3 but approached from the point of view of bond destruction. The intent is to develop an effective pavement physical modification that would achieve the task objective. Long-term performance evaluations would be required on these pavement sections.

Task 6-2.7: Improvements of Sodium Chloride as Deicer ($0.40 Million)

This task is intended to improve sodium chloride relative to its adverse environmental and corrosion effects. One subtask requires candidate materials to undergo winter traffic tests. The potential for use of LTPP sections exists, although task objectives may be developed without their use.

The four tasks noted have a combined budget of $0.75 million. Budget figures noted for the first three tasks reflect the contractor's estimate for direct field work, while the last task provides the total budget for all research conducted in the task.

Summary. Table 5.5 summarizes the potential TRA-2 interaction attributes with the other five TRA study areas. As can be seen, a total of 26 research tasks have the potential for LTPP interaction. The maximum (upper limit) of research funds noted for these tasks is approximately $25 million. However, it is estimated that $8 to $10 million may be directly available for fund transfer to cover field test and data collection costs associated within the LTPP study.

Other Interactions and Coordination

There exists in the total SHRP effort the need for other projects to interact. Table 5.6 is a subjective assessment of the potential level of interest (hence, interaction and coordination) among the SHRP research project

TABLE 5.5

SUMMARY OF POTENTIAL TRA-2 INTERACTION

TRA Study	Degree Interaction	Research Tasks	($Million) Task Budget	($Million) Budget Totals
TRA-1	Very significant	1-1.3	3.50	13.50**
		1-2.2,d	1.00	
		1-2.3	3.00	
		1-3.2	3.00	
		1-3.3	1.00	
		1-5.2	1.50	
		1-5.3	0.50	
TRA-3	Significant	3-1.1	0.04	9.88**
		3-1.2	0.04	
		3-1.3	5.57	
		3-1.4	0.36	
		3-2.1	0.10	
		3-2.3,d	1.00	
		3-3.3	0.70	
		3-3.5	0.90	
		3-4.1	0.35	
		3-4.3,c	0.82	
TRA-4	Insignificant*	-	-	
TRA-5	Minor	5-2.2	0.42	0.92***
		5-2.3	0.05	
		5-3.4	0.20	
		5-4.2	0.09	
		5-4.3	0.16	
TRA-6	Significant	6-1.2	0.25	0.75***
		6-1.3	0.05	
		6-2.2	0.05	
		6-2.7	0.40	
		27		25.05 Million

Notes: (*) LTPP traffic and environmental data may be helpful if field bridge sites are located close to LTPP sections.
(**) Budget values encompass more than field work.
(***) Budget values predominantly field work.

TABLE 5.6

SUMMARY OF SHRP RESEARCH PROJECT
INTERACTION AND COORDINATION (Exclusive of TRA-2)

TRA Project		Relative Degree of Interaction And Coordination				
		TRA-1	TRA-3	TRA-4	TRA-5	TRA-6
Asphalt						
	1-1	X	●	o		o
	1-2	X	●	o		o
	1-3	x	●	o		o
	1-4	X	●			o
	1-5	X	●			o
Maintenance						
	3-1	●	X		●	
	3-2	●	X	o	o	
	3-3	●	X	o	●	o
	3-4		X	o		o
	3-5		X			
Bridge Protection						
	4-1	o	o	X	●	
	4-2		o	X	●	o
	4-3	o	o	X	●	
	4-4	o	o	X	o	
Cement/Concrete						
	5-1		●	●	X	o
	5-2		●	●	X	o
	5-3	o	●	●	X	
	5-4	o	●	●	X	
Snow/Ice						
	6-1	●	●	●	●	X
	6-2	●	●	●	●	X
	6-3					X
	6-4		o			X
	6-5					X

Note:

(●) Potential for fair-to-strong need for research coordination and cross transfer of technology results.

(o) Potential for low-to-casual need for research coordination and cross transfer of technology results.

(X) Not applicable.

areas other than TRA-2. A general description of the potential interest area is presented by TRA.

TRA-1 Interaction. The major SHRP-TRA interactions for research work conducted in TRA-1 occurs with TRA-3, Maintenance Effectiveness, and to a more limited degree with Snow and Ice Control (TRA-6). Advances made in asphalt chemical composition can have direct spin-offs to improved maintenance materials (Project 3-3) and to chemical modification studies dealing with the ice-pavement bond study (Projects 6-1 and 6-2).

As research is conducted to improve asphalt pavement distress predictions (performance prediction) and develop performance-based specifications (Projects 1-2, 1-3, 1-4), this knowledge will also be useful directly to TRA 3-2 studies dealing with measuring systems for evaluating pavement maintenance effectiveness.

Within Project 1-5, the development of the materials reference library (1-5.2) will have the potential for direct interaction with the maintenance LTPP factorial study proposed in TRA 3-1. Finally, it should be noted that research task 1-5.3, which concerns the development of an experimental design, is conceptually identical to Task 3-1.1 within the maintenance area, and research task 1-5.4 efforts, which pertain to economics and life-cycle cost considerations, have an overlap with Project 3-2.

Other non-SHRP research that should be monitored within TRA-1 are several NCHRP projects, 10-26(A) and 9-6(1), which have to do with the development of performance-related specifications for hot-mix asphaltic concrete and an asphalt-aggregate mixture analysis system.

TRA-3 Interaction. The greatest potential for interaction with TRA-3 on Maintenance Effectiveness occurs in the Asphalt (TRA-1) and Cement and Concrete (TRA-5) areas. Projects 3-1, 3-2, and 3-3 provide the possibility of strong coordination and cross-monitoring of research results for these two material areas. In addition, peripheral advances in equipment and instrumentation within Project 3-3 may have impacts across all other SHRP areas.

In Project 3-4, studies concerning work-zone safety, it would appear that significant findings can also be transferred to maintenance and rehabilitation work associated both with snow and ice control and bridge rehabilitation projects. This technology transfer, however, will not be of direct benefit per se to the research studies of these two areas.

TRA-4 Interaction. TRA-4 (bridge protection systems) has the greatest potential interaction level with TRA-5, Cement and Concrete. Additionally, several specific tasks in TRA-4 have limited, but nonetheless real, potential for technology transfer with TRA-1 and TRA-3 (Asphalt and Maintenance Effectiveness).

In Project 4-1, research tasks dealing with bridge delamination, permeability, and chloride content will be of interest to TRA-5 (5-1 and 5-2). Study tasks dealing with asphalt-covered deck deterioration (4-1.3), membrane

integrity (4-1.4), and sealer evaluation (4-1.5) may be of some potential benefit to both TRA-1 and TRA-3 studies.

Project 4-2, which concerns the broad study of electrochemical aspects of bridge protection, may have value (particularly for chemical-type studies) to TRA-5 (Project 5-1) and TRA-6 (Projects 6-1, 6-2). Rehabilitation and maintenance techniques developed in this project may also have limited interest and potential use within TRA-3.

Similar concepts, as above, may also be stated for Project 4-3. However, inasmuch as the study relates to nonelectrochemical bridge protection concepts, a reduced emphasis on chemical composition occurs within the TRA noted previously. Research findings dealing with rehabilitation and maintenance methodologies for bridges may also be of assistance in TRA-3. In addition, this project (Task 4-3.8) will involve service life evaluation of various treatments and may be significant to studies in Projects 1-5 and 3-2 (Asphalt and Maintenance).

Within Project 4-4, the overall objective concerns the development of cost-effective (life-cycle) decision models for the protection and rehabilitation of concrete bridge components and, as such, will implicate fundamental economic concepts similar to other research studies planned in Projects 1-5 and 3-2.

In addition to the SHRP research coordination noted, there are several studies, such as NCHRP Projects 10-15, 10-30, and 12-28(1) and 12-28(8), the Federally Coordinated Research Program (FCP), and the FHWA Demonstration Studies, that should be continuously monitored and evaluated during the SHRP period.

TRA-5 Interaction. The technical area of Cement and Concrete (TRA-5) has the greatest interactive potential with the Maintenance (TRA-3) and Concrete Bridge Protection (TRA-4) study areas. Limited interaction and technology transfer to TRA-1 and TRA-6 may also be possible.

In Project 5-1, which deals with the chemistry and physics of cement and concrete, research contributions relating to new and improved materials and a better understanding of chemical properties on behavior and performance may be of direct use and benefit to researchers in the Maintenance and Bridge Protection TRA units. Secondary benefits concerning chemical behavior may also be useful to Projects 6-1 and 6-2 within the Snow and Ice Control area.

Project 5-2, which is concerned with concrete durability, is seen to have significant potential for studies in both the maintenance and bridge areas, particularly with respect to improved materials and measurement techniques. It is believed that the findings of Tasks 5-3.1, 5-3.2, and 5-3.3 (quality control during construction) may have interactive consequences of benefit to TRA-3 and TRA-4, while the research findings of 5-3.4 (the determination of residual functional capability of concrete pavements) may lead to some conceptual overlap and may be of use to TRA-1 (Projects 1-2, 1-3, and 1-4).

In Project 5-4, research task 5-4.2 concerns properties of high early strength concrete. This should be of major significance to TRA-3 and

studies dealing with improved maintenance materials. Other research tasks (5-4.1, 5-4.3, and 5-4.4) that have to do with the mechanical behavior of concrete should be monitored by researchers in TRA-1, TRA-3, and TRA-4.

TRA-6 Interaction. In Snow and Ice Control (TRA-6), only Projects 6-1 and 6-2 appear to have any potential for interaction with other SHRP-TRA. Both of these project areas deal with the physical and chemical modifications to pavements (and their surfaces) to prevent and destroy the ice-pavement bond. Because of these elements, changes in material, material behavior, pavement behavior, and eventual performance changes may possibly occur. These potential impacts are of direct concern to activities in TRA-1, TRA-3, and TRA-5 and should be continuously evaluated throughout SHRP. In addition, minor levels of research findings (particularly with chemical modifications) may be of value to TRA-4 (bridge protection).

Projects 6-3, 6-4, and 6-5 afford no potential interactive influence on the other TRA units of SHRP. The only possible exception is that some information of benefit may be obtained from Project 6-4 that would be useful to cost-effective life-cycle maintenance studies in Project 3-2.

RESEARCH TOPICS NOT INCLUDED IN SHRP

In the planning efforts that were conducted by each of the TRA contractors and Advisory groups, many potential projects were developed and considered for eventual inclusion within SHRP. However, because of funding and other justifiable reasons, not all of the individual research projects considered were able to be placed in the final program. Their discussion and development as potential research studies is, nonetheless, thought to advance significant results that should not be kept from the research community. It is hoped that other researchers and research agencies can conduct further evaluations of these topics and continue with what are believed to be important peripheral research areas worthy of investigation.

Table A.11 is a topic summary of the research areas that were not included in the funded program. For further information on these candidate projects, reference is made to the subsequent individual TRA contractor reports, each of which provides some details concerning these projects.

APPENDIX A

SHRP STATISTICS

TABLE A.1

ANNUAL BUDGET EXPENDITURES (TRA-1)

Project	Task	Expenditures ($X1,000) for SHRP Year 1	2	3	4	5	Totals
1-1	1-1.1	800	1200	1200	400	400	4000
	1-1.2	600	600	500	400	400	2500
	1-1.3	-	750	1000	1000	750	3500
	1-1.4	-	-	670	670	660	2000
	1-1.5	400	800	1000	1000	800	4000
	1-1.6	500	500	-	-	-	1000
	1-1.7	-	1250	1250	1250	1250	5000
1-2	1-2.1	-	1200	1200	1100	-	3500
	1-2.2	2100	2100	2100	2200	-	8500
	1-2.3	-	750	750	750	750	3000
1-3	1-3.1	250	250	-	-	-	500
	1-3.2	300	600	750	750	600	3000
	1-3.3	-	-	330	330	340	1000
1-4	1-4.1	-	-	1000	1000	1000	3000
	1-4.2	-	-	670	670	660	2000
1-5	1-5.2	300	300	300	300	300	1500
	1-5.3	100	100	100	100	100	500
	1-5.4	20	20	20	20	20	100
							$48,600

TABLE A.2

ANNUAL BUDGET EXPENDITURES (TRA-2)*

Regional Operations	Expenditures ($x1,000) for SHRP Year						
	1	2	3	4	5	6	Totals
Staff	3920	3920	3920	3920	3920	-	19,600
Material Testing	4412	252	384	388	60	-	5,496
Operation Cost	592	592	592	592	592	-	2,960
Equipment	1196	1840	2352	2020	476	-	7,884
Contingency	-	-	-	-	-	7,184	7,184
							$43,124

* Analysis of TRA-2 did not lend itself to the cost breakdown by project task.

TABLE A.3

ANNUAL BUDGET EXPENDITURES (TRA-3)

Project	Task	Expenditures ($x1,000) for SHRP Year 1	2	3	4	5	Totals
3-1	3-1.1	40	-	-	-	-	40
	3-1.2	40	-	-	-	-	40
	3-1.3	970	1450	1050	1050	1050	5570
	3-1.4	-	50	50	85	175	360
	3-1.5	-	-	-	15	25	40
3-2	3-2.1	100	-	-	-	-	100
	3-2.2	-	50	-	-	-	50
	3-2.3	-	350	1000	1000	960	3310
	3-2.4	-	-	-	-	40	40
3-3	3-3.1	450	350	-	-	-	800
	3-3.2	450	350	-	-	-	800
	3-3.3	-	500	200	-	-	700
	3-3.4	-	-	710	1170	1150	3030
	3-3.5	-	100	250	330	220	900
	3-3.6	-	-	-	20	50	70
3-4	3-4.1	325	25	-	-	-	350
	3-4.2	-	325	50	-	-	375
	3-4.3	-	-	750	950	415	2115
	3-4.4	-	-	-	20	40	60
3-5	--	-	-	200	500	600	1,300
							$20,050

TABLE A.4

ANNUAL BUDGET EXPENDITURES (TRA-4)

Project	Task	Expenditures ($x1,000) for SHRP Year 1	2	3	4	5	Totals
4-1	4-1.1	350	350	-	-	-	700
	4-1.2	100	100	-	-	-	200
	4-1.3	125	175	-	-	-	300
	4-1.4	75	75	-	-	-	150
	4-1.5	75	50	-	-	-	125
	4-1.6	75	50	-	-	-	75
	4-1.7	75	-	-	-	-	75
	4-1.8	-	150	250	-	-	400
	4-1.9	75	-	-	-	-	75
	4-1.10	-	-	125	75		200
4-2	4-2.1	200	350	350	175	125	1200
	4-2.2	475	575	500	450	325	2325
4-3	4-3.1	150	150	-	-	-	300
	4-3.2	300	200	100	-	-	600
	4-3.3	-	225	225	-	-	450
	4-3.4	-	175	175	-	-	350
	4-3.5	-	-	175	450	175	800
	4-3.6	-	-	100	150	50	300
	4-3.7	125	50	-	-	-	175
	4-3.8	75	100	100	100	100	475
	4-3.9	-	-	-	-	100	100
4-4	4-4.1	-	-	25	75	-	100
	4-4.2	100	-	-	-	-	100
	4-4.3	75	-	-	-	-	75
	4-4.4	-	-	-	100	-	100
	4-4.5	-	-	-	50	100	150
	4-4.6	-	-	-	-	50	50
							$10,000

TABLE A.5

ANNUAL BUDGET EXPENDITURE (TRA-5)

Project	Task	Expenditures ($x1,000) for SHRP Year 1	2	3	4	5	Totals
5-1	5-1.1	700	825	690	-	-	2215
	5-1.2	165	200	175	195	-	735
	5-1.3	-	-	-	380	290	670
5-2	5-2.1	310	340	250	240	280	1420
	5-2.2	-	225	200	215	160	800
	5-2.3	275	300	190	150	105	1020
	5-2.4	160	150	175	85	55	625
	5-2.5	-	-	-	470	280	750
5-3	5-3.1	50	100	100	50	50	350
	5-3.2	130	215	75	-	-	420
	5-3.3	150	100	50	-	-	300
	5-3.4	-	150	200	200	100	650
5-4	5-4.1	100	200	200	200	100	800
	5-4.2	100	100	50	-	-	250
	5-4.3	90	135	135	90	200	650
	5-4.4	-	95	115	90	45	345
							$12,000

TABLE A.6

ANNUAL BUDGET EXPENDITURES (TRA-6)

Project	Task	Expenditures ($x1,000) for SHRP Year 1	2	3	4	5	Totals
6-1	6-1.1	425	325	-	-	-	750
	6-1.2	-	-	200	325	325	850
	6-1.3	-	-	175	175	150	500
6-2	6-2.1	425	325	-	-	-	750
	6-2.2	-	-	175	175	150	500
	6-2.3	-	-	275	275	250	800
	6-2.4	-	-	200	150	150	500
	6-2.5	150	150	-	-	-	300
	6-2.7	200	200	-	-	-	400
6-3	-	600	300	300	-	-	1200
6-4	-	-	-	-	150	100	250
6-5	-	600	300	300	-	-	1200
							$8,000

TABLE A.7

FREQUENCY DISTRIBUTION OF PROJECT-TASK BUDGETS
(Exclusive of TRA-2)

Level of Research	Budget Range ($Million)	Number of Occurrences					
		TRA-1	TRA-3	TRA-4	TRA-5	TRA-6	Total
Project	0-1	0	0	1	0	1	2
	1-2.5	1	1	1	2	3	8
	2.5-5.0	1	2	2	2	1	8
	5.0-7.5	1	2	0	0	0	3
	7.5-10.0	0	0	0	0	0	0
	10.0-12.5	0	0	0	0	0	0
	12.5-15.0	0	0	0	0	0	0
	15.0-17.5	1	0	0	0	0	1
	17.5-20.0	0	0	0	0	0	0
	20.0-22.5	1	0	0	0	0	1
		5	5	4	4	5	23
Task	0-0.5	1	11	22	5	3	42
	0.5-1.0	2	4	3	8	7	24
	1.0-1.5	2	1	1	2	2	8
	1.5-2.0	1	0	0	0	0	1
	2.0-2.5	2	1	1	1	0	5
	2.5-3.0	1	0	0	0	0	1
	3.0-3.5	3	2	0	0	0	5
	3.5-4.0	2	0	0	0	0	2
	4.0-4.5	2	0	0	0	0	2
	4.5-5.0	0	0	0	0	0	0
	5.0-5.5	1	0	0	0	0	1
	5.5-6.0	0	1	0	0	0	1
	6.0-6.5	0	0	0	0	0	0
	6.5-7.0	0	0	0	0	0	0
	7.0-7.5	0	0	0	0	0	0
	7.5-8.0	0	0	0	0	0	0
	8.0-8.5	0	0	0	0	0	0
	8.5-9.0	1	0	0	0	0	1
		18	20	27	16	12	93

TABLE A.8

SUMMARY OF PROJECT-TASK COSTS BY TRA
(Exclusive of TRA-2)

TRA	Project	Cost ($M)	Project n	Project $\bar{x}$	Project CV(%)	Task n	Task $\bar{x}$	Task CV(%)
1	1-1	22.00				7	3.14	43.8
	1-2	15.00				3	5.00	60.8
	1-3	4.50				3	1.50	88.2
	1-4	5.00				2	2.50	28.3
	1-5	2.10				3	0.70	103.0
	Totals:	$48.60	5	$9.72	87.0	18	$2.70	73.8
3	3-1	6.05				5	1.21	201.8
	3-2	3.50				4	0.88	184.5
	3-3	6.30				6	1.05	96.7
	3-4	2.90				4	0.73	128.4
	3-5	1.30				1	1.30	-
	Totals:	$20.05	5	$4.01	53.26	20	$1.00	145.5
4	4-1	2.35				10	0.24	81.8
	4-2	3.53				2	1.76	45.2
	4-3	3.55				9	0.39	55.1
	4-4	0.57				6	0.10	34.7
	Totals:	$10.00	4	$2.50	56.1	27	$0.37	128.3
5	5-1	3.62				3	1.21	72.2
	5-2	4.62				5	0.92	33.8
	5-3	1.72				4	0.43	36.0
	5-4	2.04				4	0.51	50.3
	Totals:	$12.00	4	$3.00	45.3	16	$0.75	65.3
6	6-1	2.10				3	0.70	25.8
	6-2	3.25				6	0.54	36.2
	6-3	1.20				1	1.20	-
	6-4	0.25				1	0.25	-
	6-5	1.20				1	1.20	-
	Totals:	$ 8.00	5	$1.60	70.7	12	$0.67	47.1
SHRP Totals:		$98.65	23	$4.29	113.8	93	$1.06	133.4

Note: $\underline{n}$ = Number of projects (Tasks)
$\bar{x}$ = Average cost ($M)
CV = Coefficient of variation

TABLE A.9

SUMMARY OF RESEARCH STUDY TYPES

TRA-1		TRA-2		TRA-3		TRA-4		TRA-5		TRA-6	
Task	Study Code	Task	Study Code	Task	Study Code	Task	Study Code	Task	Study Code	Task	Study Code
1-1.1	3,8	2-1.4	8	3-1.1	1	4-1.1	8	5-1.1	3,4,5,7	6-1.1	3,7
1-1.2	3,8			3-1.2	1	4-1.2	8	5-1.2	3,4,5,7	6-1.2	2,3,4
1-1.3	2,3,5	2-2.7	1	3-1.3	2	4-1.3	8	5-1.3	3,4,5,7	6-1.3	2,3,4
1-1.4	3,4			3-1.4	5	4-1.4	8				
1-1.5	3,4,7,8	2-3.4	1	3-1.5	6,10	4-1.5	8	5-2.1	2,3,4	6-2.1	3,7
1-1.6	3,4,7	2-3.5	1			4-1.6	8	5-2.2	3,4	6-2.2	2,3,4
1-1.7	3,4			3-2.1	4	4-1.7	8	5-2.3	2,3,4,5,7	6-2.3	3,4,8
		2-4.1	1	3-2.2	4,7	4-1.8	2,3,4	5-2.4	3,5	6-2.4	3,4,8
1-2.1	3,4,8	2-4.2	1	3-2.3	8	4-1.9	4	5-2.5	10	6-2.5	4,7
1-2.2	3,4,7,8			3-2.4	10	4-1.10	5,10			6-2.7	2,3
1-2.3	3,4	2-5.1	9					5-3.1	2,3,4,5,7		
		2-5.2	9	3-3.1	7	4-2.1	2,3,4,7,8,10	5-3.1	2,4,7,8	6-3	2,3,4,5,7,8
1-3.1	5	2-5.3	9	3-3.2	7	4-2.2	2,3,4,7,8,10	5-3.3	3,4,7		
1-3.2	2,3,5	2-5.4	9	3-3.3	2,3,4			5-3.4	2,4,7,8	6-4	5,8
1-3.3	1,5	2-5.5	9	3-3.4	8	4-3.1	2,4,8				
		2-5.6	9	3-3.5	2	4-3.2	2,3,4,8	5-4.1	3,5,7	6-5	2,4
1-4.1	5,8			3-3.6	10	4-3.3	2,4,8	5-4.2	2,3,4,7		
1-4.2	5,8	2-6.1	1,6			4-3.4	4	5-4.3	2,3,4,7		
		2-6.2	2	3-4.1	2,4,7	4-3.5	2	5-4.4	3,7		
1-5.2	10	2-6.3	2	3-4.2	5	4-3.6	4,8				
1-5.3	1	2-6.4	1,4	3-4.3	8	4-3.7	2,5				
1-5.4	4,5	2-6.5	2	3-4.4	10	4-3.8	4				
						4-3.9	10				
		2-7.1	1	3-5	6						
		2-7.2	1			4-4.1	5				
		2-7.3	1			4-4.2	8				
		2-7.4	1,8			4-4.3	10				
		2-7.5	8			4-4.4	5,8				
						4-4.5	10				
		2-8.1	2			4-4.6	10				
		2-8.2	2			4-4.6	10				
		2-8.3	2								
		2-9.1	8								
		2-9.2	4								
		2-10	5								
		2-11	6								

Note: See text for Study Code Identification

TABLE A.10

SUMMARY OF END PRODUCT TYPES

TRA-1		TRA-2		TRA-3	
Proj/Task	Product Code	Proj/Task	Product Code	Proj/Task	Product Code
(1-1)	3	(2-1)	2	(3-1)	3,4
1-1.1	2,3	2-1.4	2	3-1.1	3
1-1.2	2,3	(2-2)	5	3-1.2	3
1-1.3	3	2-2.7	5	3-1.3	4
1-1.4	3,4	(2-3)	5	3-1.4	3
1-1.5	3,5	2-3.4	5	3-1.5	5
1-1.6	5	2-3.5	5	(3-2)	3
1-1.7	3	(2-4)	5	3-2.1	3
(1-2)	2,3	2-4.1	5	3-2.2	3
1-2.1	2,3	2-4.2	5	3-2.3	2
1-2.2	2,3	(2-5)	2	3-2.4	3,5
1-2.3	3	2-5.1	2	(3-3)	1,2,3
(1-3)	3	2-5.2	2	3-3.1	1,5
1-3.4	3	2-5.3	2	3-3.2	2,5
1-3.2	3	2-5.4	2	3-3.3	5
1-3.3	3	2-5.5	2	3-3.4	2,3
(1-4)	3	2-5.6	2	3-3.5	4
1-4.1	3	(2-6)	4	3-3.6	5
1-4.2	3	2-6.1	4	(3-4)	2,3
(1-5)	5	2-6.2	4	3-4.1	3,5
1-5.2	5	2-6.3	4	3-4.2	3
1-5.3	5	2-6.4	4	3-4.3	2
1-5.4	3	2-6.5	4	3-4.4	3,5
		(2-7)	2,5	(3-5)	4
		2-7.1	5		
		2-7.2	5		
		2-7.3	5		
		2-7.4	2		
		2-7.5	5		
		(2-8)	4,5		
		2-8.1	4		
		2-8.2	5		
		2-8.3	4		
		(2-9)	2,3		
		2-9.1	2		
		2-9.2	3		
		(2-10)	3		
		(2-11)	3		

TABLE A.10 (Cont'd)

TRA-4		TRA-5		TRA-6	
Proj/Task	Product Code	Proj/Task	Product Code	Proj/Task	Product Code
(4-1)	3	(5-1)	1,3	(6-1)	1,3
4-1.1	3	5-1.1	3	6-1.1	3
4-1.2	3	5-1.2	3	6-1.2	2
4-1.3	3	5-1.3	1,3	6-1.3	2,3
4-1.4	3	(5-2)	3	(6-2)	1,2,3
4-1.5	3	5-2.1	3	6-2.1	3
4-1.6	3	5-2.2	3	6-2.2	1,3
4-1.7	3	5-2.3	3	6-2.3	3,5
4-1.8	3,5	5-2.4	3	6-2.4	2,3
4-1.9	3	5-2.5	4	6-2.5	3
4-1.10	5	(5-3)	2,3	6-2.7	1
(4-2)	3	5-3.1	3	(6-3)	2
4-2.1	1,2,3,5	5-3.2	2,3,5	(6-4)	3
4-2.2	2,3,4,5	5-3.3	3,5	(6-5)	4
(4-3)	3	5-3.4	2,3		
4-3.1	3	(5-4)	3		
4-3.2	3	5-4.1	3		
4-2.3	3	5-4.2	3		
4-3.4	3	5-4.3	3		
4-3.5	3	5-4.4	3		
4-3.6	3				
4-3.7	3				
4-3.8	5				
4-3.9	3,5				
(4-4)	3				
4-4.1	3				
4-4.2	3,5				
4-4.3	5				
4-4.4	3				
4-4.5	5				
4-4.6	5				

Note: See text for Product Code description

TABLE A.11

RESEARCH TOPICS NOT INCLUDED IN SHRP

TRA	Research Topic	TRA Reference
TRA-1	a) Shrinkage Cracking	Page TRA 1-18
	b) Reflection Cracking	
	c) Surface Wear	
	d) Aggregate Properties	
	e) Special End Uses	
	f) Asphalt Emulsions	
	g) Construction Methods	
TRA-3	a) Portable NDT Sensing Equipment	Page TRA 3-A-1
	b) Quantify Public Consequences	
	c) Improved Efficient Maint. Equipment	
	d) Equipment Management Needs	
	e) Strategic Model to Guide Management	
	f) Automated Interactive Field Scheduling	
TRA-4	a) Prestressed Concrete Cathodic Protection	Page TRA 4-A-1
	b) Improvements in Deck Joints	
	c) Long-Term Additives to PCC in Corrosion Protection	
	d) Service Life of Deck Protective Systems	
	e) Effectiveness and Life of Coating and Penetrants	
	f) Concrete Cover Requirements for Large Bars	
	g) Corrosion Protection Requirements for Other than Deck Elements	
	h) Effect of Cracks on Protective Systems	
	i) Influence of Design on Rehabilitation	
	j) Effect of Deck Design on Service Life	
	k) Effect of Fatigue in Epoxy-Coated Reinforcement	
	l) Noncorrosive Reinforcing Steel	
	m) Alternative Approaches to Accommodating Surface Runoff	
	n) Fundamental Studies of Corrosion of Prestressed Concrete Members	
	o) Performance and Corrosion Protection of Pretensioned Concrete Girders	
	p) Corrosion Protection Systems for Prestressed Concrete Construction	

TABLE A-11 (Cont'd)

TRA	Research Topic	TRA Reference
TRA-5	a) Chloride Phase Equilibria in Concrete	Page TRA 5-61
	b) Fundamental Studies - Steel Corrosion Mechanisms	
	c) Latex-Modified Concrete	
	d) Mech. Properties - Thin-Layer High-Fiber Content Concrete	
	e) Roller Compacted Concrete	
	f) Fiber Shotcrete	
	g) Influence of Aggregate Gradation on Concrete Performance	
	h) Control of Plastic Shrinkage Cracking	
	i) Recycling Concrete	
	j) Aggregate Beneficiation	
	k) Free Moisture in Aggregates	
	l) Adequacy of Curing	
TRA-6	a) Thermal Methods of Snow and Ice Removal	Page TRA 6-A-1
	b) Test and Evaluation of CMA	
	c) Improvement of Resource Planning and Program Evaluation	
	d) Demonstration of Technology-Based Winter Maintenance Operation System	
	e) Productivity Improvement Through Improved Labor Management Relations	

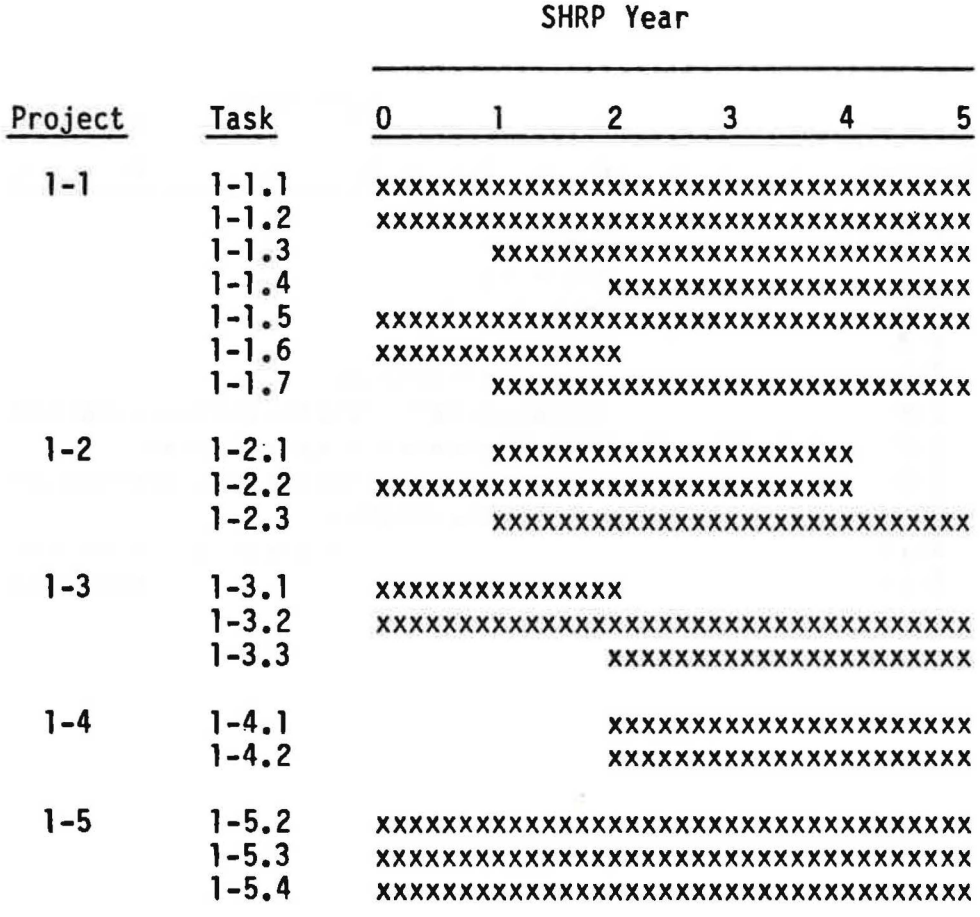


FIGURE A.1 RESEARCH PROJECT SCHEDULE (TRA-1)

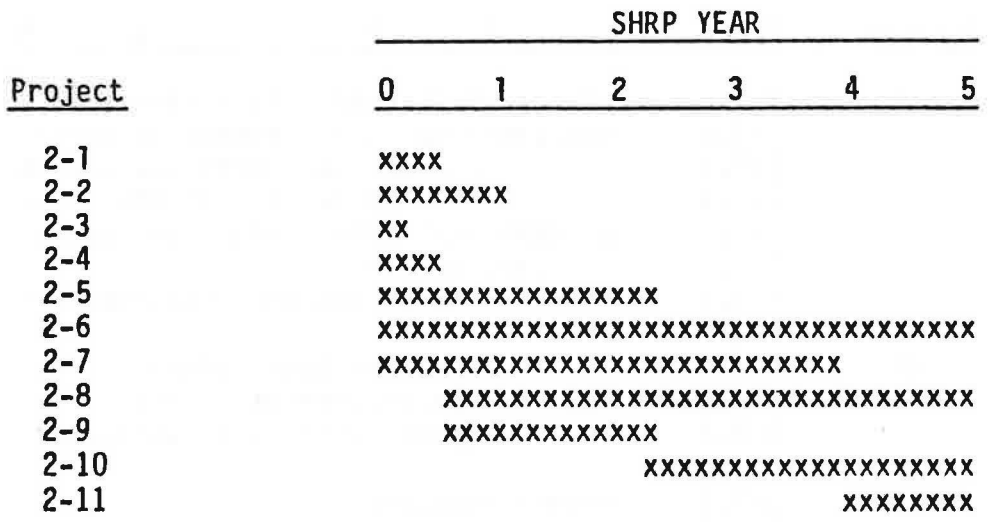


FIGURE A.2 RESEARCH PROJECT SCHEDULE (TRA-2)

Project	Task	SHRP YEAR 0	1	2	3	4	5
3-1	3-1.1	xxxx					
	3-1.2		xxxx				
	3-1.3	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	3-1.4			xxxxxxxxxxxxxxxxxxxx			
	3-1.5				xxxxxxxxxxxxx		
3-2	3-2.1	xxxxxx					
	3-2.2		xxxx				
	3-2.3			xxxxxxxxxxxxxxxxxxx			
	3-2.4					xxxxxxx	
3-3	3-3.1	xxxxxxxxxxxxx					
	3-3.2	xxxxxxxxxxxxx					
	3-3.3		xxxxxxxxxxxxx				
	3-3.4			xxxxxxxxxxxxxxxxxx			
	3-3.5		xxxxxxxxxxxxxxxxxxxxxxxx				
	3-3.6				xxxxxxxxxxxxx		
3-4	3-4.1	xxxxxxx					
	3-4.2		xxxxxxxxx				
	3-4.3			xxxxxxxxxxxxxxxxxxxx			
	3-4.4				xxxxxxxxxx		
3-5	—			xxxxxxxxxxxxxxxxxx			

FIGURE A.3 RESEARCH PROJECT SCHEDULE (TRA-3)

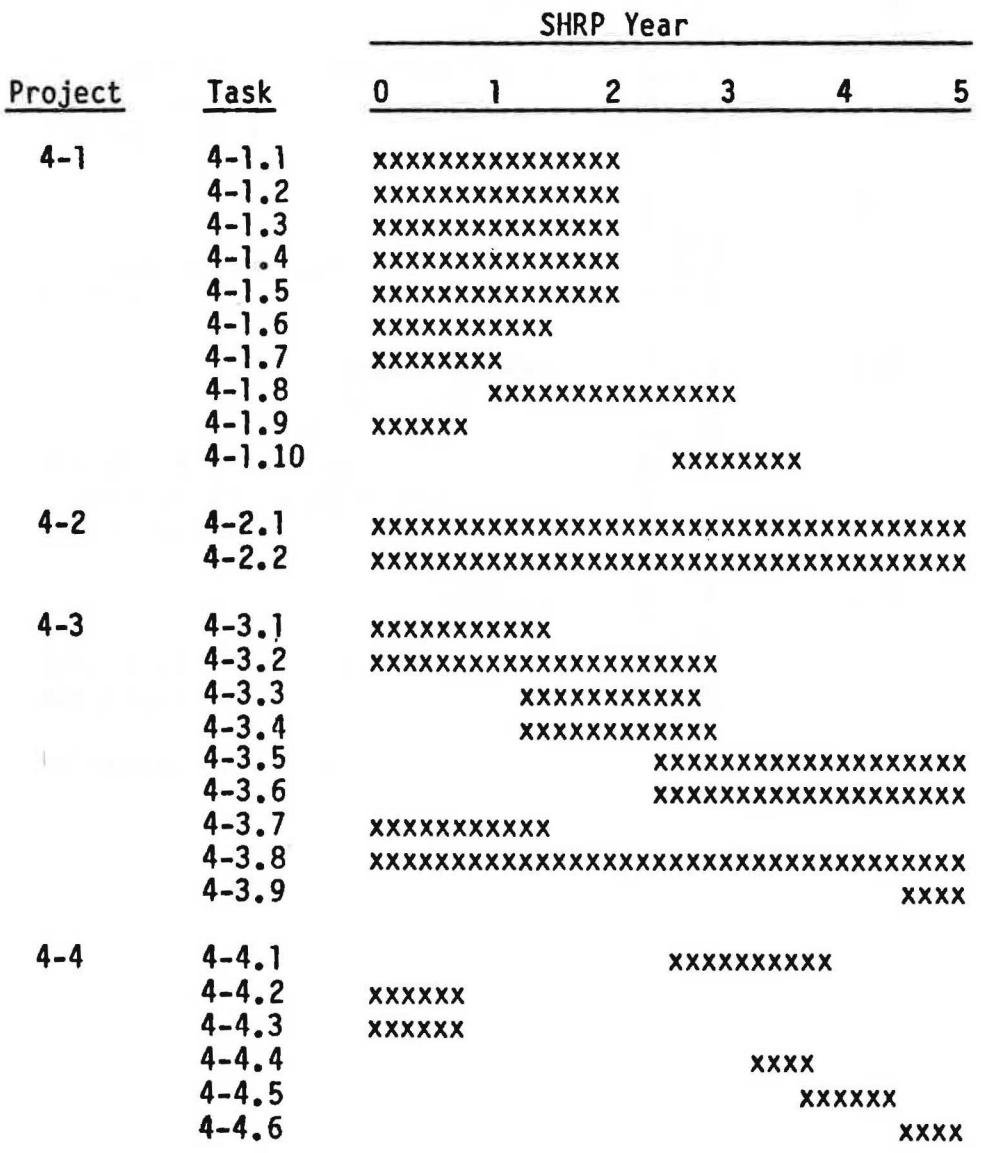


FIGURE A.4 RESEARCH PROJECT SCHEDULE (TRA-4)

Project	Task	SHRP Year 0	1	2	3	4	5
5-1	5-1.1	xxxxxxxxxxxxxxxxxxxx					
	5-1.2	xxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-1.3				xxxxxxxxxxxxxx		
5-2	5-2.1	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-2.2		xxxxxxxxxxxxxxxxxxxxxxxxxxxx				
	5-2.3	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-2.4	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-2.5				xxxxxxxxxxxxxx		
5-3	5-3.1	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-3.2	xxxxxxxxxxxxxxxxxxx					
	5-3.3	xxxxxxxxxxxxxxxxxxx					
	5-3.4		xxxxxxxxxxxxxxxxxxxxxxxxxxx				
5-4	5-4.1	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-4.2	xxxxxxxxxxxxxxxxxxx					
	5-4.3	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					
	5-4.4		xxxxxxxxxxxxxxxxxxxxxxxxxxx				

FIGURE A.5 RESEARCH PROJECT SCHEDULE (TRA-5)

Project	Task	SHRP Year 0	1	2	3	4	5
6-1	6-1.1	xxxxxxxxxxxxxxxx					
	6-1.2			xxxxxxxxxxxxxxxxxxxxxxx			
	6-1.3			xxxxxxxxxxxxxxxxxxxxxxx			
6-2	6-2.1	xxxxxxxxxxxxxxxxx					
	6-2.2			xxxxxxxxxxxxxxxxxxxxxxx			
	6-2.3			xxxxxxxxxxxxxxxxxxxxxxx			
	6-2.4			xxxxxxxxxxxxxxxxxxxxxxx			
	6-2.5	xxxxxxxxxxxxxxxxx					
	6-2.7	xxxxxxxxxxxxxxxxx					
6-3		xxxxxxxxxxxxxxxxxxxxxxx					
6-4					xxxxxxxxxxxxxxxxx		
6-5		xxxxxxxxxxxxxxxxxxxxxxx					

FIGURE A.6 RESEARCH PROJECT SCHEDULE (TRA-6)

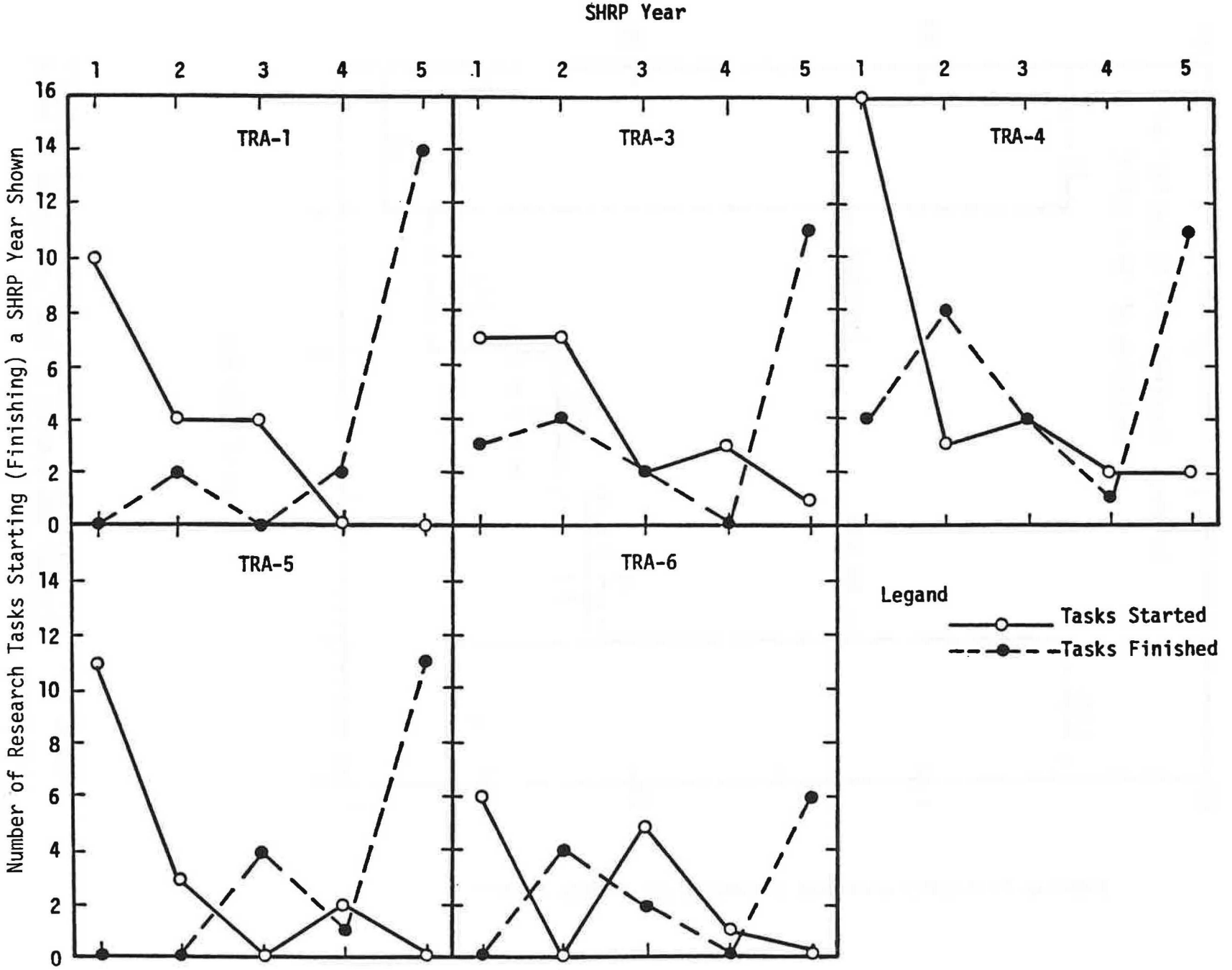


FIGURE A.7 ANNUAL DISTRIBUTION OF RESEARCH TASKS STARTING AND FINISHING (Exclusive of TRA-2)

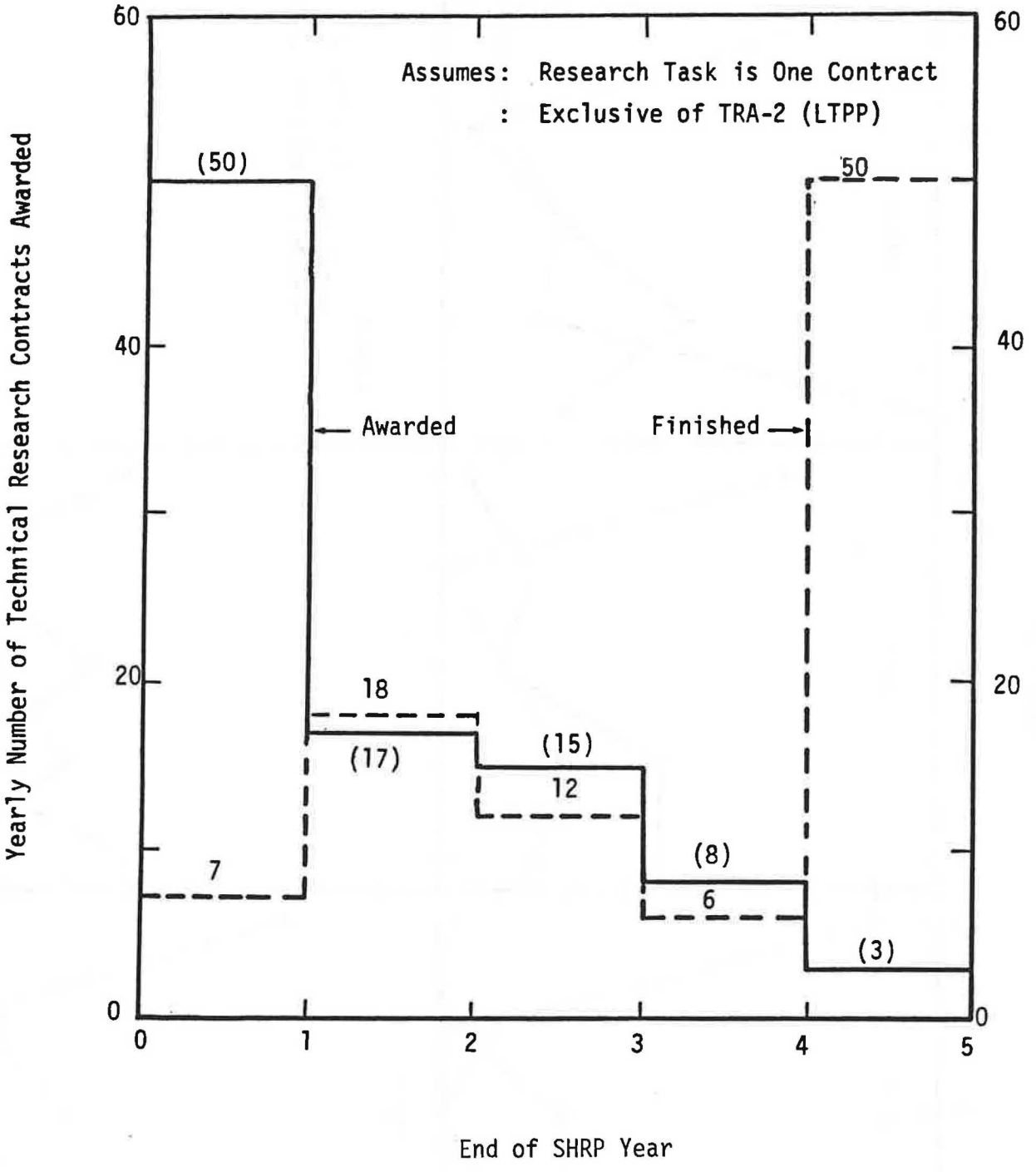


FIGURE A.8 DISTRIBUTION OF TECHNICAL RESEARCH AREA CONTRACTS FINISHED AND AWARDED BY YEAR (EXCLUSIVE OF TRA-2)

TECHNICAL RESEARCH AREA 1
DETAILED PLANNING FOR RESEARCH ON ASPHALT PROPERTIES

Prepared for:
NCHRP Project Number 20-20(3)
Pre-Implementation Activities for the
Strategic Highway Research Program (SHRP)

January 1986

Prepared by:
ARE Inc - Engineering Consultants
2600 Dellana Lane
Austin, Texas 78746

TABLE OF CONTENTS

		Page
	LIST OF FIGURES.	TRA 1-ii
	LIST OF TABLES	TRA 1-iii
	ABSTRACT	TRA 1-iv
	ACKNOWLEDGEMENTS	TRA 1-v
SECTION 1	STATEMENT OF THE PROBLEM	TRA 1-1
SECTION 2	GOALS AND OBJECTIVES OF THE PLAN	TRA 1-5
SECTION 3	FORMULATION OF THE PLAN.	TRA 1-11
SECTION 4	RECOMMENDED RESEARCH PLAN.	TRA 1-19
SECTION 5	RESULTS TO BE ACHIEVED	TRA 1-54
SECTION 6	IMPLEMENTATION OF RESULTS.	TRA 1-57
SECTION 7	SCHEDULE OF PROJECTS, TASKS, AND SUBTASKS.	TRA 1-59
SECTION 8	BUDGET	TRA 1-61
	REFERENCES	TRA 1-66
APPENDIX A	BIBLIOGRAPHY	TRA 1-A-1

LIST OF FIGURES

		Page
FIGURE 1	FIVE RESEARCH PROJECTS IN TRA 1	TRA 1-16
FIGURE 2	ORGANIZATION CHART FOR TRA 1 RESEARCH TASKS	TRA 1-17
FIGURE 3	RESEARCH PLAN FOR TRA 1	TRA 1-22
FIGURE 4	SCHEDULING PLAN FOR TRA 1	TRA 1-60
FIGURE 5	SCHEDULING AND BUDGET DIAGRAM FOR TASKS IN TRA 1. . .	TRA 1-62
FIGURE 6	SCHEDULING AND BUDGET DIAGRAM FOR SUBTASKS IN TRA 1 .	TRA 1-63

LIST OF TABLES

		Page
TABLE 1	SUMMARY OF PROJECTS, TASKS AND BUDGET ESTIMATES . . .	TRA 1-12
TABLE 2	RESEARCH TOPICS NOT INCLUDED IN TRA 1	TRA 1-18
TABLE 3	ESTIMATED BUDGET REQUIREMENTS FOR EQUIPMENT ACQUISITIONS.	TRA 1-64

ABSTRACT

The Strategic Highway Research Program has been organized into six research areas; each area has specific objectives designed to reduce costs and improve pavement performance.

The primary goals for each research area have been described in some detail in Transportation Research Board Special Report 202, "America's Highways - Accelerating the Search for Innovation." Technical Research Area 1 (TRA 1) is designed to carry out a program of fundamental and applied research leading to: 1) specifications for an asphalt binder which will reliably contribute to improved performance of asphaltic mixtures and 2) new requirements for asphalt-aggregate mixtures which will improve the peformance of asphalt-type pavements.

The recommended plan includes provision for the development of a better understanding of the basic properties of asphalt and how these properties influence performance of asphalt-aggregate mixtures.

A study of ways to modify asphalt to obtain an improved binder is an important aspect of the research plan.

In order to achieve objectives within the constraints of time and budget, the program is focused on specific activities, i.e., to improve the properties of the asphalt binder and to reduce the possibilities of premature distress of asphalt-aggregate mixtures.

Based on recommendations of the Asphalt Advisory Committee, the applied research will emphasize problems associated with asphalt-aggregate adhesion, fatigue cracking, low temperature shrinkage cracking and permanent deformation.

Some 25 research tasks have been identified in the plan. Because of the interrelationships of the various tasks, it will be necessary to provide close coordination between each task in order to assure that the combined research effort will achieve the required results.

The final results of TRA 1 are:

1. Develop a set of performance-based specifications for asphalt, with or without modification using virgin or recycled asphalt.
2. Develop performance-based requirements for an asphalt-aggregate mixture system, utilizing asphalts with and without modification using virgin or recycled asphalt.

ACKNOWLEDGEMENTS

This research plan has been prepared under the supervision of Fred N. Finn, ARE Inc - Engineering Consultants with assistance from Dr. Claine Petersen, Distinguished Scientist, Western Research Institute, Dr. Jon Epps, Professor of Civil Engineering, University of Nevada (Reno), Dr. Virgil Anderson, Professor of Statistics, Purdue University, C. L. Monismith, Professor of Civil Engineering, University of California (Berkeley), and B. A. Vallerga, Consulting Engineer, Oakland, California.

SECTION 1
STATEMENT OF THE PROBLEM

As the number of vehicles using the nations highways increase, the challenge to maintain the pavements in serviceable condition at reasonable (acceptable) cost becomes increasingly difficult. Not only are the number of vehicles increasing, but the axle weights, axle configuration and tire pressures are also increasing and each is placing more demands on construction materials. Progress has been made through research; however, there are mounting indications that there is a need for a major leap forward in order not to incur an increasing burden on the public in terms of cost and/or inconvenience through poor pavement performance.

Research designed to extend the life cycle of pavements, to reduce maintenance costs and to minimize the number of premature pavement failures would be highly beneficial and will justify a major research effort. It has been estimated that "... a 1 percent improvement in product life would mean a saving of $100 million a year" (1). Achieving such an objective should be within the grasp of technology, providing adequate resources are available.

The research literature contains a considerable amount of information concerning the chemical and physical properties of asphalt and the properties of asphalt-aggregate mixtures. Unfortunately, there have been very few opportunities to evaluate the various research hypotheses put forward by these research efforts.

Most of the fundamental research on asphalt has been carried out by the producers of asphalt, while specifications have traditionally been prepared jointly by users and producers of asphalt. Improvements in specifications have generally been limited to: 1) improved methods of testing to measure consistency in fundamental units, 2) studies of temperature susceptibility measured in terms of asphalt consistency, 3) short term aging properties based on change in consistency or 4) studies of asphalt-aggregate adhesion as measured by strength retention after being subjected to simulated environmental conditions.

While significant, these modifications in specifications have not attempted to incorporate the results of fundamental research on asphalt and its relationships to pavement performance. In large part, the research findings have been fragmented, sometimes contradictory and lacking in any significant amount of well-documented, long-term field studies to determine the effect on pavement performance. In fact, the results of research have led to a general proliferation of specifications; for example, at last count, there were 32 distinct state specifications for an AC-20 asphalt cement.

A major problem contributing to the lack of a better understanding of the desired properties of asphalt has been the lack of funds to support a well

planned research program and the general absence of a coordinated effort to apply research findings to asphalt specifications. Similar problems exist with regard to research and implementation of information concerning asphalt-aggregate mixtures. Nevertheless, the research that has been accomplished should provide an excellent basis from which to initiate a well-planned and coordinated effort to improve the properties of asphalt and to develop procedures for combining asphalt and aggregate to produce mixtures with properties to reduce the rate of aging, to minimize the adverse influence of environment and to sustain repeated numbers of traffic loadings without exhibiting distress.

Examples of asphalt research in the United States can be found in the Proceedings of the Association of Asphalt Paving Technologists, publications of the Transportation Research Board, the Journal of the Institute of Petroleum, the Journal of Applied Chemistry and Transactions of the Society of Rheology. Similar types of research also appear in international journals and publications. A bibliography of pertinent publications is contained in Appendix A.

Research synthesis reports prepared by Halstead (2) and Petersen (3) provide an excellent background of information and a general summary of the current (1985) state of the knowledge concerning the status of asphalt technology.

Publications by Welborn (4), Heukelom (5), Duthie (6), McLeod (7), Puzinauskas (8), Jennings (9), Corbett (10), Rostler (11), Anderson (12) and Brule (13) provide more in depth indication of the status of asphalt research with both U.S. and international contributions.

Technical Research Area Number One (TRA 1) of the Strategic Highway Research Program has been prepared as a plan to overcome the problems which have, to date, contributed to a lack of understanding of the properties of asphalt and their influence on pavement performance. The results will contribute to more reliable and reduced life cycle costs for asphaltic pavements.

The problems related to the study of asphalt for use in pavements is extremely complicated. For example, it has been estimated (10) that there are over 600 different sources of asphalt used in the United States involving up to 200 crude sources (1), and produced to comply with a variety of regional and agency specification requirements. In addition, the role of asphalt and its in-service properties are affected by the composition and morphology of the aggregate. Add to this the variable influence of environment, i.e., temperature, rainfall or moisture accumulation, solar radiation, etc. and the problem becomes very complex.

An important result of TRA 1 will be the development of new performance-based specificatons for asphalt which will not only take into account properties needed for construction, but will specify properties important to the long-term performance and durability of the pavement.

Elements of the program are highly interrelated and interdependent requiring a high degree of coordination among research tasks. Some diversification of the research effort is considered desirable in order to maximize the amount of expertise available to work on the total problem and

ultimately provide support for implementation.

At the first meeting of the TRA 1 Advisory Committee, a set of study area projects was established as having sufficient merit and potential benefits to justify inclusion in the Strategic Highway Research Program. The specific study areas, by priorities were:

Priority	Study Area
1	Asphalt Durability
2	Asphalt Aggregate Adhesion
3	Permanent Deformation
4	Fatigue Cracking
5	Low Temperature Cracking
6, 7 (tie)	Reflection Cracking and Performance Based Specifications
8	Wear Resistance
9	Shrinkage Cracking

There were other study areas considered; e.g., special requirements for surface treatments, patching, open graded mixes, thin overlays or research on emulsions. It was recognized, however, that the program should be focused on asphalt cement and dense graded mixtures. If the program were to be diluted by adding too many study areas, there would be an unacceptable risk of not making adequate progress to develop needed benefits. In fact, some of the nine priority items were eventually deleted from the recommended program.

The Federal Highway Administration had, with the help of knowledgeable experts, previously established a similar list of priorities for guidance in planning a federal coordinated program of research. The top ten from the FHWA list included all of those identified by the Advisory Committee. In addition, the FHWA list included provision for training. The Advisory Committee also considered training (and construction) to be a high priority item; however, since training, per se, is not considered to fall within the general definition of research, it was deleted. The role of construction was considered implicit to specific study areas; however, it will not be included as a specific research topic.

The members of the AASHTO Subcommittee on Materials were canvassed by a member of the Advisory Committee relative to asphalt topics which they considered appropriate for research within SHRP. Their responses were more specific with regard to asphalt research and included the following ten items:

	Topic	Number of States Indicating Topic to be Included in SHRP
1.	Stripping	14
2.	Asphalt additives	12
3.	Asphalt chemistry	9
4.	Asphalt test methods	9
5.	Asphalt aging	8
6.	Mix design	8
7.	Asphalt specifications	7
8.	Asphalt temperature-susceptibility	6
9.	Low temperature properties	5
10.	Tire pressure	4

Items such as: construction, rutting, recycling and compaction were nominated from one or two states.

In summary, research dealing with the fundamental properties of asphalt and the role of asphalt to pavement performance has been undertaken piecemeal with limited funds and very little opportunity to obtain correlations with performance. Implementation of research results has generally been applied to the grading of asphalt cement by consistency categories and to short term aging related primarily to the time frame required to mix, place and compact the mixture. SHRP provides the first real opportunity to exploit research opportunities in a coordinated, adequately funded research program designed to improve the cost-effective use of asphalt binders in asphalt-aggregate systems.

A nationally accepted specification for a quality asphalt binder, and the ability to measure the properties which contribute to quality, is a worthwhile objective for SHRP.

SECTION 2
GOALS AND OBJECTIVES OF THE PLAN

Goals and objectives for the detailed planning of research on asphalt properties have been prepared with input from four primary sources: 1) Transportation Research Board Special Report 202, 2) AASHTO Task Force for SHRP, 3) National Asphalt Advisory Committee appointed by the Task Force and 4) consultants retained to prepare research plan.

The AASHTO Task Force has provided policy guidelines to be used in formulating the research plan. The Advisory Committee has provided information and recommendations which they believed would result in a productive research program.

Special Report 202 (1) has provided a series of guidelines which have been used by the Advisory Committee and the Consultant in preparing a research plan. Specific objectives and goals from Special Report 202 are reproduced herein for ready reference for readers of this report.

The overall objective of the asphalt research effort was given in Special Report 202 as follows:

> Objective: To improve pavement performance through a research program that will provide increased understanding of the chemical and physical properties of asphalt cements and asphaltic concretes. The research results would be used to develop specifications, tests, and construction procedures needed to achieve and control the pavement performance desired.

Thus, the overall objective for the program was to study the chemical and physical properties of asphalt cement and asphaltic concrete. The results of the research are to be used to develop specifications, standard tests and construction procedures.

The research plan outlined in Section 4 of this report places considerable emphasis on the study of the chemical and physical properties of asphalt, i.e., approximately 59 percent of the budget. Specifications, tests and pavement performance are also apparent in the plan. Construction procedures, while not specifically incorporated in the research plan, will evolve from the results of research. For example, research on asphalt will help to determine what asphalt to use in various design and construction situations (traffic, environment, etc.) and research on asphaltic concrete will help determine construction requirements in order to achieve desired properties of the mixture. The construction procedures to achieve the desired results will generally be left to the various specification writing agencies

and state highway agencies. Nevertheless, in preparing implementation packages for research findings, research contractors will be required to give consideration to the role of construction needed to achieve the desired results. The overriding consideration expressed in Special Report 202 is summarized in the following sentence "... Construction defects, which account for numerous failures, might be less costly if more reliable, durable asphalts were developed and functional specifications were drawn so that products were more forgiving of field errors."

Some of the "forgiving" characteristics considered appropriate and beneficial were enumerated in Special Report 202 as follows:

- A tolerance for a wide range of mixing temperatures and physical and chemical properties of aggregates used in the mix;
- Sustained adhesion to aggregates of different composition, temperature, and dryness;
- Stability under varying asphalt cement proportions in the mix;
- Stability under high ambient temperatures;
- Long-term retention of adhesion;
- Flexibility under low temperatures and over a long service life of exposure to atmosphere, sunlight, dust, moisture and traffic; and
- Recyclability.

Five major objectives provided in Special Report 202 are reproduced with comments in the following paragraphs of this report.

1. Identify and describe asphalt properties. Research would be directed at better identification and description of the chemical and physical properties of asphalt cements and their interrelationships. Chemical analyses would determine the chemical characteristics of asphalts by using the most modern chemical and instrumental techniques available. Chemical characteristics would be correlated with existing and newly developed measures of the physical characteristics of asphalt cement. The research would be used to identify the characteristics of, and ranges of variation in, crude petroleums and assess the effects of these variations on asphalt properties. It would also be used to analyze existing and prospective refining processes in terms of their effects on asphalts.

This objective is considered one of three cornerstones used to develop the TRA 1 research program. The research goals within this objective can be divided into two categories: 1) basic research, and 2) fundamental research.

Basic research, as used here, refers to those activities which are designed to produce basic information intended to develop a better understanding of the chemical and physical properties of asphalt and their interrelationship. This is general "high risk" research, in that no implementable benefits are identified at the beginning of the research but may evolve as the research progresses. Basic research is likely to produce benefits in the long term, but such "break-throughs" could potentially have major impacts on a multiplicity of problems. Examples of basic research could include the study of molecular composition of asphalt or the relationship between heteroatoms in asphalt and the physical properties of asphalt.

Fundamental or applied research refers to research directed toward solving specific problems. For example, to determine what chemical or physical properties of asphalt most significantly influence long-term bonding of asphalt to aggregate, or the durability of asphalt.

It was the consensus of the Advisory Committee, as well as views reported by the FHWA/FCP panel, that chemical properties of asphalt would not be useful in preparation of asphalt specifications but would have application for: 1) manufacture of asphalt by refiners based on a knowledge of the chemistry of the crude source and 2) an understanding of how and which chemical properties influence the physical properties of asphalt.

It should not be concluded that asphalt specifications will not include some measure of the chemical properties of asphalt. While there is no suggestion in the research plan to discard what is known about asphalt properties, there is also no constraint on new and innovative concepts which could be beneficial; in fact, the Strategic Highway Research Program encourages the study of non-traditional "ideas" which can be exploited through a well-documented research plan.

2. Design improved testing and measuring systems. Weaknesses in the asphalt pavement design and construction process are in part attributable to the limited ability of outdated testing and descriptive methods to identify the characteristics of asphalts. The investigations would be used to develop totally new tests that are not tied to colligative properties of asphalt to determine the physical characteristics of asphalts and that would reflect the more realistic temperature ranges of asphalts in the field.

For the most part, the objectives of testing asphalts for inclusion in specifications has undergone very little change in the past 50 years. The basic measurement of consistency remains as the primary specification requirement. The method of measurement has been improved by the introduction of viscosity requirements rather than measures of penetration; however, even this change is subject to some disagreement. Agencies have developed aging indices as a measure of durability; however, these are empirically based indices which do not reflect any significant background of fundamental research. Temperature-susceptibility has also been studied based on measurements of viscosity over a range of temperatures not always representative of field conditions. Fracture and shear-susceptibility properties, which may influence the role of asphalt in an asphalt-aggregate system, are not specified directly, although they may be indirectly evaluated

by the ductility test at various temperatures.

The "bottom-line" will be to determine if new tests and measurements will help to identify the properties of asphalt and to develop test methods which can be realistically incorporated in a standard specification.

3. Determine relationship of asphalt cement and pavement performance. Physical testing of asphalt cement performance in paving mixes would be performed using mechanical testing devices to simulate loads, wear, and environmental conditions at normal and accelerated rates. Validation of these test results would be sought through field testing of in-service pavement sections, using existing old pavements where adequate historical data are available and new pavement sections as required.

   The pavement testing phase of the study would be in part incorporated with the long-range pavement performance studies that are a separate part of the Strategic Highway Research Program. The research would include evaluation of both the micro- and macro- conditions affecting performance. Consideration would be given to materials, placement, homogeneity, and other factors. The study may include fracture mechanics and the mechanisms of degradation. The opportunity to use state-of-the-art computer analyses and artificial intelligence concepts in addressing the extensive data and correlation of variables would be considered.

This objective is clearly a key to a successful research program. Without performance information, it will not be possible to determine which properties to specify in the asphalt cement or asphaltic concrete which will lead to the optimal performance of the system. However, it must be recognized that the measurement of pavement performance alone will not be sufficient. Performance will be the dependent variable in the research effort, influence variables (independent) as developed in objective No. 1 will also be essential.

In order to relate the properties of the virgin asphalt to pavement performance, it will be necessary to obtain a sample of the original, unadulterated and unaged asphalt. This is possible for in-service pavements but is unlikely for pavements which have been in service for extended periods of time. It is also unlikely that construction records would contain sufficient information to satisfy research requirements.

The most probable sources of performance and material information needed for TRA 1 will be provided from special pavement studies (SPS) incorporated in TRA 2, Long Term Pavement Performance. Unfortunately, these studies are not likely to be underway before three years into the program and useful performance information will not be available in that time frame. Nevertheless, a well-planned experiment design to meet TRA 1 requirements, and incorporated into the TRA 2 program, will be an essential component of the research plan.

If in-service pavements are not suited to TRA 1 requirements and the

SPS sections in TRA 2 will not produce timely information, the plan must provide for performance information from other sources. Some possibilities in the research plan include:

1. Special research projects underway by state highway agencies, the Federal Highway Administration or industry.
2. Historical projects which have been extensively described in the literature and for which asphalt properties and pavement performance are described. Appendix A contains a number of references for projects in the United States and abroad.
3. Accelerated laboratory tests designed to obtain specific types of information over a relatively (1-3 yrs) short time frame (14).
4. Accelerated field tests, such as those at Pennsylvania State University or Washington State University, (15, 16) or on a somewhat smaller scale, the AMOCO test facility (17) would be possibilities.
5. The use of experienced materials engineers as a rapid source of information concerning asphalt properties and pavement performance is a source of information which should not be overlooked. These techniques (Bayesian methodology or knowledge based expert systems) have been described in the literature and are of sufficient merit to warrant investigation (18, 19).
6. Use of the planned accelerated loading facility (ALF) of the Federal Highway Administration could provide another source of accelerated information relative to pavement performance and asphalt properties.
7. Consideration can also be given to SPS sections designed for early failure. For example, such an approach could test hypotheses for poor quality asphalt and, when combined with structural design considerations, could be useful in comparisons between sections constructed with asphalts and asphalt-aggregate systems of widely different properties. A carefully designed experiment would be required for this type evaluation; the procedure does not necessarily need to be limited to field studies.

A major problem in any accelerated testing program is the problem of accelerating the effects of time. Some investigators have attempted to accelerate the aging of asphalts prior to testing the asphalt-aggregate system (20) with some success. However, the process of accelerated aging will require further evaluation to assure the credibility of the process. Also, aging in sufficient quantities to undertake meaningful testing will be a problem for research agencies.

4. Analyze the desired characteristics of a pavement material. The research would identify the key characteristics required for asphalt paving materials using measures and criteria developed in the study to define asphalts more precisely and predict service more accurately.

In order to achieve the overall objective of this research area (TRA 1), it will be necessary to carefully analyze all of the information which can be made available in the five year program and to determine: 1) the properties of the asphalt which significantly influence pavement performance, 2) the properties of asphalt-aggregate systems which significantly influence

pavement performance and 3) to predict pavement performance as a function of asphalt properties and asphalt-aggregate properties.

The key to this activity will be to develop performance prediction models which incorporate the properties of asphalt and which are responsive to the properties of the asphalt-aggregate combinations, environment, traffic and structural design. It can be expected that prediction models related to physical distress in pavements will be dependent on the physical properties of the asphalt or asphalt-aggregate system. However, in order to be useful for formulating an asphalt binder the physiochemical relationships need to be established, i.e., how do the chemical properties influence the physical properties of asphalt.

5. Develop model asphalts. Research would be performed to separate asphalt cements into their basic molecular structures and reconstitute them as artificial asphalts with the desired properties. Model asphalts would be determined or hypothesized for various regions of the nation. Asphalt cements modified by polymers, sulfur, rubber, and other additives would be studied as candidates for improved asphalt cements.

The development of procedures to produce a binder, asphalt or a modified asphalt, which will enhance the performance of asphalt pavements is the goal of this objective. All of the previous objectives are directed toward identifying the required properties of an asphalt binder; the output for this objective would be to describe how to produce an asphalt type binder which would be more cost-effective than asphalts being produced under current specifications.

Taking into consideration the guidelines and objectives provided in Special Report 202 and the SHRP Task Force, the Consultant with the help of the Advisory Committee has prepared a research plan as described in the following sections of this report.

SECTION 3
FORMULATION OF THE PLAN

Formulation of the research plan for TRA 1 was accomplished as a joint effort of the National Asphalt Advisory Committee, the SHRP Task Force and the Consultant team charged with preparation of the research plan.

A listing of members of the National Advisory Committee is shown in front matter. This Committee provided specific recommendations and advice regarding preparation of the research plan. It was not possible to incorporate all of the recommendations of the Advisory Committee in the research plan. All of the advice provided by the Advisory Committee was considered to have merit; however, due to constraints of funding and the need to focus research on specific objectives, some research needs were not considered appropriate under the SHRP plan.

In order to comply with the research objectives contained in Special Report 202, and to meet the requirements of the Task Force to focus on asphalt properties as an emphasis area, specific constraints were established in preparing the TRA 1 research plan. However, operating within these constraints will not detract from the opportunity to make major breakthroughs in asphalt technology which will lead to improved performance and, in the long term, reduced costs. Specific constraints or guidelines used to prepare the research plan were:

1) the research program must conform to the objectives of Special Report 202,
2) the total funding must not exceed 50 million dollars,
3) results must be obtained within the five (5) year time frame established by SHRP,
4) emphasis will be placed on research related to bulk asphalt and modified asphalt to produce a more forgiving asphalt, and
5) the final product will be performance-based specifications for asphalt, with or without modification, and the development of an asphalt-aggregate mixture analysis system (AAMAS).

As would be expected, there were differences of opinion among members of the Advisory Committee as to research topics, funding for specific tasks and the problems of achieving results within five years. Each of these subjects was discussed thoroughly during the three (3) meetings of the Advisory Committee and during working sessions at the National Workshop in September, 1985.

The program as finally formulated is summarized in Table 1, listing five (5) projects and 25 tasks and subtasks. Total funding for each project and task is also provided. It is expected that the main features and focus of

Table 1

Summary of Projects, Tasks and Budget Estimates

Project 1-1 Asphalt Properties

1-1.1*	Asphalt Chemical Composition		4,000,000
1.2	Physical Properties of Asphalt		2,500,000
1.3(2)**	Relationships Between Asphalt Chemical and Physical Properties		3,500,000
1.4(3)	Relationships of Asphalt Chemical and Physical Properties to Pavement Performance		2,000,000
1.5	Fundamental Properties of Asphalt-Aggregate Interaction Including Adhesion and Absorption		
	1.5,a.***	Physiochemical Properties of Asphalt at the Asphalt-Aggregate Interface	2,500,000
	1.5,b.	Physiochemical Properties of Asphalt Used with Absorptive Aggregates	1,500,000
1.6	Survey of Current Manufacturing Practices		1,000,000
1.7(2)	Asphalt Modification		5,000,000
		TOTAL	22,000,000

* 1-1.1 First number designates research area, and second number identifies project; number following decimal point identifies task.

** 1.3(2) Numeral in parentheses indicates program year in which task is to be started.

*** 1.5,a. Alpha letter identifies subtask.

Table 1 (Cont'd)

Project 1-2 Performance-Based Testing and Measuring Systems

2.1(2)	Testing and Measuring Systems for Asphalt (with and without asphalt modification)	3,500,000
2.2	Testing and Measuring for Asphalt-Aggregate Systems (with and without asphalt modification)	
	2.2,a. Fatigue Cracking of Asphalt-Aggregate Systems	2,000,000
	2.2,b. Permanent Deformation of Asphalt-Aggregate Systems	2,500,000
	2.2,c. Low Temperature Cracking of Asphalt-Aggregate Systems	1,500,000
	2.2,d. Aging of Asphalt-Aggregate Systems	1,000,000
	2.2,e. Water Sensitivity of Asphalt-Aggregate Systems	1,500,000
2.3(3)	Relationship of Asphalt Chemical and Physical Properties to Asphalt-Aggregate Mixture Properties	3,000,000
	TOTAL	15,000,000

Project 1-3 Pavement Performance Studies

3.1(2)	Model Development	500,000
3.2	Asphalt Performance Studies	3,000,000
3.3(3)	Evaluation Procedures for Prediction Models	1,000,000
		4,500,000

Table 1 (Cont'd)

Project 1-4 Preparation of Performance Based Specifications for Asphalt and Asphalt-Aggregate Systems

4.1(3)	Performance-Based Specifications for Asphalt	3,000,000
4.2(3)	Performance Based Specifications for Asphalt-Aggregate Systems (AAMAS)	2,000,000
	TOTAL	5,000,000
	Totals for Projects 1-1, 1-2, 1-3 and 1-4	46,500,000
	Available for coordination activities, Project 1-5	3,500,000
	GRAND TOTAL	50,000,000

Project 1-5 Coordination

5.1	Research Project Coordination	1,000,000
5.2	Operate Materials Reference Library	1,500,000
5.3	Experiment Design	500,000
5.4	Economic Considerations	100,000
5.5	Implementation Packages	400,000
	TOTAL	3,500,000

the plan will remain in place during the term of the program; however, it can be expected that specific tasks and funding may be modified or deleted and new requirements added as the program proceeds. To a large extent, changes will be the result of research findings which emerge as the program proceeds.

Figure 1 indicates the five project areas included in TRA 1. Figure 2 illustrates the overall organization of the specific projects and tasks and provides some indication of major interactions between tasks. In actual conduct of the research, it is expected that there will be some interrelationships among all of the tasks in the program, i.e., each task will have some impact on virtually every other task in the program. Figure 2 attempts to illustrate some of the more obvious interrelationships between tasks; a more complete indication would require connections from each task to all other tasks.

Because of the interdependence between projects, emphasis has been placed on Task 5 - Coordination. Some of the coordination tasks tend to be administrative, while others are technical; both will require close attention to avoid a breakdown in the program and to assure maximum productivity.

A certain amount of redundancy is built into the overall program. For example, Tasks 1.1 and 1.2 deal with studies of asphalt chemical and physical properties. This research will include both basic research and fundamental research as previously defined. Task 1.3(2), starting in the second year, will deal with the relationships between chemical and physical properties of asphalt to pavement performance. In the process of undertaking Task 1.3, the researcher will be using tentative findings from the previous two tasks and will have an opportunity to interact with researchers in each of these tasks. In this way an increased number of investigators will become involved in the overall research program. Similar types of interaction and to some extent duplications will occur in a number of other tasks. In the total program, it is considered that a certain amount of overlapping will provide quality assurance for the total program and will expand the number of technologists involved in the program.

As previously indicated, and in order to maintain the focus of the program and to avoid diluting the research effort, a number of worthwhile projects have not been included in TRA 1. Table 2 summarizes those topics which had significant support from the Advisory Committee, the National Workshop or the Consultants retained to prepare the research statements but were not included in the recommended research program.

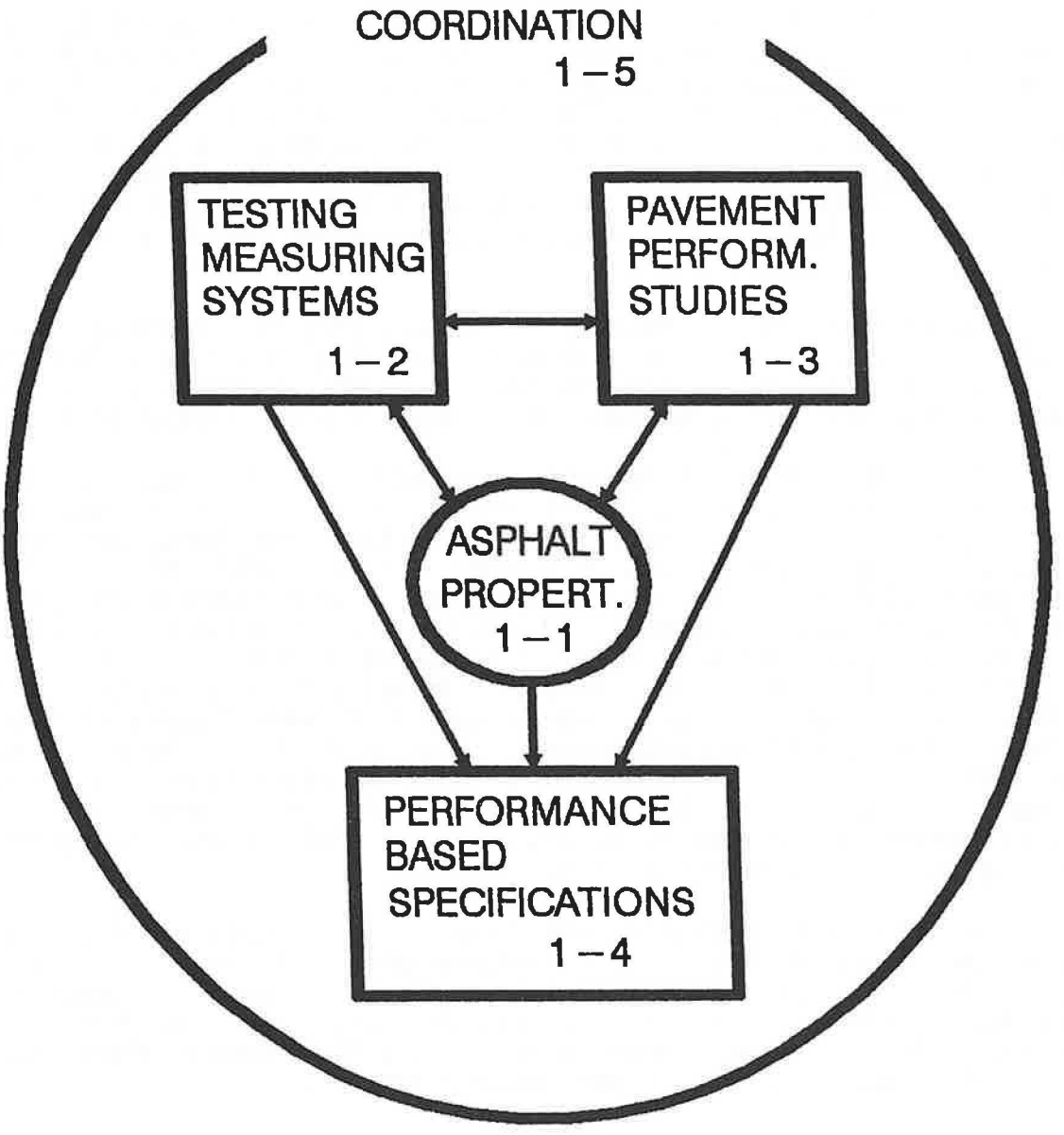


FIGURE 1. FIVE RESEARCH PROJECTS IN TRA 1.

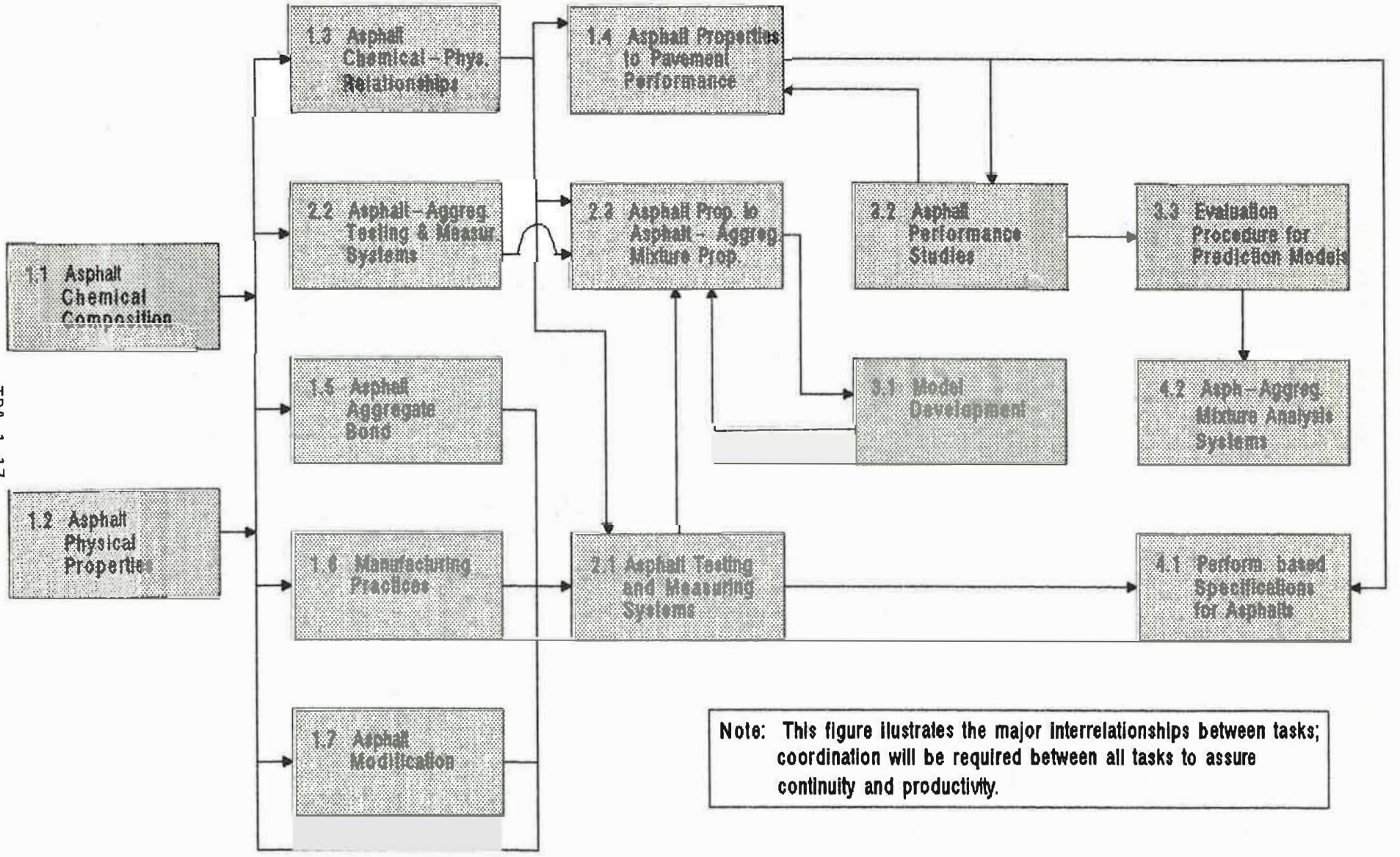


FIGURE 2. ORGANIZATION CHART FOR TRA 1 RESEARCH TASKS.

Table 2 Research Topics Not Included In TRA 1

Topic	Description of Research Objectives
1. Shrinkage cracking	Low temperature shrinkage cracking is included in the program; however, other types of shrinkage, e.g., aging, absorptions etc. will not be included.
2. Reflection cracking	Consensus of Advisory Committee was that reflection cracking is a structural problem; however, some support for the idea that reflection cracking could be mitigated by changing fracture and fatigue properties of asphalt.
3. Surface wear	Surface wear or raveling as related to asphalt properties and mix design were not considered of sufficient priorities to be included in program.
4. Aggregate properties	Strong support expressed at Workshop for a project or task on aggregate properties. Aggregates will be evaluated in a number of research tasks, e.g., bonding, fatigue, deformation. Studies will generally be related to aggregates which now qualify under ASTM, AASHTO or agency specifications. Within that limitation, a good deal of information will be obtained; however, no specific effort will be made to improve quality of aggregates or write new specification requirements for aggregates.
5. Special end uses	A number of categories for the use of asphalt were identified as possible research areas, e.g., surface treatments (seal coats, slurry seal, etc.), open graded mixes, (wearing surface or drainage layer) thin overlays, all-weather patching materials, inter-layers and non-eroding subbase under portland cement concrete. While each special end use could benefit from research, these topics were not included in order to maintain the focus on asphalt cement used in dense graded asphalt concrete.
6. Asphalt emulsions	It is acknowledged that asphalt emulsions are used extensively in the United States for surface treatments, maintenance and other special uses. However, emulsions have not been identified for special studies since such an effort would not be compatible with the narrow focus required for TRA 1.
7. Construction methods	It is expected that desired in-place properties of asphalt-aggregate combinations will be identified from various tasks included in TRA 1; however, no task with this specific objective is identified in the program. It can be expected that implementation of findings from TRA 1 will include studies of construction methods to achieve the desired properties.

SECTION 4
RECOMMENDED RESEARCH PLAN

INTRODUCTION

The research plan for Technical Research Area Number One has been designed to produce; 1) a specification for asphalt, with or without modification, which is designed to produce a binder with desired performance based properties, and 2) a method for combining asphalt and aggregate to produce a mixture with desired performance-based characteristics.

The end product for TRA 1 will be a performance-based specification for asphalt and an asphalt-aggregate mixture analysis system to facilitate mixture designs.

Performance-based specifications have been defined by the Advisory Committee as specifications which are based on: (a) relevant and reproducible test data from standard test methods, (b) test values (parameters) that can be related to performance, and (c) performance requirements which can be defined quantitatively.

Performance of asphalt will involve at least two considerations: 1) identification of those properties of asphalt which will significantly mitigate various forms of physical distress in pavements and 2) durability of the asphalt; or its ability to retain desired properties (resistant to change) when exposed to different environmental conditions.

The asphalt-aggregate mixture analysis system (AAMAS) will provide an improved asphalt concrete mix design method to facilitate the selection of durable asphalt and aggregate combinations to produce mixtures uniformly resistant to all forms of distress, such as rutting, low temperature cracking, fatigue cracking and moisture damage.

In preparing the research plan, the SHRP Task Force Advisory Committee and Consultants have attempted to evaluate the status of past research, and planned future research and particularly planned NCHRP projects dealing with mixture requirements.

Two important projects will have specific impact on studies of asphalt-aggregate combinations; specifically, NCHRP Projects 10-26(A) and 9-6(1).

Project 10-26(A) is an effort to develop performance-related specifications for hot-mix asphaltic concrete. The specific objective for the research effort is "... to identify the relationships between materials and construction test data and the performance of hot-mix asphaltic concrete." A

major task of project 10-26(A) will be to locate data useful in establishing performance of asphaltic concrete. A budget of $250,000 has been allocated to this project.

Project 9-6(1) is an effort to develop an asphalt-aggregate mixture analysis system (AAMAS). This project is a result of a resolution passed by the SHRP Asphalt Advisory Committee and supported by the SHRP Task Force. The intent of the Advisory Committee resolution was to encourage broad-based research to determine properties of mixtures necessary to mitigate different forms of distress as a function of material properties, traffic and environment. The NCHRP problem statement and objective for this project includes the following information which is compatible with the intent of the resolution.

> The highway community recognizes the need for improved procedures and analysis systems for the design of asphaltic concrete pavement mixtures that will be resistant to heavy truck loads, the use of higher tire pressures, and the wide extremes of climate. Such systems should optimize the selection, proportioning, and processing of asphalt binders and aggregate materials to produce pavements resistant to all forms of distress.
>
> The Strategic Highway Research Program (SHRP) plans to develop improved asphalt and/or new binders, tests and specifications for these binders, and performance-related specifications for asphaltic concrete paving materials. Improved procedures and analysis systems could be used for evaluation of the improved and/or new binders and for the design of the paving mixtures for test sections of the SHRP to obtain the necessary pavement performance information to develop performance-related specifications.
>
> Research is needed to develop and refine an asphalt-aggregate mixture analysis system (AAMAS) for design of optimum paving mixtures based on performance-related criteria. These criteria would encompass a wide variety of failure modes, e.g., fatigue cracking, thermal cracking, permanent deformation, moisture damage, age hardening, etc. The AAMAS should be capable of accommodating conventional asphalt binders, modified asphalts, mixture modifiers, and the range of aggregate materials used in the United States. It should also be capable of evaluating the mixtures under conditions analogous to those found in service, including a wide range of climate, traffic, and age factors.
>
> The objective of this research is to develop an asphalt-aggregate mixture analysis system (AAMAS) for the laboratory evaluation of asphaltic concrete mixtures. The system shall be based on specimens that, as nearly as possible, duplicate the characteristics of the mixtures in the field. Its application shall be limited to hot-mixed aspahltic concrete, excluding open-graded friction courses and drainage layers; and shall accommodate mixture variables, such as modified binders, aggregates, and

fillers, used in the construction of asphaltic concrete pavements and shall provide for resistance to all forms of distress associated with both load and environment. The evaluation system shall include such elements as the preparation of test specimens, conditioning of the specimens, testing the specimens, and criteria for mixture selection.

A budget of $350,000 has been allocated to Project 9-6(1). Thus, the projects 10-26(A) and 9-6(1) will provide a total funding of $600,000 for research on asphalt-aggregate mix design. These two projects will not only be complementary to the planned research for SHRP, they will also provide an early start and basis for continuing research under SHRP.

ORGANIZATION

Figure 2 has provided an overall organization for TRA 1. Figure 3 provides a somewhat consolidated perspective of the research plan.

Each of the elements considered in Figure 3 will be addressed in the final research plan described in Section 4. However, further explanation relative to materials selection is appropriate.

Recognizing that there may be up to 200 source asphalts used in the United States, it will be necessary to limit the number of asphalts that can be included in the research program. While no specific number of asphalts are being recommended at this time, it is likely that no more than 16 to 24 will be included for in-depth research, and that two or three times that many could be included in the extended studies designed to evaluate regional asphalts and aggregates.

Criteria for selection of the asphalts will be a part of the research effort to be carried out under SHRP. The Advisory Committee considers that: 1) temperature susceptibility, 2) aging, 3) bonding, and 4) compatibility properties will be candidates to be used for selection of asphalt. The objective will be to obtain asphalts which are representative of the range of materials produced and used in the United States.

Criteria for aggregates will also need to be established since it will be impossible to incorporate all aggregate sources available from the various parts of the United States. The Advisory Committee considers that: 1) gradation, 2) surface texture, 3) porosity, and 4) mineralogy are prime factors to be considered in selection of aggregates.

In the following section of this report is a detailed description of research projects, tasks and subtasks as were outlined in Section 3. The descriptions are divided into five categories or projects. Objectives for each project are provided and followed by task descriptions which include; objectives, scope and specific requirements. Task and subtasks represent potential research contracts to satisfy the objectives of TRA 1.

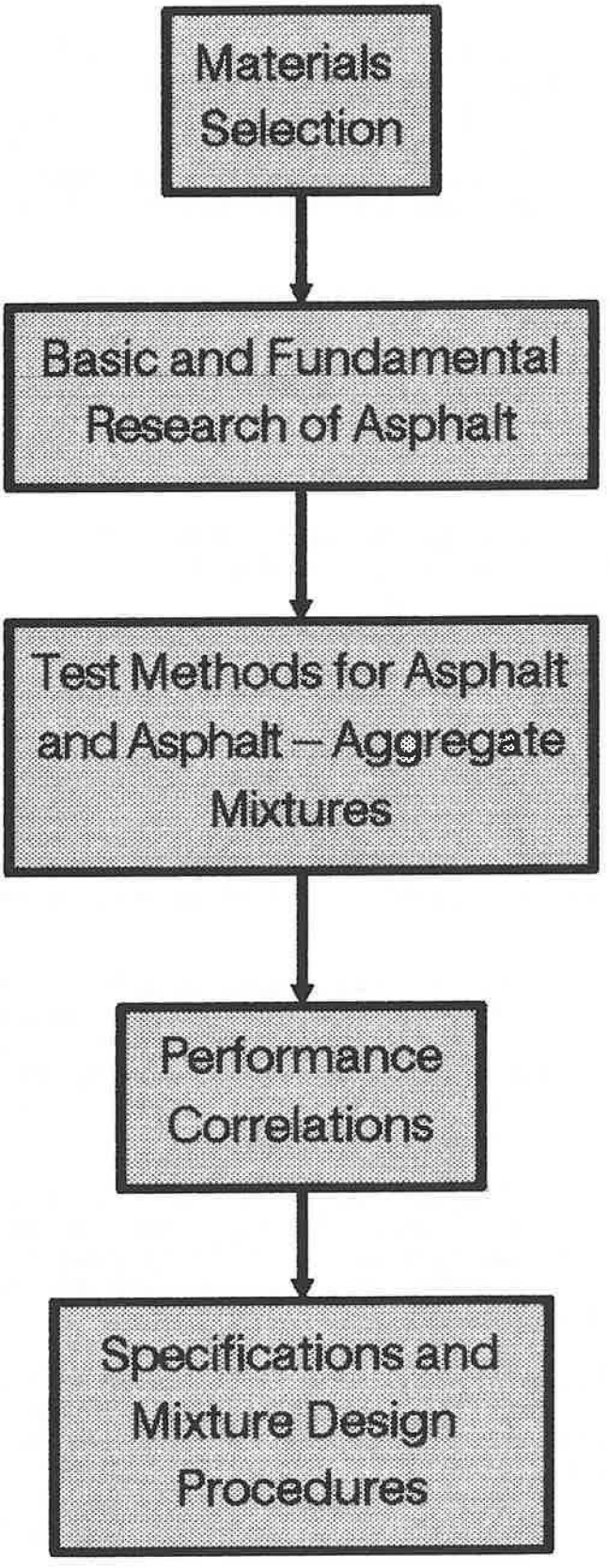


FIGURE 3. RESEARCH PLAN FOR TRA 1

RESEARCH STATEMENTS

Project 1-1: Asphalt Properties

The objective of this project will be to develop a better understanding of the chemical compositional factors of asphaltic materials that determine its physical properties and influence asphalt durability. The project will also be concerned with developing an understanding of the unique properties of asphalt, including recycled asphalt, which significantly influence the performance of asphalt-aggregate systems.

In order to achieve these objectives, the project has been divided into seven tasks as follows:

Task No.	Description
1.1	Asphalt chemical composition
1.2	Physical properties of asphalt
1.3	Relationships between asphalt chemical and physical properties
1.4	Relationships of Asphalt Chemical and Physical Properties to Pavement Performance
1.5	Fundamental properties of asphalt-aggregate interaction including adhesion (bonding) and absorption
1.6	Survey of current asphalt manufacturing practices
1.7	Asphalt modification

This research project will address the fundamental aspects of asphalt chemical and physical properties, their interrelationships, and the interaction between asphalt and aggregate. The information developed will provide a data base needed to: a) relate asphalt chemical composition, and physical properties and pavement performance, b) develop new test methods relevant to asphalt properties, c) improve asphalt quality, d) provide criteria for the design and production of modified asphalts with desired properties, e) provide a basis for preparation of performance-based specifications, and f) provide tools for diagnosing the role of asphalt in pavement performance.

Several facts should be considered when planning research under this project:

1) Physical properties and performance of asphalt-aggregate systems are a direct result of chemical composition and changes in composition of asphalt on aging in service.
2) Asphalt composition varies widely with source.
3) Asphalt composition is not uniquely defined by classically used separation techniques, i.e., the chemical composition of the same fraction can vary widely with source.
4) Asphalts are not true solutions, but are mixtures of chemical compounds of widely differing composition. This mixture produces a dispersion of highly agglomerated molecular species, thus creating a delicate balance of components whose mutual compatibility is critical in determining the complex flow properties and aging characteristics of the asphalt in service.
5) Interactions between chemical functionality of both asphalt and aggregate, change the physical properties and aging

characteristics of the asphalt in the paving mixture compared with that of the bulk asphalt.

This research project will identify the important chemical compositional parameters that determine and control the physical properties of asphalts, and will quantify their effects on physical properties and performance-related variables. New and innovative approaches will be needed in addition to classically used separations and characterizations and should take into account the interacting chemical functionality of the whole asphalt as a complete system. A major cause of premature pavement distress can be related to changes in the physical properties from oxidative and structural (steric) hardening of the asphaltic binder. These fundamental changes in composition and physical properties must be understood.

The performance of pavements constructed with asphaltic material is dependent upon the physical properties of the binder over a wide range of temperatures and stress-producing conditions; yet, physical property measurements used to specify asphalts often do not measure or define the desired in-service properties. This research program will develop new and improved techniques for measuring the physical properties of asphalt which can be related to performance of the asphalt and asphalt-aggregate combinations. Techniques are needed to measure the complex flow properties, particularly in the low temperature region and on stiff, highly aged binders. Special attention will be given to the measurement of such properties as reversible molecular structuring (steric hardening), low temperature creep, permanent deformation, low temperature fracture, and the in-situ properties of the asphalt in the pavement mixtures.

Although it is important to know and understand the properties of the asphalt, the properties of the asphalt-aggregate system are dependent upon interactions between the asphalt, as a binder, and the mineral aggregate. The physiochemical properties of the asphalt-aggregate bond play a major role in determining mixture properties and subsequent changes in properties that take place from the effects of environmental and traffic-induced factors. These changes are a function of the chemical composition of both the asphalt and mineral aggregate. Research will provide a better understanding of the chemistry and physiochemistry of the asphalt-aggregate interaction, how it may be beneficially altered, and how the parameters relate to important pavement performance properties and distress. Predictive tests will also be sought for matching asphalts and aggregates which will produce those properties that provide optimal performance.

Refining practices will be surveyed to define the current state-of-the-art for the production of asphalt. The effects of different refinery practices on asphalt properties and performance characteristics will be evaluated.

Asphalt modification offers promise as a means for correcting performance deficiencies not obtainable by crude source selection, blending or refining practices and thus provide for better utilization of inferior asphalts. Properties of the ideal forgiving asphalt will be determined and a means sought for its development through modification.

Finally, there is a need to develop laboratory procedures to accelerate the aging of asphalt in order to study the effect of aging on

asphalt properties. Test methods to recover asphalt from in place asphalt-aggregate mixtures will be a requirement for specific tasks in this project.

Task 1.1 Asphalt Chemical Composition.

Objective: Identify the chemical compositional factors of asphalt that significantly influence its performance-related properties and develop and measure those properties of asphalt which can significantly influence the physical properties of asphalt and the performance of asphalt-aggregate systems.

Scope: This task will identify qualitatively, and measure quantitatively, the chemical compositional factors in asphalt that significantly influence asphalt properties. As a minimum, asphalt properties to be measured will be those determined to be most significant to physical properties and pavement performance. Emphasis will be placed on innovative methods for identifying chemical composition and on strongly interactive chemical functionalities in asphalt that will exert a significant effect on physical properties. Methods used should have a high degree of probability of being useful for the development of information related to performance-related physical properties such as long-term, in-use oxidative hardening and rheological properties such as complex flow. Investigators will be required to coordinate their research closely with that of Task 1.3 which deals with relationships between compositional factors to physical and performance related properties of asphalt.

Asphalts used in this task will, as a minimum, consist of a carefully selected set representing broadly different compositional types available in the United States. The contractor will recommend selection criteria which will be reviewed and approved by the contracting agency. Criteria for selection of asphalts will be developed based on the current state of knowledge. It is not anticipated that any testing will be required for this purpose; data available in the literature, or as part of the investigating agencies' records and experience should be adequate. However, as research progresses, new criteria or requirements may develop which will necessitate incorporation of additional materials. Research will include studies of virgin asphalts and recycled asphalts.

Some emphasis will be placed on the polar and/or strongly interacting chemical functionality, particularly that containing hetero-atoms and condensed aromatic ring systems since they may exert a disproportionately large effect on physical properties. The asphalt components that act as solvents and dispersants for the associated species and resulting interactions of asphalt components will also need characterization. Emphasis should be placed on the study of the asphalt as a complete system. The use of modern instrumentation, techniques and experimental approaches should also receive emphasis.

Emphasis will be placed on the compositional factors that control asphalt rheology or complex flow properties, particularly as they affect low temperature properties. In addition to chemical compositional factors initially present in asphalt, compositional factors affecting oxidative aging and compositional changes on aging will also be characterized together with those factors that influence molecular structuring (steric hardening). The properties of aged asphalts will require special attention since these

properties are major determinants of pavement distress.

The researcher should indicate what tests and measurements are planned, for what purpose and on what basis such tests and measurements are considered appropriate. It is expected that a significant proportion of the research will involve chemical and some physical testing of asphalt and the development of techniques and instruments to measure the chemical properties of asphalt.

Specific requirements for this task include:

1) Define the chemical compositional factors of asphalt that are important to physical properties, including the compositional factors of aged asphalts.
2) Develop techniques for qualitative determination and quantitative measurement of the chemical compositional factors important to characterize asphalt properties.
3) Identify the factors that control asphalt component compatibility and/or the component dispersion (or solubility) characteristics and develop techniques for their measurement.
4) Determine the chemical compositional factors related to oxidative aging and develop techniques for their measurement.
5) Define the chemical compositional factors that influence molecular structuring (steric hardening) in asphalt and develop techniques for their measurement.
6) Define the chemical compositional factors that influence complex flow, fracture and asphalt rheology covering in-service temperatures and develop techniques for their measurement.
7) Define the special composition, component compatibility and blending requirements to produce acceptable and durable recycled asphalts and develop techniques for their measurement.
8) Develop an accelerated aging procedure for virgin or recycled asphalt that simulates oxidative aging in the field.

A total of 4 million dollars has been allocated for this task.

Task 1.2 Physical Properties of Asphalt

Objective: This task will develop new and improved techniques for measuring the physical properties of asphalt.

Scope: Useful methods and techniques do not exist for defining or measuring many of the physical properties of asphalt related to in-service pavement conditions. This is particularly true for both low and high temperature rheological properties under realistic temperature and loading conditions and for in-situ properties of the asphalt in the pavement mixture. This task will emphasize development of new techniques for measurement of asphalt physical properties, particularly as related to in-service use. It is anticipated that new instrumentation may need to be developed; e.g., non-destructive testing of asphalt in-place, low temperature properties, fracture, stiffness, etc. as necessary. Results of fundamental studies in this task will provide important input for the evaluations in Tasks 1.3 relating asphalt chemical and physical properties, 1.4 relating physiochemical properties to performance and in Task 2.1 for the development of testing and measuring procedures for asphalt use in performance-based specifications.

This task will primarily involve testing of physical properties of asphalt with some chemical testing as necessary to relate to Task 1.1. Techniques for testing, development of new equipment and methods for aging of asphalt and asphalt-aggregate mixtures will be required as part of this task.

Specific requirements for this task include:

1) Identify physical properties believed to significantly influence the performance of asphalt-aggregate systems and develop techniques for their measurement.
2) Develop methods to measure the complex flow and rheological properties of asphalt; coordinate with research in 1.1.
3) Develop methods to measure fracture properties of asphalt.
4) Develop methods to simulate the effects of long term aging of asphalt on physical properties that will take into account both oxidative and steric hardening. This method should include aging of neat asphalt, as well as asphalt in an asphalt-aggregate system. The method should be capable of evaluating the effect of mixing temperatures and especially the effect of mixing at high temperatures.
5) Develop new and innovative methods to measure or measure and calculate the physical properties of asphalt cement, in-situ, by means of non-destructive testing.
6) Develop methods to measure asphalt adhesion to mineral substrates.
7) Develop tests needed to characterize the significant (to performance) properties of recycled asphalts when combined with soft asphalts, recycling agents or emulsions (cold mix recycling).

A total of 2.5 million dollars has been allocated to this task.

Task 1.3(2) Relationships Between Asphalt Chemical and Physical Properties

Objective: The objective of this task will be to identify the important interrelationships between the chemical and physical properties of unaged and aged asphalts for the purpose of associating such relationships with the properties of asphalt-aggregate mixtures and ultimately with pavement performance. This research will help to establish the cause and effect relationships between chemical composition and physical properties of asphalt cement.

Scope: State-of-the-art techniques and data together with data and techniques developed in Task 1.1 and 1.2 on chemical and physical property characterization will serve as a major resource for developing chemical composition-physical property relationships. Close coordination with these tasks will be necessary. The relationships developed in this task will provide information needed for development of improved testing and measurement systems (Project 1-2) and the development of performance-based specifications (Project 1-4). Asphalts to be used in this task should be representative of the wide range of products currently in use in the United States and will include the core asphalts used in 1.1 and 1.2. This research will extend the results from tasks 1.1 and 1.2 to include some emphasis on the relationship of

asphalt chemical and physical properties to asphalt-aggregate properties. Provision will be made in this task to test those asphalts used in any long term pavement performance test sections to be evaluated as part of TRA 1. It is expected that approximately 300 different asphalts could be included in the LTPP study.

The interrelationship between tasks 1.1, 1.2 and 1.3 is provided in the following paragraphs.

Task 1.1 will identify the chemical properties of asphalt. Some of these properties will add to the basic understanding of asphalt chemistry and may not contribute directly to task in 1.3. Some of the chemical properties from Task 1.1 will potentially influence the physical properties and investigations included in Task 1.1 will provide some indicators of relationships to standard (traditional) physical properties, i.e., consistency tests.

Task 1.2 will develop new and improved methods for measuring physical properties of asphalt.

Task 1.3 will develop meaningful relationships between chemical and physical properties using results from Tasks 1.1 and 1.2. Task 1.3 will also extend these relationships to properties of asphalt-aggregate mixtures using conventional testing methods to measure; a) stability tests, b) creep, c) fatigue, d) low temperature tensile strength and e) stiffness.

Relationships established in Task 1.3 will include the effects of oxidative aging and long term field exposure. Effects of asphalt blending and recycling on physiochemical properties will also be evaluated.

Task 1.3 will evaluate the effects of component compatibility and molecular structuring (steric hardening) on physical properties.

Procedures used for accelerated aging will be coordinated with Tasks 1.1 and 1.2.

The work of this project will involve analysis of information from Tasks 1.1 and 1.2 to establish quantitative relationships between asphalt chemical and physical properties. Laboratory testing necessary to evaluate such relationships for virgin, aged and recovered asphalts will be required. Preliminary relationships between physiochemical properties and properties of asphalt-aggregate mixtures will be identified. No field studies will be required and properties of asphalt-aggregate mixtures will be based on ASTM, AASHTO or other standard test methods considered to be related to pavement performance.

The work of this task will seek to establish cause and effect relationships between chemical composition and performance-related physical properties of asphalt. Variables related to oxidative aging and long-term field exposure will receive special attention. Effects of blending and recycling will also be studied. Composition and physical property relationships will be extended to effects on asphalt-aggregate combinations where applicable. Effects of component compatibility and molecular structuring (steric hardening) on long term durability will also be considered. Results of this research will allow the development of

relationships between chemical composition, physical properties, accelerated laboratory testing, and long-term performance characteristics of field mixtures. Procedures used for accelerated aging will be coordinated with Tasks 1-1.1 and 1-1.2. Information developed in this task will be useful in diagnosing pavement performance problems as they are related to chemical composition and physical problems of the asphalt.

Specific requirements for this task include:

1) Relate asphalt composition and component compatibility with asphalt durability.
2) Correlate compositional changes resulting from oxidative aging with changes in physical properties of the asphalt including changes from long-term, reversible molecular structuring (steric hardening).
3) Relate compositional factors, including oxidative aging, with rheological properties of asphalt. Emphasis will be placed on low temperature flow properties and include permanent deformation and fracture properties.
4) Apply component compatibility/durability principles to pavement recycling to develop scientifically sound methods for matching aged asphalts with recycling agents (including soft asphalts) for optimum performance.
5) Measure performance-related chemical and physical properties of asphalt cement used in LTPP program.

A total of 3.5 million dollars has been allocated to this task.

Task 1.4(3) Relationships of Asphalt Chemical and Physical Properties to Pavement Performance.

Objective: Tasks 1.1, 1.2 and 1.3 will concentrate on in-depth research studies of a selected set of asphalts. Task 1.4 will extend and evaluate these findings and test procedures to a broader group of asphalts representative of products available for use in the United States.

Scope: Corbett (10) estimates there are at least 600 source compositions of asphalt being used in North America at the present time. Task 1.4 will be charged with obtaining and testing a sufficiently large sample of these asphalts in order to develop a data base of physical and chemical properties which will include the dominant crude sources used to produce asphalts in the United States.

Criteria for selection of asphalts will be recommended by the contractor and approved by the contracting agency.

Task 1.4 will be charged with accumulating information concerning the relationship between asphalt chemical and physical properties and their influence on pavement performance. This association will be particularly applicable to those asphalts to be sampled and tested in task 1.4. The source of information relative to performance will be documented reports or technical papers as well as interviews with knowledgeable and experienced persons from both user and producer agencies.

Task 1.4 will consist of selecting and testing a sufficiently large

number of asphalts needed to "finger print" the dominant sources with regard to both chemical and physical properties and to measure aging and adhesion properties using findings from 1.1, 1.2, 1.3 and 1.5. In selecting asphalts to be included in this task, some consideration will be given to the volume of material produced from a given source.

Specific requirements for this task include:

1) Carry out a testing program to evaluate the chemical composition and physical properties of asphalts from a wide range of crude sources used to produce asphalt in the United States.
2) Based on the state of the knowledge, including research in TRA 1, develop a set of chemical and physical tests and measurements for asphalt which are associated with pavement performance under a range of load and environmental conditions.
3) Based on test data accumulated in this task provide a data base of information, for the national data base, describing chemical and physical properties and a performance rating, based on asphalt durability and occurrence of distress in systems.

A total of 2 million dollars has been allocated to this task.

Task 1.5 Fundamental Properties of Asphalt-Aggregate Interaction Including Adhesion and Absorption

Objective: To determine the chemical and physical properties of asphalt in the asphalt-aggregate interphase (bonding) region.

Scope: This task will determine the different chemical functionalities in asphalt that are absorbed on the aggregate surface, their competitive adsorption, and also the chemical nature of the bonding sites on the aggregate surface responsible for their adsorption. Research will be designed to determine how bonding varies as a function of differences in asphalt and aggregate composition with emphasis on the fundamentals of adhesion of asphalt to aggregate in the presence of water. The physiochemical properties of the asphalt in the interphase region will also be determined with emphasis on how these properties change on aging and also how they relate to such asphalt-aggregate mixture properties as setting characteristics, rutting, tender mixtures, cracking, and moisture damage. Studies will include the interaction of asphalt with mineral dust. The influence of using absorptive and non-absorptive aggregates will be considered as part of this task. The selection of aggregates and asphalts will be coordinated with Tasks 1-1.1, 1-1.2 and 1-1.3 as necessary.

Subtask 1.5,a. Physiochemical Properties of Asphalt at the Asphalt-Aggregate Interface

The chemical functionality of both asphalt and aggregate responsible for the adhesive bond at the surface of the aggregate will be determined as a function of both asphalt and aggregate composition. Particular emphasis will be placed on 1) determining the chemical and physical mechanisms of moisture-induced damage in pavements, 2) development of techniques to match asphalts and aggregates to enhance desirable bonding characteristics, and 3) the search for a means to alter chemical and physical properties of the asphalt and aggregate for optimum bonding. Special laboratory techniques and testing

methods will be devised to control the variables involved; however, fundamental findings should be verified on laboratory prepared asphalt-aggregate combinations where possible, using proper controls and carefully selected tests to evaluate critical physical properties. This research will also consider the fundamental physiochemical properties of asphalt-aggregate bond associated with such pavement performance problems as reduced structural capacity, tender mixtures, poor setting characteristics, embrittlement, raveling, and cracking in pavement mixtures. It is anticipated that aggregate-induced molecular structuring of asphalt in the bonding region will be an important consideration in this research. The effects of oxidation, both during mix preparation and long-term aging on the fundamental properties of the asphalt bond, will also be considered. Effects of pavement recycling on bond properties of both old and new components (aggregates) will also be evaluated.

Results from this subtask will be provided to Projects 1-3 and 1-4 for consideration in performance modeling of selected pavements and for development of performance specifications.

The research agency will establish a set of criteria for the selection of asphalts and aggregates which include a balance between those with good field performance records and poor performance records, depending on the specific performance variables under consideration. Performance in this respect will refer to the presence or absence of premature distress of the types mentioned in previous paragraphs. The number of samples to be specified will be sufficient to establish prediction models to estimate the probability of premature distress considering environment, traffic and mix properties as well as the chemical functionality of the asphalt and aggregate.

Task 1.5,a. will consist of developing new methods of testing to evaluate asphalt-aggregate bonding and will include testing sufficient to identify desired properties of asphalt to enhance bonding characteristics.

Specific requirements for this subtask include:

1) Develop procedures to identify the fundamental chemical and physical properties that influence the bonding of asphalts with aggregates with special emphasis to moisture induced damage.
2) Define the physiochemical properties of the asphalt-aggregate bond as they relate to such pavement performance properties as mix setting characteristics, tender mixtures, rutting, age hardening, embrittlement, and moisture damage.
3) Determine the mechanisms of action and long-term effectiveness under oxidative aging conditions of conventional anti-stripping agents.
4) Develop laboratory test methods to measure asphalt-aggregate bonding characteristics considering: (1) temperature cycling including freezing and thawing, (2) moisture cycling, (3) oxidative aging and (4) load cycling.
5) Develop simplified tests that can be used for routine laboratory testing to evaluate asphalt-aggregate mix setting characteristics (aggregate-induced property changes), and moisture susceptibility and stripping.
6) Develop procedures to evaluate the effects of asphalt recycling on asphalt and aggregate bonding properties.

7) Develop methods to match and/or modify asphalt properties and aggregate properties to enhance desirable bonding characteristics.

A total of 2.5 million dollars has been allocated for this subtask.

Subtask 1.5,b. Chemical Composition and Physical Properties of Asphalt Used with Absorptive Aggregates

Most aggregates used in asphaltic mixtures will absorb some percentage of the asphalt cement used as a binder. The properties of the asphalt not absorbed are affected by absorption. This subtask will develop methods to measure the properties of the asphalt which is not absorbed into the aggregate.

Aggregates with at least three levels of water absorption, e.g., approximately 1.0, 2.5 and 5.0 percent or more will be included. At least two types of aggregate, acidic and basic, will be selected for each level of absorption. Aggregate selection criteria will be approved by the contracting agency.

Information from this subtask will be coordinated with Tasks 1.1, 1.2, 1.3 and Subtask 1.5,a.

Task 1.5,b. will consist of developing new methods of testing to evaluate asphalt-aggregate absorption and will include testing sufficient to identify the effect of absorption on asphalt properties and ways to minimize adverse effects of absorption.

Specific requirements for this subtask include:

1) Review and evaluate methods used to measure asphalt absorption in an asphalt-aggregate combination.
2) Develop techniques to improve the measurement of asphalt absorption.
3) Develop a method to measure the properties of the non-absorbed asphalt in absorptive asphalt-aggregate systems and develop methods to recover the non-absorbed asphalt.
4) Develop recommendations for asphalt requirements to minimize the adverse effects of aggregate absorption on properties of the effective asphalt.
5) Develop recommendations to minimize the adverse effects of absorption on pavement performance, e.g., shrinkage cracking, ravelling, etc.

A total of 1.5 million dollars has been allocated to this subtask.

Task 1.6 Survey of Current Asphalt Manufacturing Practices

Objective: This task will define the current state of the art of asphalt production in the refining industry and determine how refining practices affect the compositional and functional characteristics of asphalt.

Scope: An industrywide survey will be conducted to identify and describe the various refining practices and processes used to produce asphalts for pavement application. Asphalt samples will be collected from the different processes with consideration for variations in crude wherever possible. Asphalt samples will be collected first with consideration of refining practices and second with regard to crude sources. Consideration will also be given to the volume of asphalt produced by a particular manufacturing process. The samples shall be characterized by suitable chemical and physical property tests, including applicable tests developed in Tasks 1.1, 1.2, and 1.3 for the characterization of asphalt and relationships between properties and performance. When sampling asphalts from selected refineries, a determination will be made as to where and on what projects the asphalts are being used during the sampling period.

This information will be transmitted to the contracting agency for possible inclusion in the national data base. An effort will be made in this task to relate asphalt refining practices to pavement performance, taking into consideration the crude source.

As part of this task, consideration will be given to health and safety factors associated with the use of asphalt in paving.

This task will consist of summarizing manufacturing practices, obtaining and testing asphalt samples representative of such practices and evaluating potential effects of manufacturing practices on pavement performance.

Specific requirements for this task include:

1) Literature survey of current refining practices will be conducted.
2) Refineries producing asphalts for use in the United States will be contacted to determine current refinery practices.
3) A plan for collecting asphalt samples representative of refinery practices will be developed and submitted to the contracting agency for approval.
4) An approved set of asphalts will be tested to identify chemical and physical properties. Test methods and measurements will be coordinated with Tasks 1.1, 1.2, 1.3 and 1.4.
5) The effects of refining practices with regard to safety and environmental factors as they affect the paving industry will be evaluated.

A total of 1.0 million dollars has been allocated to this task.

Task 1.7(2) Asphalt Modification

Objective: This task will define the desired properties of asphalt as a binder for asphalt-aggregate mixtures for use in pavements and seek to obtain those properties through asphalt modification.

Scope: A "forgiving" binder with optimum properties may not be attainable from petroleum by conventional blending or refining processes because of inherent characteristics of the crude oil. Asphalt modification holds promise as a means of correcting asphalt deficiencies and producing a

binder with preferred performance properties from a wide variety of crude sources, many of which might otherwise be deficient. New and innovative techniques beyond the current state of the art will be required for successful completion of this task. Research under this task will be directed to producing a modified asphalt binder by whatever means which can be shown to be feasible considering product availability, construction and economics.

This task will define the desired properties of modified asphalts (binders) required for use in pavements under a range of environments and loading conditions. Correction of deficiencies in currently available asphalts and enhancement of desirable performance-related properties will be sought through modification. Important asphalt performance-related properties will include: a) durability, b) adhesion, c) properties at high and low temperatures, d) resistance to permanent deformation, e) flexibility and f) resistance to cracking due to environment, i.e., temperature, moisture, traffic. Other performance-related considerations will be included based on results of field experience or findings from Projects 1-2, 1-3, and other tasks in Project 1-1.

It is anticipated that methods will need to be developed to fully characterize and specify some modified asphalts. Promising modified asphalts will be evaluated in asphalt-aggregate systems for specific uses and recommended for incorporation into the long-term pavement performance research area.

Desirable end uses to be included in this study are:

1. dense graded asphalt concrete for surface and base,
2. recycled mixtures,

The emphasis in this task will be placed on, but not limited to, the use of asphalt additives or modifiers, such as:

1. minerals (dust, lime, portland cement, sulphur, carbon black, etc.),
2. elastomers (random SBR, block SBS, cross linked SB etc),
3. plastics (polyethylene, polypropylene, EVA etc.),
4. oxidants (manganese and other metal salts etc.),
5. antioxidants (lead compounds, carbon, calcium salts, etc.),
6. hydrocarbons (aromatic oils), i.e., additional or blending of desired components to form a "tailor made" asphalts,
7. surface active agents (cationic, anionic, nonionic, etc.) and
8. recycled crumb rubber.

Task 1.7 will include extensive chemical and physical testing similar to that required in tasks 1.1, 1.2, 1.3 and 1.5. Results from 1.1, 1.2, 1.3 and 1.5 should be useful in guiding the research in 1.7; however, it is expected that new test methods will be developed and that desired binder properties will be uniquely related to the type or method of modification.

Specific objectives for this task include:

1) Define the desired properties of a modified asphalt.
2) Develop, by means of a comprehensive testing program, how the various modifiers change chemical and physical properties of

asphalt binder.
3) Develop additional test methods required to identify the desired properties of a modified asphalt which are unique to the method of modification.
4) Evaluate the effects of such factors as long term aging on the properties of the modified asphalt.
5) Evaluate the asphalt (modified)-aggregate adhesion properties by methods developed in task 1.5.
6) Evaluate the potential for recycling of modified asphalt after long term aging.
7) Prepare recommendations for use of modifiers to produce an asphalt binder with desired properties.
8) Health and environmental aspects of modification materials and, manufacturing and construction requirements will be evaluated.

A total of 5 million dollars has been allocated to this task.

Project 1-2 Performance-Based Testing and Measuring Systems

Researchers conducting tasks under Projects 1-1 on asphalts and asphalt-aggregate mixtures will utilize numerous testing and measuring systems to define the chemical and physical properties of binders and the mechanical properties of asphalt-aggregate systems. Tests which appear to correlate well with pavement performance (Project 1-3) and useful for acceptance specifications will be identified by the researchers. This Project (1-2) will be responsible for describing in ASTM/AASHTO format the promising tests and their associated measuring system. Specific items to be included in the development of each test method will include:

1. scope,
2. applicable documents,
3. significance and use,
4. apparatus,
5. calibration,
6. sampling,
7. sample preparation,
8. procedure, including test conditions,
9. report,
10. precision and bias, and
11. definitions of applicable terms.

The precision and bias statement will be prepared according to ASTM C670 and C802.

In order to achieve these objectives, it will be necessary to plan and carry out sufficient testing to satisfy each of the eleven items enumerated above.

This project is divided into three tasks:

1. Development of standardized testing and measuring systems for asphalts, with or without modification, for use in preparation of performance-based specifications.
2. Development of standardized testing and measuring systems for use in design of asphalt-aggregate mixture analysis system using

virgin, recycled or modified asphalt.

3. Establish relationships between chemical and physical properties of asphalt, or modified asphalt, and the physical properties of the asphalt-aggregate mixture. Emphasis will be given initially to correlations with standardized tests and measurements. During the second year and beyond, emphasis will be given to properties required in prediction models developed in task 3.1.

Task 2.1(2) Testing and Measuring Systems for Asphalt (With and Without Modification)

Objective: The objective of this task will be to develop standardized test methods for asphalt or modified asphalts which could satisfy requirements for ASTM and AASHTO and which can be used to specify and accept asphalt binders for use with performance-based specifications.

Scope: Promising asphalt characterization tests and relationships developed in Project 1-1 will be adapted for use as specification tests. It is anticipated that these test methods will consider such factors as:

1. asphalt durability related to both short-term hot mix aging and long term in-service aging,
2. asphalt-aggregate interactions, with and without modification, in the presence of water or moisture,
3. extraction and recovery methods for asphalt from asphalt-aggregate systems,
4. properties required for prediction models developed in Project 1-3,
5. in-situ, non-destructive measurement of asphalt properties existing in the asphalt-aggregate mixture,
6. chemical properties as necessary,
7. physical properties including the rheological properties of the asphalt binder system over a range of temperatures used in construction and ambient temperatures for in-service conditions.

Test methods will consider, as much as is possible, the need for simplicity, time required for testing, number of replicate tests and equipment cost when standardizing test methods.

Cooperative testing programs, i.e., interlaboratory etc., with federal, state, industry and universities and other SHRP contractors will be arranged by the research agency in order to develop information required for standardization by ASTM and AASHTO. It is recognized that it may not be possible to satisfy all of the ASTM requirements for precision statements, i.e., participation by 10 laboratories; however, an effort will be made to satisfy statistical requirements sufficient for consideration by ASTM and AASHTO.

When newly designed equipment is required for test methods, and is not already available to the cooperating agencies, it will be furnished to participating laboratories by the research agency. Equipment furnished in this manner will remain the property of AASHTO to be sold or returned at completion of the task.

Task 2.1 will involve the development of testing techniques, testing

procedures and test results sufficient for consideration by ASTM and AASHTO as acceptable for standardization.

The contracting agency will participate in all phases of the testing program for this task.

Specific requirements for this task include:

1) Select and obtain the cooperation of a sufficient number of testing laboratories to establish precision and bias information for standardizing test methods.
2) Prepare test method descriptions to satisfy requirements for a standardized test.
3) Plan and implement test programs as necessary to satisfy requirements for ASTM and AASHTO.
4) Prepare plans and arrange for fabrication of new testing equipment.
5) Obtain and distribute samples of asphalt to participating agencies.
6) Analyze test results from participating agencies.
7) Prepare final test method descriptions for submittal to ASTM and AASHTO.
8) Evaluate any safety or health hazards associated with test procedures.

A total of 3.5 million dollars has been allocated to this task.

Task 2.2(2) Testing and Measuring for Asphalt-Aggregate Systems (With and Without Asphalt Modification)

Objective: The objective of this task will be to describe standardized test methods for asphalt-aggregate systems which could satisfy requirements for ASTM and AASHTO and which can be used for the development of an asphalt-aggregate mixture analysis system.

Scope: It is anticipated that standardized test methods will be required to measure the following properties:

1. aging of asphalt (in asphalt mixtures), both long term and short term (1 year or less), including oxidation and molecular structuring (steric hardening),
2. evaluation of water sensitivity for each measured property,
3. tensile strength at in-service temperatures,
4. thermal coefficients,
5. creep or plastic deformation at high temperatures (i.e., greater than 70 ^{o}F),
6. creep properties at low temperatures (i.e., less than 0 ^{o}F), and
7. fatigue properties at in-service temperatures.

Test methods should consider, as much as possible the need for simplicity, time requirements and equipment cost as part of selection criteria.

Cooperative testing programs, i.e., interlaboratory etc., with federal, state, industry and universities and other SHRP contractors will be

arranged by the research agency in order to develop information required for standardization by ASTM and AASHTO. It is recognized that it may not be possible to satisfy all of the ASTM requirements for precision statements, i.e., participation by 10 laboratories; however, an effort will be made to satisfy statistical requirements sufficient for consideration by ASTM and AASHTO.

When newly designed equipment is required for test methods, and is not already available to the cooperating agency, it will be furnished to participating laboratories by the research agency. Equipment furnished in this manner will remain the property of AASHTO to be sold or returned at completion of the task.

Methods of testing for: 1) fatigue properties, 2) permanent deformation and 3) low temperature cracking will be developed under this task.

Task 2.2 will involve the development of testing techniques, testing procedures and test results sufficient for consideration by ASTM and AASHTO as acceptable for standardization. It has been divided into five subtasks (2.2, a, b, c, d, e) with the following common requirements.

Requirements for each subtask under this task include:

1) Select and obtain cooperation of a number of testing laboratories necessary to establish precision and bias information for standardizing test methods.
2) Prepare test method descriptions to satisfy requirements for asphalt-aggregate mixture analysis system.
3) Plan and implement interlaboratory test program as necesary to satisfy ASTM and AASHTO test method requirements.
4) Prepare plans and arrange for fabrication of new testing equipment.
5) Obtain and distribute samples of asphalt and aggregate to participating agencies.
6) Analyze test results from participating agencies.
7) Prepare final test method descriptions for submittal to ASTM and AASHTO.
8) Evaluate any safety or health hazards associated with test procedures.

Specific requirements for each of the five subtasks are included in the following descriptions.

Subtask 2.2(2),a. Testing Methods for Fatigue Cracking of Asphalt-Aggregate Systems

This subtask will be responsible for developing standardized test methods that are suitable for use with mechanistic or mechanistic-empirical models for predicting fatigue cracking of pavements, regardless of the thickness of the bound layers in the pavement. Consideration wil be given to sample preparation, test sample configuration, test mode (controlled stress or controlled strain), test temperature, moisture and procedures to relate laboratory results to field performance. Consideration will also be given to define the fatigue life of mixtures as a function of aging. Development of this test method will take into consideration the need to use procedures

easily duplicated between laboratories and which are suitable for routine use by state agencies.

A number of fatigue tests have been developed in the United States and Europe. Specimen preparation, specimen-shape, test configuration, loading time and test temperature have varied widely. Test configurations have been developed, including test beams, trapezoidal prisms, and cylinders. Controlled stress and controlled strain tests have been performed with widely different loading times and temperatures. Rest periods have been introduced. Fracture mechanics technology has been utilized for prediction of fatigue life and to define the shift factor between laboratory and field test results. These methods will be evaluated by literature review as part of the initial activities to be included in this subtask.

Subtask 2.2(2),a. will involve: 1) review of literature, 2) development of testing techniques and equipment, and 3) a testing program to standardize fatigue test methods.

Specific requirements for this subtask include:

1) Develop a test or tests to characterize the fatigue properties of asphalt-aggregate mixtures.
2) Plan and implement a fatigue testing program sufficient to incorporate dominant asphalt and aggregate types used in the United States as identified in Project 1-1.
3) Identify the major chemical and physical properties of asphalt, aggregate and mixtures which influence fatigue properties.
4) Prepare recommendations which will improve fatigue properties of asphalt-aggregate mixtures.
5) Coordinate research activities with Projects 1-1 and 1-3.

A total of 2 million dollars is allocated to this subtask.

Subtask 2.2(2),b. Testing Methods to Measure Permanent Deformation of Asphalt-Aggregate Systems

Permanent deformation of asphalt-aggregate mixtures is of increasing concern to pavement performance as truck weights and tire pressures of highway vehicles continue to increase. As loads and contact pressure increase and the empirical procedures become less reliable, a better understanding of the mechanisms influencing permanent deformation in asphalt-aggregate mixtures is required in order to design mixes to resist this type of distress.

Mechanistic models using analytical procedures to predict stress, strain and deformation have been described in the literature and used in practice to design mixes to control rutting. These methods need to be evaluated further and either improved or otherwise rejected.

Test methods have been developed which are compatible with the mechanistic models. Depending on the evaluation of existing procedures for predicting deformation, these tests would also be modified or otherwise rejected. If new models are developed, new test methods will be required.

This subtask will be responsible for developing standardized test methods that are suitable for use with mechanistic or mechanistic-empirical

models for predicting permanent deformation in asphalt-aggregate mixtures. Consideration will be given to sample preparation, sample configuration, stress state, temperature, moisture and other conditions necessary to relate laboratory results to field performance. Consideration will also be given to the influence of asphalt aging and water susceptibility to permanent deformation characteristics. Development of this test method(s) will take into account the need to use procedures easily duplicated between laboratories and which are suitable for routine use by state agencies.

Subtask 2.2(2), b. will involve: 1) review of literature, 2) development of testing techniques and equipment, and 3) a testing program to standardize test methods to be used for prediction of permanent deformation in asphalt-aggregate mixtures.

Specific requirements for this subtask include:

1) Develop a test or tests to measure properties of asphalt and asphalt-aggregate systems which influence permanent deformation.
2) Plan and implement a permanent deformation testing program sufficient to incorporate dominant asphalt and aggregate types used in the United States as identified in Project 1-1; coordinate with subtask 2.2,a.
3) Identify the main physical properties of asphalt and asphalt-aggregate mixtures which influence permanent deformation.
4) Prepare recommendations which will minimize permanent deformation in new construction or overlays on both flexible and rigid type pavements.
5) Coordinate research activities with Projects 1-1 and 1-3.

A total of 2.5 million dollars has been allocated to this subtask.

Subtask 2.2(2),c. Testing Methods to Evaluate Low Temperature Cracking of Asphalt-Aggregate Systems

Thermal cracking (or low temperature cracking) is a major problem in those sections of the United States subjected to ambient temperatures near and below freezing. Recent research has indicated that transverse cracks typical of thermal cracks occur in regions not subjected to low (below freezing) temperatures. Researchers report that these cracks may be due to thermal cycling, rate of change in temperature and/or the age hardening of asphalt in asphalt-aggregate mixtures.

Test methods have been developed which measure the low temperature properties of asphalt and asphalt-aggregate mixtures which influence low temperature cracking. These tests and the related material properties will be evaluated to determine their applicability. New tests will be developed if necessary. The test method recommended will provide input parameters for use in thermal cracking models to be used in Project 1-3.

This subtask will be responsible for developing standardized test methods that are suitable for use with mechanistic or mechanistic-empirical models for predicting low temperature cracking in asphalt-aggregate mixtures. Consideration will be given to sample preparation, sample configuration, test conditions, temperature, moisture and other conditions necessary to relate laboratory results to field performance. Consideration will also be given to

the influence of asphalt aging and water susceptibility to low temperature cracking characteristics. Development of this test method(s) will take into consideration the need to use procedures easily duplicated between laboratories and which are suitable for routine use by state agencies.

Subtask 2.2(2),c. will involve: 1) review of literature, 2) development of testing techniques and equipment, and 3) a testing program to standardize test methods to be used for prediction of low temperature cracking in asphalt-aggregate mixtures.

Specific requirements for this subtask include:

1) Develop a test or tests to measure the properties of asphalt and asphalt-aggregate mixtures which influence low temperature cracking.
2) Plan and implement a low temperature testing program sufficient to incorporate dominant asphalt and aggregate types used in the United States as identified in Project 1-1; coordinate with subtasks 2.2,a. and b.
3) Identify the main physical properties of asphalt and asphalt-aggregate mixtures which influence low temperature cracking.
4) Prepare recommendations which will minimize the occurrence of low temperature cracking.
5) Coordinate research activities with Projects 1-1 and 1-3.

A total of 1.5 million dollars has been allocated to this subtask.

Subtask 2.2(3),d. Aging of Asphalt-Aggregate Systems

The primary objective of this task will be to develop accelerated laboratory procedures which can simulate the effects of aging on asphalt-aggregate mixtures when subjected to different climatological environments.

A method of accelerated aging of asphalt-aggregate mixtures is required in order to adequately simulate life cycle conditions for asphalt concrete in service. Project 1-1 is concerned with accelerated aging of bulk asphalt, researchers on Task 2.2,d. will be concerned with the aging of asphalt-aggregate mixtures including the asphalt incorporated in the mix.

Methods have been developed for aging of asphalts during the hot mix process associated with batch type asphalt plants. This task will be concerned with the effects of aging on the properties of the asphalt and asphalt-aggregate mixture as a function of in-service age. Consideration will be given to at least six environmental conditions: three levels of ambient temperature (i.e., high, moderate and low) and two levels of rainfall (i.e., wet and dry). Specific levels for each condition will be determined by the research agency based on prevailing conditions in the United States. When developing aging procedures, consideration will be given to the effect of both oxidative and steric hardening.

Test methods will be evaluated by comparison with in-service pavements using both short-term and long-term service periods. An approved experiment design will be used to establish the reliability of the aging procedure and the algorithm to predict aging.

It is likely that more than one method of aging will be developed in the laboratory. Those methods which show the most promise in the laboratory will be evaluated by comparisons with selected in-service projects.

The research will also establish relationships between the chemical functionality of the asphalt and the aggregate in order to determine how to reduce the age hardening of the mixture in specific environments.

This subtask will be responsible for developing standardized test methods to simulate field aging of asphalt and asphalt-aggregate mixtures and will involve: 1) development of testing techniques and equipment, 2) planning and implementing a testing program to evaluate the reliability of the procedure and 3) obtaining field information to be used in the evaluation.

Specific requirements for this subtask include:

1) Develop a laboratory procedure which will simulate the field aging of virgin, recycled or modified asphalt and asphalt-aggregate systems taking into account reversible time dependent changes in asphalt properties.
2) Verify the laboratory aging procedure and establish reliability based on comparisons with in-service pavements.
3) Identify chemical functionality properties of asphalt and aggregate which affect aging.
4) Prepare recommendations to improve the aging properties of asphalt used in asphalt-aggregate mixtures.
5) Coordinate all activities with research under Project 1-1.
6) Coordinate measurements of aging with Project 1-3 on prediction models.

A total of 1.0 million dollars has been allocated to this subtask.

Subtask 2.2(3),e. Water Sensitivity of Asphalt-Aggregate Mixtures

The objective of this subtask will be to extend the fundamental research effort and findings of task 1.5 to applications useful for the development of a testing procedure for use with an asphalt-aggregate mixture analysis system. The research will include considerations of asphalt-aggregate mixtures incorporating virgin asphalt, modified asphalt or recycled asphalts before and after aging. The testing procedure will evaluate water sensitivity as it applies to standard test procedures developed in subtasks 2.2,a, b, c and d (aging).

Materials to be used in this subtask will, as a minimum, include asphalts and aggregates evaluated in 1.3, 1.4, 1.6, 2.2.

Criteria will be developed for the interpretation of test results; specifically, requirements for initial mix design and diagnosing premature distress. The contractor will be required to establish criteria based on field performance information. Coordination with task 1.5 will be a requirement for this subtask.

This subtask will involve: 1) evaluation of existing methods for evaluating water or moisture sensitivity of asphalt-aggregate mixtures, 2) development of testing techniques and equipment, 3) planning and implementing

a testing program to evaluate the reliability of the procedure, and 4) obtaining performance information useful to establish criteria.

Specific requirements of this subtask include:

1) Develop a standard test or tests for evaluating the moisture sensitivity of asphalt-aggregate mixtures. This requirement will include provision for asphalt-aggregate mixes containing virgin, recycled and modified asphalts as well as consideration of the effect of aging on mix properties.
2) Establish criteria for interpretation of test results.
3) Identify the chemical functionality and physical properties of virgin, recycled or modified asphalt and aggregate which significantly affect water sensitivity.
4) Prepare recommendations describing the desired properties of the asphalt binder for use in asphalt-aggregate mixtures to mitigate the adverse effects of moisture or water on the properties of the mixture.

A total of 1.5 million dollars has been allocated to this subtask.

Task 2.3(3) Relationship of Asphalt Chemical and Physical Properties to Asphalt-Aggregate Mixture Properties

Objective: The objective of this task will be to establish relationships between the chemical and physical properties of asphalts defined in Project 1-1 and the asphalt-aggregate mixture properties for which test procedures have been developed in this Project, i.e., 2.2.

Scope: In tasks 1.1 and 1.2 important chemical and physical properties will be defined and their influences on pavement performance will be ascertained in task 1.4. In tasks 2.1 and 2.2 measuring systems will be developed for both asphalt and asphalt-aggregate mixtures.

The scope of task 2.3(3) includes testing of dense graded asphalt-aggregate mixtures meeting gradation requirements of ASTM 3515, containing the asphalts which have been used in tasks 1.1 and 1.2 to define the influence of the asphalt properties on:

1. Fatigue cracking
2. Permanent deformation
3. Low-temperature cracking

In addition, the influences of aging and water-sensitivity as defined in tasks 2.2(d), and 2.2(e) on these characteristics will be studied.

The task will include the testing of selected modified asphalts (materials examined in task 1.7) to define their influences on the above listed mixture properties.

Testing and measuring systems established in tasks 2.1 and 2.2 will be used for the entire test program associated with this task.

This task is scheduled to begin in year 3 to be able to utilize results of the studies completed in tasks 1.1, 1.2, 1.3, 1.4, 1.7, 2.1, and

2.2.

In year 4, the procedures used to examine the influence of tasks 1.1 and 1.2, asphalts, and task 1.7, modified asphalts, to mixture response, will be used to define the characteristics of the materials used in the Long Term Pavement Performance study.

Provisions will be included in this task for the testing of additional asphalts, if required, to insure that a representative range of asphalts is included.

Specific requirements of this subtask include:

1) Combine information in tasks 1.1 and 1.2 into one comprehensive summary report.
2) Carry out a testing program using standardized test methods developed in 2.1 and 2.2 using asphalts and aggregates representative of materials currently used throughout the United States. An experiment design will be necessary to meet this requirement. The experiment design will be developed by the contractor and approved by the contracting agency.
3) Prepare recommendations for the desired chemical and physical properties of asphalt, virgin or modified, which best meet requirements for: 1) aging, 2) adhesion, (water sensitivity) 3) fatigue, 4) permanent deformation and 5) low temperature cracking.
4) Prepare recommendations for the desired properties of an asphalt-aggregate system which will provide optimal performance based on: 1) aging, 2) adhesion, 3) fatigue, 4) permanent deformation and 5) low temperature cracking.

A total of 3 million dollars has been allocated to this task.

Project 1-3 Models to Predict Pavement Performance

The primary objectives of research in TRA 1 will be to develop performance-based specifications for asphalt and an asphalt-aggregate mixture analysis system for design of asphaltic concrete mixtures. In order to achieve these objectives, it will be necessary to: 1) develop performance (prediction) models using empirical or mechanistic-empirical procedures, 2) calibrate performance prediction models to field performance, and 3) evaluate calibrated models with additional field observation.

To achieve the overall objective of this project, it will be necessary to establish the interrelationships between asphalt properties and asphaltic concrete mixture properties using test methods recommended by Project 1-2. For example, the properties of the asphalt can be used to estimate the stiffness of the asphalt which in turn can be used to predict similar relationships for asphalt-aggregate mixtures based on asphalt properties, aggregate properties, density, gradation, asphalt content etc. Conversely, assuming that pavement performance can be related to pavement response (stress, strain or deformation), it should be possible to establish the desired properties of the asphalt and asphalt-aggregate mixtures. A prediction model will be necessary in order to relate properties to performance. This project will include provision for incorporation of modified asphalts (binders) in addition to asphalts without modification.

A requirement of each of the subtasks described in this Project will be to determine appropriate parameters related to asphalt and asphalt-aggregate properties which can be used to predict fatigue cracking, low temperature cracking and permanent deformation. Consideration will be given to: 1) practicality of the models, 2) ability or reliability of correlations to in-service performance, 3) difficulty in measuring material properties, 4) variability of test measurements.

This project is divided into three (3) tasks as follows:

3.1 Model development
3.2 Asphalt performance studies
3.3 Evaluation of prediction models

Task 3.1(2) Model Development

Objective: The objective of this task will be to develop performance prediction models for asphalt and asphalt-aggregate mixtures. Each model will be required to simulate the effects of a) asphalt and asphalt mixture durability, b) environment, c) traffic, d) construction variables, e) properties of asphalt and asphalt-aggregate mixtures, f) age and g) influence of pavement structure.

Scope: The performance prediction models will apply to the following types of distress:

1. rutting,
2. fatigue cracking and
3. low temperature cracking.

The use of analytically based mechanistic models are preferred; however, it is recognized that the empirical adjustments may be required based on field observations. Empirical models will be developed if mechanistic procedures are unsuitable. For purposes of this investigation the term analytical will refer to the use of theory to calculate pavement response, i.e., stress, strain or deformation; mechanistic refers to the algorithm used to translate response to performance. For example, one model that has been proposed for fatigue cracking of asphalt concrete includes both requirements as follows:

$$N_f = k_1 * \left[\frac{1}{\varepsilon}\right]^{k_2} * \left[\frac{1}{|E^*|}\right]^{k_3}$$

where:

N_f = number of load repetitions to specified amount of cracking,

ε = maximum tensile strain in the asphalt concrete,

$|E^*|$ = dynamic modulus of asphalt concrete,

k_1 = fitting coefficient based on observations of in-service pavements, and

k_2, k_3 = fitting coefficients from laboratory fatigue test.

Strain in the asphalt concrete is calculated using analytical procedures for structural analysis of the pavements. The repetitions to failure is based on the cumulative damage hypothesis which is the mechanism which results in fatigue cracking.

Both strain and modulus are a function of asphalt and asphalt-aggregate properties in the above illustration; hence, the model would be a candidate for predicting fatigue cracking.

A limited number of models have been developed to predict deformation. The permanent deformation model selected will include provision for asphalt properties and mixture properties for both short (0.01 seconds) and long periods of loading (1 hour) as required to simulate field loading conditions under moving loads and standing loads.

The permanent deformation model will also include provisions for evaluating effects of various wheel loads, configurations, tire pressures and mixture temperatures.

Several models exist which relate laboratory fatigue characteristics of asphalt bound materials to mixture properties such as stiffness (dynamic modulus, complex modulus, etc.) and air voids. These models will be evaluated and modified as necessary to improve their reliability. If currently available models are considered unsatisfactory, new models will be developed.

In addition to material properties, including those of asphalt and asphaltic concrete, the model shall consider: wheel loads and configurations, time of loading, effect of mixed traffic, tire pressure and temperature cycles.

Models have been developed for the prediction of low temperature cracking. These models relate the occurrence of transverse cracking to asphalt properties and asphalt mixture properties. In selecting the low temperature transverse cracking model(s), consideration will be given to rate of change in temperature (i.e., temperature drop), the influence of friction between the supporting layer, and age hardening of asphalt and asphalt-aggregate combinations.

The low temperature model will be capable of predicting cracks resulting from a single thermal cycle as well as repeated cycles over long periods of time, i.e., 15 to 20 years. The model will provide some means for predicting the cracking index or average expected frequency (spacing) of cracks.

This project does not involve any testing; it is primarily an investigation of models; mechanistic, mechanistic-empirical or empirical which can be used to predict specific types of performance based on asphalt properties or asphalt-aggregate properties.

Specific requirements for this task include:

1) Develop performance prediction models for each of the three types of distress identified.
2) Describe methods for validation of models including the need for and type of field data required.

A total of 0.5 million dollars has been allocated to this task.

Task 3.2 Asphalt Performance Studies

Objective: The objective of this task will be to obtain as much documented performance information as possible from as many sources as possible in an effort to establish criteria which will be used for asphalt specifications and for the design of asphalt-aggregate mixtures.

Scope: The scope of this task includes: 1) observations of field performance, 2) collection of samples and performances of tests necessary to evaluate prediction models and 3) development of empirically based fitting coefficients to calibrate models to observed performance. Emphasis in data collecting, sampling and testing will be given to projects with long term performance records and for which samples of the original asphalt and aggregate are available for testing.

The task will include the following activities:

1) Develop a sampling and testing program for in-service pavements.
2) Summarize and analyze field and laboratory data.
3) Develop empirical coefficients to adjust theoretical models from 3.1 to applied prediction models.
4) Develop procedures for updating empirical coefficients.

Planning for this task will require a well-planned experiment which will provide information indicative of differences due to materials and environments.

This task will involve collection of performance data from any source considered useful for evaluation of prediction models and for establishing specification or mixture design requirements. A laboratory testing program necessary to support prediction models will be required.

Specific requirements for this task include:

1) Obtain samples of asphalt-aggregate materials from designated in-service pavements.
2) Conduct necessary testing program to develop information required to evaluate prediction models for a) fatigue cracking, b) permanent deformation, c) low temperature cracking and d) reflection cracking.
3) Analyze performance information and test data to establish specification requirements and criteria to be used with asphalt-aggregate analysis system.

A total of 3.0 million dollars has been allocated to this task.

Task 3.3(3) Evaluation Procedures for Prediction Models

Objective: This task will provide guidelines for state highway agencies to maintain and update performance prediction models and to modify specification requirements recommended in task 4.2.

Scope: The scope of this task will include the development of methods for interpreting information from the Long Term Pavement Performance research area (TRA 2) as it applies to TRA 1 objectives, and to develop a comprehensive satellite SHRP program for future enhancement of specifications based on a well-planned experiment design and data acquisition requirements.

This task will involve methods to be used for obtaining and analyzing research information useful for updating (improving) prediction models and for revising specification requirements for binders of all types, i.e., asphalt, recycled asphalt or modified asphalt. Criteria and recommended procedures to be used in establishing local or national satellite SHRP research will be developed. Mathematical examples with hypothetical or real data will be analyzed to illustrate the recommended procedures. No testing, laboratory or field, will be required for this task although data useful in illustrating procedures may be acquired from other tasks within TRA 1.

Specific requirements for this task include:

1) Develop mathematical guidelines to be used for evaluation of prediction models from performance data. Relate such procedures to future interpretation of LTPP data.
2) Prepare a step by step procedure for establishing data requirements and analysis procedures to be used in updating specification requirements and design criteria for incorporation in the asphalt-aggregate mixture analysis system.
3) Prepare experiment design recommendations for use at the local or national level for obtaining information required to increase the data base of information useful for future updating of goals established for TRA 1; in effect, a planned SHRP satellite program.
4) Illustrate the step by step procedures for interpreting information from experiment design in items 3 above; use hypothetical or real data as is available and is appropriate.

A total of 1.0 million dollars has been allocated to this task.

Project 1-4 Preparation of Performance-Based Specifications and an Asphalt-Aggregate Mixture Analysis System

This project will prepare performance-based specifications for asphalt and recommendations for a comprehensive mixture design method to be referred to as an asphalt-aggregate mixture analysis system (AAMAS).

For purposes of this project, a performance-based specification for asphalt must satisfy the following requirements:

1) It must be based on standardized tests which have been shown to satisfy requirements of ASTM and AASHTO.
2) It should include measurements (test data) which have been related to performance.
3) It should be based on types of performance which can be defined quantitatively.

The asphalt-aggregate mixture analysis system will describe laboratory procedures and requirements for the laboratory evaluation of

asphalt binders, virgin, recycled or modified, and aggregate to minimize the occurrence of fatigue cracking, low temperature cracking and permanent deformation. The system will be sensitive to asphalt binder properties, aggregate properties and regional factors which could influence mixture performance.

The project will be divided into two tasks: 1) performance-based specifications for asphalt and 2) development of an asphalt-aggregate mixture analysis system.

The performance-based specifications for asphalt and asphalt-aggregate systems will incorporate the findings of each of the projects included in this research area. It is acknowledged that a limited amount of field performance information will be available during the term of the project, i.e., five years. It will, therefore, be necessary to develop an interim or model specification for recommendation at the completion of the project but which can be modified (improved) as additional information becomes available.

Task 4.1(3) Performance-Based Specifications for Asphalt

Objective: The objective of this task will be to develop performance-based specifications for asphalts, with and without modification. A sufficient number of specifications will be formulated to accommodate a wide variety of conditions which can be encountered in the United States.

Scope: The development of the asphalt specifications will fully consider the following requirements.

1) Will be tolerant to a wide range of mixing temperatures without damaging the asphalt and adversely affecting its desirable mixing and placing characteristics or its long-term performance in-service.
2) Will not be adversely affected by the chemical and physical properties of the aggregate used in the mix.
3) Will develop the needed adhesion (i.e., bond) to aggregates of different composition at different temperatures and degrees of wetness.
4) Will be resistant to migration (i.e., bleeding) at high temperatures.
5) Will be resistant to the adverse effects of aging (i.e., long-term durability).
6) Will remain flexible at in-service temperatures and resistant to cracking at low temperatures.

Specific requirements for this task include:

1) Select significant properties and their related test methods for use in the specifications.
2) Specify limits for the properties measured by the applicable test methods for each type and grade of asphalt included.
3) Provide guidelines for selecting asphalt grades for use in different environments, types of construction and characteristics of traffic.

Each specification will be the result of that combination of the above requirements considered to be "optimal," all factors considered.

A total of 3.0 million dollars has been allocated for this task.

Task 4.2(3) Performance-Based Specification for an Asphalt-Aggregate Mixture Analysis System (AAMAS)

Objective: The objective of this task will be to develop a performance-based specification for an asphalt-aggregate mixture analysis system (AAMAS), utilizing asphalts with and without modification.

Scope: The asphalt-aggregate mixture analysis system will include guidelines for specifying the properties of the asphalt-aggregate mixture which will produce a mix with the following characteristics:

1. Resistant to creep and permanent deformation (i.e., rutting).
2. Resistant to repeated bending stresses and strains (i.e., fatigue).
3. Resistant to low temperature cracking (i.e., thermal cracking).
4. Resistant to aging in-service at relatively high air voids (i.e., long-term durability).
5. Resistant to the effects of moisture and water (i.e., water sensitivity).
6. Compactible over a wide temperature range.

Specific requirements for this task include:

1) Select test methods considered necessary and sufficient for use with AAMAS.
2) Designate required specification limits for properties measured by the applicable test method for the full range of design considerations.
3) Provide guidelines for implementing AAMAS.

Typical examples of the application of AAMAS to situations representative of the variety of environments, types of construction and traffic loading characteristics encountered throughout the United States will be presented.

A total of 2.0 million dollars has been allocated for this task.

Project 1-5 Coordination

The objective of the coordination project is to assure that the combined effort from each task will adequately focus on the requirements for TRA 1. In order to achieve this objective, coordination has been divided into five tasks as described herein.

Task 5.1 TRA 1 Research Project Coordination

The objective of this task will be to monitor the activities of each project and task and to establish a mechanism for interaction between each ongoing research activity.

An important responsibility for the TRA 1 project coordination will be to interface the work under NCHRP 10-26(A) and 9-6(1) with activities in TRA 1. These two projects could contribute to the work under the following tasks:

2.2 - Testing and measuring methods for asphalt-aggregate systems
2.3(2) - Relationships between asphalt properties and asphalt-aggregate mixture properties
3.2 - Asphalt pavement performance studies
4.2 - Performance-based specifications for asphalt-aggregate mixture analysis system

Depending on the results from these two NCHRP projects, it may be desirable to modify the scope of work under any of the above tasks or, in the case of task 4.2, to accelerate activities by at least one year.

Specific requirements for this task include:

1) Schedule monthly meetings for representatives from each active research task or subtask in order to exchange and discuss specific accomplishments and problems.
2) Assist in resolving problems in order to achieve on time results.
3) Organize quarterly meetings of user-producer advisory committee to summarize results of research activities. (Note: If this committee is organized, it would be appointed by SHRP office with approval by the Task Force).
4) Provide quarterly executive summaries of progress on each research activity in progress indicating achievements, problems and overall evaluation.

A total of 1 million dollars has been allocated to this task.

Task 5.2 Operate Materials Reference Library

The objective of this task will be to develop and maintain a "library" of asphalts, aggregates and modifiers for use by contract agencies and other interested and authorized organizations.

The contractor will be required to procure asphalts and aggregates in suitable quantities to support the TRA 1 research activities. The cost of procurement, transport, storage, cataloging, packaging and shipping will be included in this project.

The specific requirements for this task include:

1) Procure samples of asphalts, aggregates and modifiers necessary to support research and long term requirements for TRA 1.
2) Store materials in proper containers or areas to minimize any changes in properties with time.
3) Package and ship materials to authorized users and in sufficient quantity to support specified research activities.
4) Monitor properties of materials in order to determine if specific properties are changing and by how much and if additional precautions are necessary to assure stable properties.

A total of 1.5 million dollars has been allocated to this task.

Task 5.3 Experiment Design

The objective of this task will be to develop a statistically sound experimental design for each research activity and to prepare a coordinated plan for selecting and testing materials. As a minimum the following items will be considered:

1. data requirements,
2. data storage and transmittal to the central data bank,
3. type and number of materials required to satisfy objectives of TRA 1 and
4. data analysis methodology.

Specific requirements for this task include:

1) Provide input and coordinate experiment design requirements for each task and subtask.
2) Provide assistance in planning for data acquisition and data analysis for each task and subtask.
3) Provide assistance in furnishing data to the central data bank to be established for SHRP projects.
4) Coordinate plans for the asphalt study area with requirements for the Long Term Pavement Performance Study Area.

A total of 0.5 million dollars has been allocated for this task.

Task 5.4 Economic Considerations

The objective of this task will be to provide expertise in evaluating the economic consequences of implementing specific findings from TRA 1 research activities. Preliminary indications from knowledgeable persons from both user and producer groups suggest that efforts to improve the properties of binders by introducing new asphalt specifications, or by the use of modifiers may increase the unit cost of binder systems. If this increased cost can be offset by either more reliable performance or an extended life cycle the overall benefits of increased initial cost would be justified.

A defensible method for making life cycle cost or benefit-cost comparisons will need to be established.

Specific requirements of this task include:

1) Provide a centralized group to study and evaluate the effectiveness of introducing new asphalt specifications and asphalt-aggregate requirements.
2) Prepare reports summarizing economic analysis procedures including assumptions required to estimate life cycle cost analysis and benefit-cost ratios.
3) Prepare estimates of the possible national benefits of introducing specific changes in asphalt-aggregate mixture requirements.

A total of 0.1 million dollars has been allocated to this task.

Task 5.5 Implementation Packages

In order to encourage and facilitate implementation of the research findings, it will be necessary to assemble information appropriate for use by user agencies into a series of implementation packages. Such information will include as a minimum:

1. preparation of material for SHRP to use in newsletters,
2. preparation of reports detailing the benefits of research findings and
3. conduct of regional workshops to explain research findings and to recommend procedures for implementation.

Specific requirements of this task include:

1) Prepare information regarding how to obtain materials and prepare construction specifications for incorporation of research findings.
2) To provide a step by step procedure for implementing research findings to be applied to site specific conditions.
3) Prepare specific information for use by SHRP officials in making presentations to Congress, AASHTO or other selected groups.
4) Prepare information for use by SHRP in preparing news releases.
5) Plan and conduct workshops in the fifth year of SHRP to explain findings and benefits available by implementing research results.

A total of 0.4 million dollars has been allocated to this task.

SECTION 5
RESULTS TO BE ACHIEVED

The major focus of Technical Research Area No. 1 will be the development of specifications for an asphalt type binder which is more tolerant to uncertainties related to conditions during or resulting from construction practices and is less sensitive to environmental factors. Asphalt properties produced in accordance with the SHRP specifications will be independent of the crude or refinery process. In order to achieve this objective, it is likely that methods for blending or modifying base asphalts will be necessary.

The net results of the performance-based specifications will be: 1) a longer life cycle for pavements constructed with asphaltic materials and 2) increased reliability to achieve anticipated performance, i.e., fewer premature failures.

In order to exploit the benefits of a more robust asphalt binder, it will be highly desirable under SHRP to develop requirements for the asphalt-aggregate combinations. Unlike asphalt, SHRP research is not designed to modify the properties of aggregates by manufacturing practices or chemical modification. However, by establishing appropriate relationships between asphalt properties and aggregate properties, it will be possible to maximize the performance of the combination. Consideration will be given to aggregate properties such as absorption, texture, size and mineralogy. In order to maximize the performance potential of asphalt-aggregate mixtures, it will be necessary to develop a set of tests and relevant criteria to minimize the occurrence of premature distress.

The SHRP program has been designed to address those types of distress which could incur major performance problems and rehabilitation costs; specifically, fatigue or traffic related cracking, low temperature cracking or environmentally induced shrinkage cracking and permanent deformation resulting in rutting and corrugations. It is acknowledged that there are other forms of distress which are of concern to users of asphalt binders. However, in order to maintain focus and increase the chances of successful achievement of important objectives, the number of distress types to be studied has been restricted.

In addition to the more obvious results to be achieved, as discussed in the previous paragraphs, additional research findings relevant to the basic and fundamental properties of asphalt will be developed. Specifically, basic research will lead to a comprehensive understanding of the make-up of asphalt and modified asphalt and an understanding of how such properties influence physical properties. The fundamental research with asphalt binders will help to understand the relationship between the physiochemical properties and

performance of asphalt, i.e., durability, bonding, rheology, fracture, and temperature susceptibility. In addition to a better understanding of the factors which influence the properties of bulk asphalt, virgin, modified or recycled, information will be developed as to how these properties influence the performance of asphalt-aggregate.

The development of new and improved standardized test methods to evaluate both binder properties and asphalt-aggregate properties will be a much needed achievement. It is not known exactly what form the tests will take; however, it can be expected that some of the achievements will include the following:

1. tests on binders over a range of temperatures representative of construction and in-service conditions,
2. methods for accelerated (laboratory) aging of asphalts during construction and after an extended life cycle in various environmental regions,
3. methods to recover asphalt binder from asphalt-aggregate mixtures after extended periods of in-service aging,
4. non-destructive method to evaluate in-situ properties of asphalt,
5. methods to measure relevant properties of recycled and modified asphalts,
6. standardized methods for testing asphalt-aggregate mixtures to measure: a) stability, b) fatigue, c) low temperature fracture, d) elastic or visco-elastic properties, e) plastic properties, f) thermal properties, and g) water sensitivity.

Special Report 202 has commented on the potential cost-effectiveness of the SHRP research effort. The projected budget planned for TRA 1 is 50 million dollars. Report 202 discusses the merits of such a research program.

> Is such an ambitious research effort worth it? Would it repay its costs? Firm answers cannot be given at this stage because research on asphaltic materials, like any research, involves some risk. These risks appear worth taking when the scale of the potential rewards is taken into account. The U.S. government will spend over $200 billion on asphalt pavements before the end of the century. A $50-million research project would repay its costs in 6 months even if it achieved a reduction of only 1 percent in asphalt pavement costs. Similarly, a $50-million reseach project spread over the next 5 years would repay its costs even if it only achieved a 0.1 percent reduction in costs. Moreover, in view of the incremental component-by-component research that has characterized asphalt throughout the years it has been used in highways, substantial payoffs far in excess of 1 percent might come from well-integrated, in-depth research on this material.

If this part of the overall SHRP research effort is to be cost effective it will be necessary to establish specific guidelines to be used to measure benefits. For example, if the asphalt binder produced to meet new specifications is more restrictive it will probably be more expensive; the question becomes, how much increase in life cycle, improved reliability or reduced maintenance is required to more than offset the additional cost? An

effort has been made to include in Project 1-5 the basis for development of sound economic criteria to be used in evaluating benefits.

In summary, TRA 1 has defined for itself a set of ambitious and yet achievable objectives. By keeping the research program focused on the results expected to provide maximum benefits the project has a high probability of being cost effective. It should be noted that the research is not starting without a foundation of previous work by a large number of investigators as can be concluded from the representative number of publications contained in Appendix A.

SECTION 6
IMPLEMENTATION OF RESULTS

Quoting from the Executive Summary of Special Report 202:

> "Research often fails to change practice because of limited understanding, organizational inertia, inflexible standards, preoccupation with first costs, mistrust of change, or a desire to perpetuate jobs. A research program designed without taking into account such obstacles will fail."

One might also add mistrust of research representations (findings) on the part of management level personnel.

Each of the factors enumerated in the Executive Summary above must be addressed if the SHRP program is to be exploited to achieve its potential benefits.

Six basic factors need to be addressed:

1) commitment,
2) communications,
3) demonstration,
4) cooperation,
5) financing, and
6) evaluation.

No research results will be possible without commitment from top level management persons in both user and producer organizations. These persons need to be convinced that the research, in fact, will benefit the public by reducing life cycle costs and user inconvenience (costs).

One method of obtaining commitment from management is through direct communications at a non-technical level, concise and understandable life. Executive summary type reports furnished in a timely manner will be helpful. However, the most effective communications will occur if administrators can communicate with other administrators. Thus, the creation of an AASHTO Task Force, similar to the SHRP Task Force, will be a first step in establishing credible channels of communications. The Task Force will need to be supported by technologists who can answer questions pertinent to problems associated with implementation and with communications specialists who can prepare write-ups and visual aids useful for presentations to the AASHTO Policy Committee.

Some type of upper level management committee at a national level involving highway administrators, asphalt producers, contractors and chemical

manufacturers (modifiers) will be essential if a commitment from both users and producers is to be obtained. Benefits to both communities need to be established as quickly as possible and preferably as part of the on-going SHRP activities.

The commitment by management is essential and it must be real.

Demonstration projects such as will evolve from the LTPP program will help convince all parties of the merits of research findings. Involvement by personnel from state highway and federal agencies, industry and the consultant community will be important. Technical reports have not been effective in this regard. The most effective method of communicating results from demonstration projects is by direct contact; workshops, seminars, regional meetings, etc. have proven effective. Persons to make representations should be trained and supported with visual aids in order to make the desired impact.

As part of the workshops, sufficient step by step guidance should be provided to enable an agency to implement the results. Help on specific projects on a regional basis would also provide examples of "how it can be done."

The cooperation of all agencies will be required; again involving both users and producers in all categories. Cooperation can usually be obtained if the benefits can be explained.

Since projects involving new binders may be more expensive than conventional projects, some provision will be necessary for funding initial constructions. Deviations from standard state and federal requirements may be necessary in order to implement on a scale sufficient to provide a data base large enough to offset some results which may not meet expectations.

Implementation of research always involves some risk; however, if the potential benefits are sufficiently large, the risk can be justified. When implementing new ideas, the unexpected is likely to occur in the initial stages. It will, therefore, be important to have enough projects spread over large areas to allow a realistic long term evaluation of the results and benefits.

In summary, implementation of results from the SHRP research will require a commitment from upper management based on meaningful communications and well-planned methods to demonstrate and evaluate benefits.

SECTION 7
SCHEDULE OF PROJECTS, TASKS AND SUBTASKS

Technical Research Area Number 1 has been organized in this report into 5 projects, 20 tasks involving 7 subtasks. Table 1 in Section 3 has enumerated each project, task and subtask with recommended budget allocations for each activity. This section provides recommendations concerning start and stop times for each project. Subtasks within tasks would be keyed to their respective tasks.

Figure 4 provides a bar diagram indicating start and stop times for each task, also indicating the interrelationships between tasks such as were indicated in Figure 2. The vertical lines with arrows indicate the approximate time when initial interaction can take place. Check marks indicate milestone points for review of progress and modification or redirection of the task as necessary to achieve project goals. Figure 4 does not comply with requirements for a PERT diagram. The difficulty in attempting to use such procedures is a result of the fact that several critical tasks, e.g., tasks 1.1, 1.2, 3.2 are planned to be continuous during the full 5 year term of the program, and 11 of 15 tasks shown (not including Project 1-5) are estimated to be completed at the end of the 5-year term. Extending projects through the fifth year provides for continuous feedback between key tasks.

The critical requirement for TRA 1 will be to complete Project 1-4 at the end of the 5-year term.

The key to achieving the objectives designated for TRA 1 will be coordination. Project and task coordination is provided in Project 1-5. Continuous interactions from ongoing projects and using results from completed tasks will be essential in order for the research to be effective.

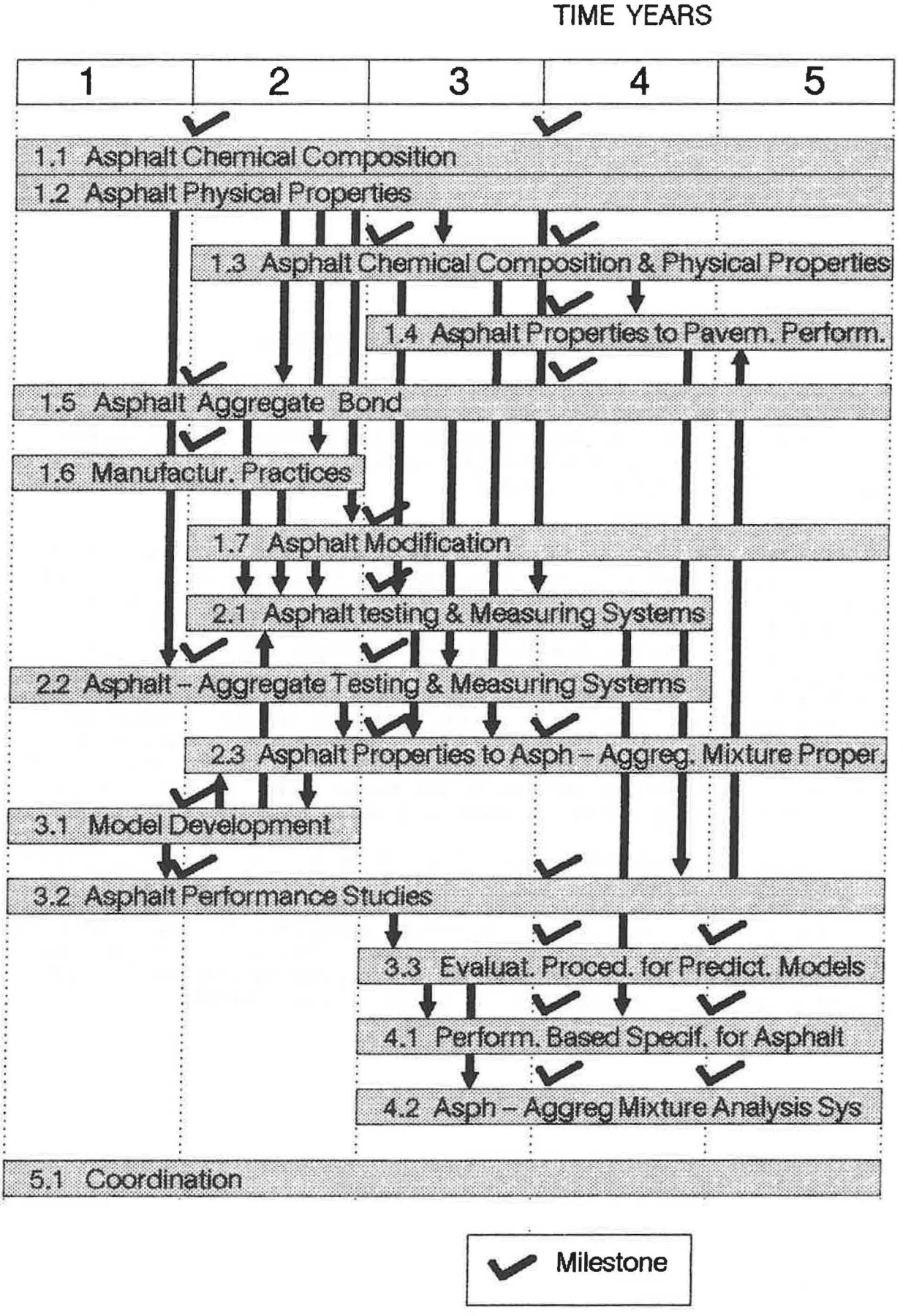


FIGURE 4. SCHEDULING PLAN FOR TRA 1

SECTION 8
BUDGET

Table 1 summarized the budget by project and task. Figure 5 provides recommended guidelines for budget allocations for each task and Figure 6 provides the same information for subtasks within tasks 1.5 and 2.2.

The total budget allocation by years is shown on the bottom of Figure 5. Budget estimates tend to start relatively low, i.e., 5.65 million in the first year, increasing to 13.12 million in the third year. The first year will serve to provide sufficient research developments to enable the research area to build on a sound foundation. Actually, a high percentage of the tasks and subtasks could be underway in the first year; however, the level of effort will not require complete mobilization of personnel and equipment during that time frame.

Equipment requirements will fall into two categories: 1) those pieces of equipment which have traditionally been used for testing and measuring the properties of asphalt and asphalt-aggregate mixtures and 2) new equipment resulting from research supported by SHRP.

It is not expected that the SHRP budget would be required to allocate funds for the purchase of standard testing equipment. Cost of testing will include cost of equipment.

New equipment will need to be designed, fabricated and evaluated by the research agency; the cost of such developments should be provided for in the SHRP budget.

It should be recognized that equipment design and fabrication will be developed in at least two stages: 1) research model and 2) production model. The research model will usually be less "finished" and may evolve through research. The production model will incorporate improvements in the overall design and will incorporate those features necessary to simplify the testing procedure.

Table 3 summarizes the estimated costs for equipment by task. These costs are primarily to illustrate a need for funds. The final costs may differ significantly depending on research developments.

Each contractor selected to undertake research in TRA 1 should provide resources of the following types:

1) equipment for standard tests,
2) laboratory space dedicated to asphalt research, and
3) personnel with experience in testing asphaltic materials appropriate to the particular task.

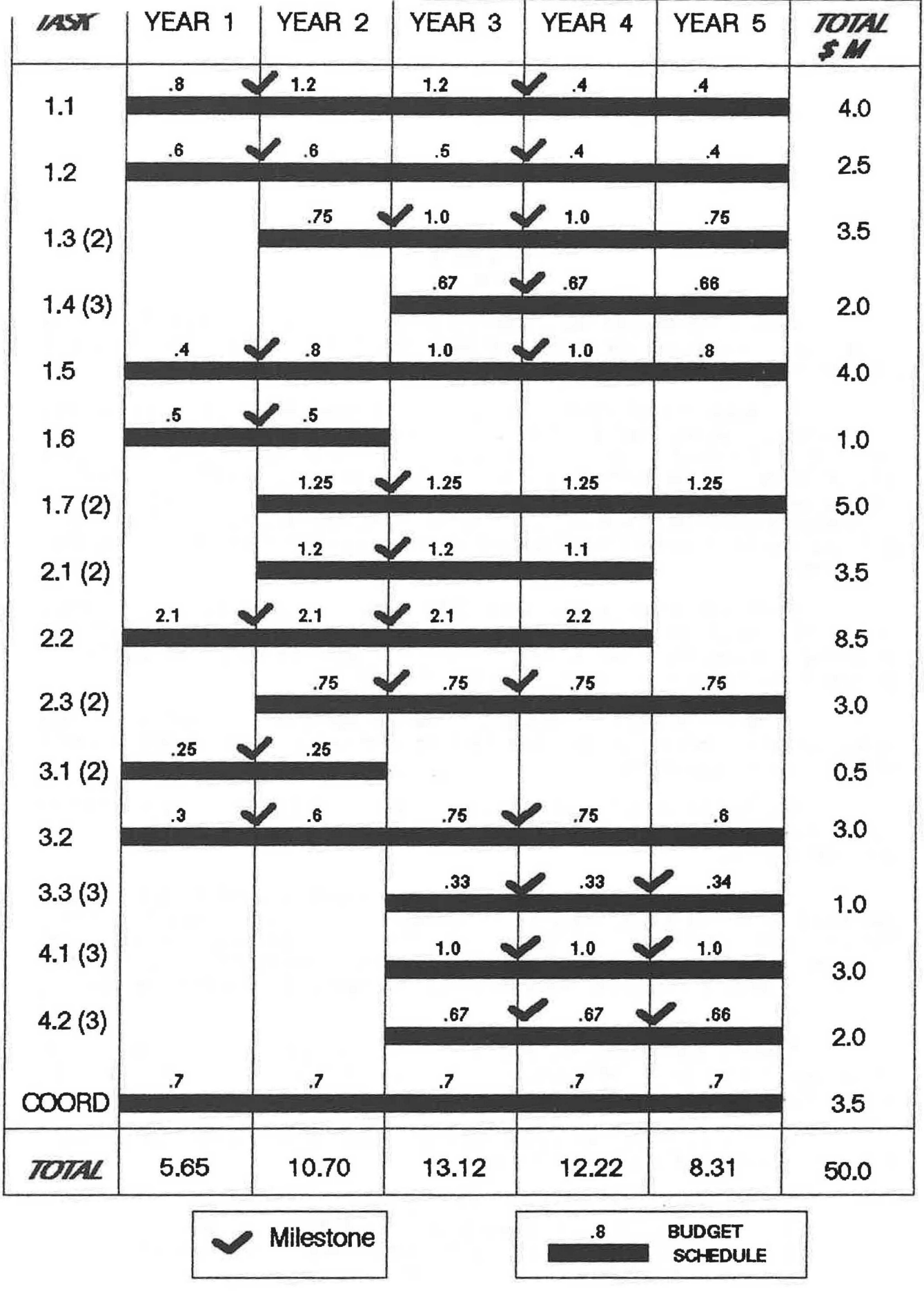


FIGURE 5. SCHEDULING AND BUDGET DIAGRAM FOR TASKS IN TRA 1.

SCHEDULING AND BUDGET DIAGRAM

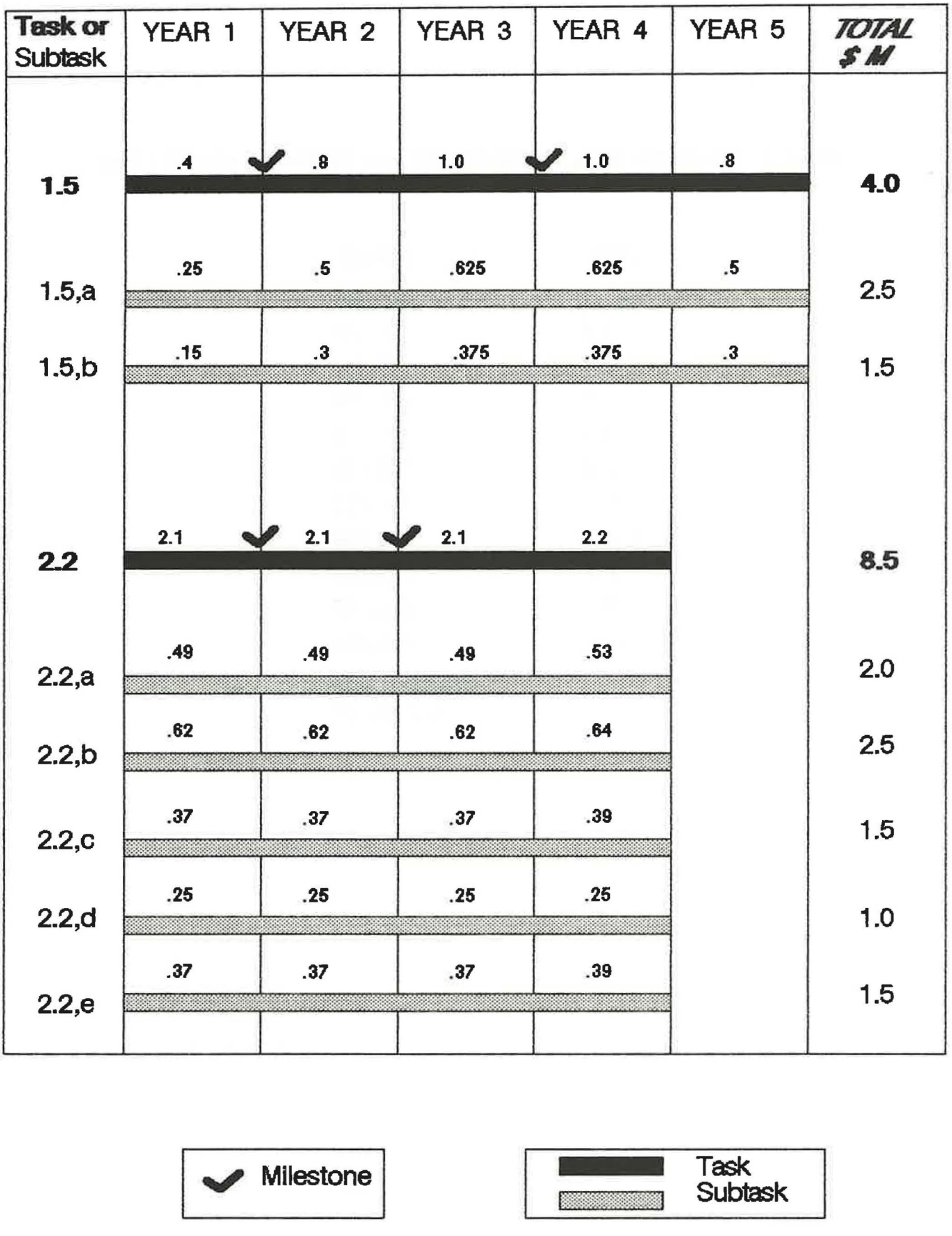


FIGURE 6. SCHEDULING AND BUDGET DIAGRAM FOR SUBTASKS IN TRA 1

TABLE 3 ESTIMATED BUDGET REQUIREMENTS FOR EQUIPMENT ACQUISITIONS

Task	Budget
1-1.1	300,000
1.2	300,000
1.3	200,000
1.4	200,000
1.5	250,000
1.6	200,000
1.7	300,000
1-2.1	200,000
2.2	200,000
2.3	200,000
1-3.2	200,000
	$2,550,000

The specifics of items 2 and 3 remain to be specified; however, equipment and space without qualified people will result in confusing and contradictory results between contracting agencies.

REFERENCES

1. _____ _____ "America's Highways - Accelerating the Search for Innovation," Transportation Research Board, Special Report 202, 1984.

2. Halstead, W., "Relation of Asphalt Chemistry to Physical Properties and Specifications," Proceedings, Assocation of Asphalt Paving Technologists, 1984.

3. Petersen, J. C., "Chemical Composition of Asphalt as Related to Asphalt Durability," Federal Highway Administration, Report No. FHWA/RD-84/047, July, 1984.

4. Welborn, J. Y., and W. J. Halstead, "Properties of Highway Asphalts, Parts I and II," Public Roads, Vol. 30, No. 9, August 1959 and Vol. 31, No. 4, October 1960.

5. Heukelom, W., "Observations on the Rheology and Fracture of Bitumens and Asphalt Mixes," Proceedings, Association of Asphalt Paving Technologists, Vol. 35, 1966, p. 358.

6. Duthie, J. L., "Proposed Bitumen Specifications Derived from Fundamental Parameters," Proceedings, Association of Asphalt Paving Technologists, 1972, p. 70.

7. Mc Leod, N. W., "Asphalt Cement Specifications - Some Facts and Challenges," Proceedings, American Association of State Highway and Transportation Officials, 65th Annual Meeting, 1979.

8. Puzinauskas, V. P., "Properties of Asphalt Cements," Proceedings Association of Asphalt Paving Technologists, Vol. 48, 1979.

9. Jennings, et al, "The Expanded Montana Asphalt Quality Study Using High Pressure Liquid Chromatography," Montana Department of Highways, 1980.

10. Corbett, L. W., and H. E. Schweyer, "Composition and Rheology Considerations in Age Hardening of Bitumen," Proceedings, Association of Asphalt Paving Technologists, Vol. 50, 1981, p. 571.

11. Rostler, F. and K. Rostler, "Basic Considerations in Asphalt Research Pertaining to Durability," Proceedings, Association of Asphalt Paving Technologists, Vol. 50, 1981, p. 582.

12. Anderson, D. A., E. L. Dukatz, J. L. Rosenberger, "Properties of Asphalt Cement and Asphaltic Concrete," Proceedings, Association of Asphalt Paving Technologists, Vol. 52, 1983.

13. Brule, B., G. Ramond, and C. Such, "Relationships Between Composition Structure and Properties of Road Asphalts: State of Research at French Laboratorre Central Des Ponts Et Chausees," prepared for distribution at the SHRP National Workshop, Dallas, Texas, August 1985.

14. Monismith, C. L. and S. Yuce, "Prediction of Load Associated Cracking in Pavement Slabs from Laboratory Determined Fatigue Data," Proceedings, Association of Asphalt Paving Technologists, Vol. 43, 1974, p. 332.

15. Larson, T. D., "The Use of Test Roads and Test Tracks in Developing Pavement Design and Performance Information," FHWA Pavement Testing Conference, March 1984.

16. Krukar, M. and J. C. Cook, "Comparison of Washington State University Test Track Experimental Pavement Rings Nos. 2 and 3," Proceedings, Association of Asphalt Paving Technologists, Vol. 40, 1971, p. 1.

17. Speer, T., "Laboratory Traffic Tests of Miniature Highways - Second Progress Report," Proceedings, Association of Asphalt Paving Technologists, Vol. 31, 1962, p. 507.

18. Smith, W., F. Finn, R. Kulkarni, C. Saraf and K. Nair, "Bayesian Methodology for Verifying Recommendations to Minimize Asphalt Pavement Distress," National Cooperative Highway Research Program, Report No. 213, June 1979.

19. Hendrickson, C. T., D. R. Rehak, and S. J. Fenves, "Expert Systems in Transportation Systems Engineering," Transportation Research, 1985.

20. Vallerga, B. A., F. N. Finn, and R. G. Hicks, "Effect of Asphalt Aging on the Fatigue Properties of Asphalt Concrete," Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, University of Michigan, 1967, p. 595.

APPENDIX A

BIBLIOGRAPHY

1. Relation Between Hardening and Composition of Asphalt
   Preprints Div. of Petroleum Chemistry, American Chemical Society, Vol. 5, No. 4-A, pp. A-71 to A-77
   R. N. Traxler, 1960

2. Molecular Interactions of Asphalt: An Infrared Study of the Hydrogen-Bonding Basicity of Asphalt
   Analytical Chemistry, Vol. 46, No. 2, pp. 273-277.
   Barbour and Petersen, Feb. 1974

3. An Inverse GLC Study of Asphalts Used in the Zaca-Wigmore Experimental Road Test
   Proc. of AAPT, Vol. 36, pp. 1-10.
   T. C. Davis and J. C. Petersen, 1967

4. Direct Evidence of Ketones in Oxidized Asphalts
   Analytical Chemistry, Vol. 46, No. 14, pp. 2242-2244.
   S. M. Dorrance, F. A. Barbour and J. C. Petersen, Dec. 1974

5. Changes in Chemical Composition of a Kuiwait Short Residue During Air Blowing
   Analytical Chemistry, Vol. 47, No. 14, pp. 2432-2437.
   G. A. Haley, Dec. 1975

6. The Fractionation of Asphalt
   Paper prepared for AAPT Meeting
   M. M. Hattingh, Jan. 1984

7. Compositional Analysis Used to Explore Asphalt Hardening
   Proc. of AAPT, Vol. 29, pp. 104-114.
   L. W. Corbett and R. E. Swarbrick, 1960

8. Inverse GLC--An Extension of the Technique to The Study of Oxidation of Asphalts
   Highway Research Record No. 134, Highway Research Board, National Academy of Sciences, pp. 1-7.
   T. C. Davis and J. C. Peterson, 1966

9. Compositional Considerations of Asphalt for Durability Improvement
   TRB Record 544, pp. 46-55.
   R. J. Peters, 1975

10. Relationships Between Asphalt Chemical Composition and Performance-Related Properties
Paper presentation at AEMA
J. C. Petersen, March 1982

11. Reduction of Oxidative Hardening of Asphalts by Treatment with Hydrated Lime--A Mechanistic Study
Proc. of AAPT, Vol. 45, pp. 1-24.
H. Plancher, E. L. Green, and J. C. Petersen, 1976

12. Composition and Changes in Composition of Highway Asphalts, 85-100 Penetration Grade
Proc. of AAPT, No. 31, pp. 35-89.
F. S. Rostler and R. M. White, 1962

13. Influence of Chemical Composition of Asphalts on Performance, Particularly Durability
ASTM STP No. 277, pp. 64-88.
F. S. Rostler and R. M. White, 1959

14. Relationship Between Composition and Physical Properties of Asphalt
Proc. of AAPT, Vol. 39, pp. 481-491.
L. W. Corbett, 1970

15. Contributions of Components to Asphalt Consistency
Presentation to Div. of Petroleum Chem., American Chemical Society, Vol. 16, No. 1, pp. D5-D17.
J. V. Evans, et.al., 1971

16. Changing Asphalt Through Creation of Metal Complexes
Proc. of AAPT, Vol. 50, pp. 442-468.
T. W. Kennedy, L. O. Cummings, and T. D. White, 1981

17. Relationship of Asphalt Properties to Chemical Constitution
J. Chem. Eng., Vol. 6, No. 3, pp. 426-429.
W. C. Simpson, R. L. Griffin, et.al., July 1961

18. Integrated Structural Analysis. A Method for the Determination of Average Structural Parameters of Petroleum Heavy Ends
Anal. Chem., Vol. 42, pp. 1330-1339.
K. H. Altgelt, Oct. 1970

19. Organic Functional Group Analysis by Micro and Semimicro Methods
Interscience, John Wiley & Sons, New York
N. D. Cheronis and T. S. Ma, 1964

20. The Mass Spectrometric Analysis of Asphalt - A Preliminary Investigation
Symposium on Fundamental Nature of Asphalt, Div. of Petroleum Chem., American Chemical Society, New York, Vol. 5, No. 4-A.
R. J. Clerc and M. J. O'Neal, Sept. 1960

21. Aromatic Structure in Asphalt Fractions
I&EC Prod. R & D, Vol. 6, No. 2, pp. 127-132.
S. W. Ferris, et.al., June 1967

22. High Resolution Mass Spectrometry of Asphalt Fractions
Proc. 7th World Petroleum Congress, Vol. 4, pp. 249-260.
E. J. Gallegos, 1967

23. Chemical Reactivity of Asphaltic Bitumen
The Properties of Asphaltic Bitumen (Ed. J. Ph. Pfeiffer),
Elsevier, New York, pp. 109-120.
J. W. A. Labout, 1950

24. Quantitative Determination of Carboxylic Acids and Their Salts and Anhydrides in Asphalts by Selective Chemical Reactions and Differential Infrared Spectrometry
Anal. Chem., pp. 786-789.
J. C. Petersen and H. Plancher, May 1981

25. Identification of Dicarboxylic Anhydrides in Oxidized Asphalts
Anal. Chem., Vol. 47, No. 1, pp. 107-111.
J. C. Petersen, F. A. Barbour and S. M. Dorrance, Jan. 1975

26. Identification of Chemical Types in Asphalts Strongly Adsorbed at the Asphalt-Aggregate Interface and Their Relative Displacement by Water
Proc. of AAPT, Vol. 46, pp. 151-175.
H. Plancher, S. M. Dorrance and J. C. Petersen, 1977

27. The Compactness of the Aromatic Systems in Petroleum Asphaltics
Presentation to Div. of Petroleum Chem., American Chemical Society,
Vol. 11, No. 3, pp. 49-54.
T. F. Yen and J. P. Dickie, 1966

28. GPC in Structural Research of Asphalt
Bitumen, Teere, Asphalte, Peche, Vol. 21, pp. 475-486.
K. H. Altgelt, 1970

29. Investigations on Romanshkino asphalt bitumen. 1. Use of ion-exchange and adsorption chromatography for the separation of maltenes
Fuel, Vol. 56, pp. 145-148.
M. M. Boduszynski, 1977

30. Investigations on Romanshkino asphalt bitumen. 2. Study of maltene fractions using inverse gas-liquid chromatography
Fuel, Vol. 56, pp. 149-152
M. M. Boduszynski, 1977

31. Investigations on Romanshkino asphalt bitumen. 3. Fractionation of asphaltenes using ion-exchange chromatography
Fuel, Vol 56, pp. 432-436.
M. M. Boduszynski, 1977

32. Gel Permeation Chromatography Data on Asphalts Before and After Service in Pavements
Proc. of AAPT, Vol. 39, pp. 683-702.
D. Bynum and R. N. Traxler, 1970

33. A Correlation of the Studies of Inverse GLC of Paving Asphalts with Paired Comparison Performance Results
Proc. of AAPT, Vol. 40, pp. 438-462.
J. C. Robertson and J. R. Moore, 1971

34. Refinery Processing of Asphalt Cement
Paper presented at TRB
L. W. Corbett, Jan. 1984

35. Fractional Components of Asphalt--Compatibility and Interchangeability of Fractions Produced from Different Asphalts
Proc. of AAPT, Vol. 39, pp. 492-531.
R. M. White, W. R. Mitten and J. B. Skog, 1970

36. Clues to Asphalt Composition
Proc. of AAPT, Vol. 27, pp. 107-121.
L. W. Corbett and R. E. Swarbrick, 1958

37. Properties of Highway Asphalts--Part III, Influence of Chemical Composition
Proc. of AAPT, Vol. 35, pp. 91-138.
W. J. Halstead, F. S. Rostler, R. M. White, 1966

38. Quantitative Method Using Differential Infrared Spectrometry for the Determination of Compound Types Absorbing in the Carbonyl Region in Asphalts
Anal. Chem., Vol 47, No. 1, pp. 112-117.
J. C. Petersen and H. Plancher, Jan. 1975

39. Fingerprinting of Highway Asphalts
Proc. of AAPT, Vol. 41, pp. 685-715.
F. S. Rostler, K. S. Rostler, et.al., 1972

40. Fractional Composition: Analytical and Functional Significance
Bituminous Materials: Asphalts, Tars, and Pitches, Vol. 2, Part 1 (Ed. A. J. Hoiberg), Interscience, New York, pp. 151-223.
F. S. Rostler, 1965

41. Proc. of ASTM - Composition Tests
Vol. 36, II, p. 554
R. N. Traxler and H. T. Schweyer, 1936

42. Composition of Asphalt Based on Generic Fractionation, Using Solvent Deasphalting, Elution-Adsorption Chromatography and Densimetric Characterization
Anal. Chem., Vol. 41, p. 576
L. W. Corbett, 1969

43. Effect of Solvents and Temperature on the Separation of Asphalts by Gel Permeation Chromatography
American Chemical Society Convention, San Francisco
H. R. Drushel and W. W. Schultz, 1980

44. A Study of the Crystalline Phases in Asphalts
Journal of the Institute of Petroleum, Vol. 56, (551), pp. 261-268.
F. Noel, L. W. Corbett, 1970

45. Separating Asphalt into its Chemical Constituents
Anal. Chem., Vol. 23, p. 894
Gordon J. O'Donnell, June 1951

46. Composition as Related to Manufacturing and Weathering of Roofing Asphalts
ASTM Symposium on Bituminous Materials, Atlantic City
L. W. Corbett and R. E. Swarbrick, June 26, 1963

47. Constitution of asphaltic bitumen. Characterization of bitumens by a combination of pyrolysis, hydrogenation and gas-liquid chromatography
American Chemical Society Preprints 151st Mtg., Pittsburgh, Vol. 10, No. 2 - B-109; Ind. Eng. Chem. Product Res. Dev., Vol. 6, p. 43
J. Knotnerus, 1966 and 1967 respectively

48. A determination of the wax content of bitumens
J. Inst. Petrol., Vol. 54, p. 232
C. J. Krom, 1968

49. Bitumen Research
Shell Bitumen Review No. 33, 14
Koninklijke/Shell-Laboratorium Amsterdam, 1971

50. The Application and Performance of Asphalts
Proceedings, 8th World Petroleum Congress, Moscow, 5, 117
A. J. G. Klemp, 1971

51. Association of Asphalt Paving Technologists Symposium on Asphalt Properties as Related to Pavement Performance
Whiting Lab Memo M63-58
T. L. Speer, March 25, 1963

52. The Effect of Asphalt Properties on the Fatigue Resistance of Paving Mixtures
Proc. of AAPT, (1969), pp. 65-97
Santucci, L. E. and Schmidt, R. J.

53. Use of HPLC to Determine the Effects of Various Additives and Fillers on the Characteristics of Asphalt
Paper prepared for Montana Department of Highways and U.S. DOT Federal Highway Admin., June 1982, 24 pp.
Jennings, P. W., Pribanic, J. A. S. and Dawson, K. R.

54. Use of HPLC and NMR Spectroscopy to Characterize Asphaltic Materials
Preprints Div. of Petrol. Chem., American Chemical Society, Vol. 26, No. 4, Sept. 1981, pp. 915-922
Jennings, P. W., Pribanic, J. A. S., Dawson, K. R. and Bricca, C. E.

55. Chemical Composition of Commercial Asphalt Cement as Determined by High Pressure Liquid Chromatography
FHWA Report No. MY-7929, Department of Chemistry, Montana State University, Bozeman, Montana, Dec. 1977
Jennings, P. W., Pribanic, J. A. S., Dawson, K. R. and Bricca, C. E.

56. High Pressure Liquid Chromatography as a Method of Measuring Asphalt Composition
FHWA Report No. MTDOH-7930, Department of Chemistry, Montana State University, Bozeman, Montana, March 1980
Jennings, P. W., Pribanic, J. A. S., Dawson, K. R. and Bricca, C. E.

57. Requirements for the Gel Permeation Mode (HP-GPC) of Asphalt Cement
Montana State Department of Highways Special Provision, November 14, 1983

58. Relation of Asphalt Composition to its Durability in Service
Preprints Div. of Petroleum Chem., American Chemical Society, Vol. 3, No. 2 (1958), pp. A-29-37
Knowles, E. C., McCoy, F. C., et al

59. Basic Considerations in Asphalt Research Pertaining to Durability
Proc. of AAPT, Vol. 50 (1981), pp. 582-621
Rostler, F. and Rostler, K.S.

60. Relationship Between Asphalt Flow Properties and Asphalt Composition
Presentation at AAPT, April 1984
Anderson, D. A. and Dukatz, E. L.

61. Asphalt Properties and Composition: 1950-1980
Proc. of AAPT, Vol. 49 (1980), pp. 1-29
Anderson, D. A. and Dukatz, E. L.

62. Influence of Asphalt Temperature Susceptibility on Pavement Construction and Performance
Texas Transportation Institute, Nov. 1983, rev. June 1984
Button, J. W., Epps, J. A., Little, D. W. and Gallaway, B. M.

63. Influence of Composition of Paving Asphalt on Viscosity, Viscosity-Temperature Susceptibility, and Durability
Presentation at Div. of Petroleum Chem., American Chemical Society, Vol. 3, No. 2 (1958), pp. A13-27
Griffin, R. L., et al

64. Some Correlations of Asphalt Composition with Physical Properties
Proc. of AAPT, Vol. 20 (1951), pp. 1-22
Hughes, E. C. and Hardman, H. F.

65. Relationship of Flow Properties to Chemical Composition for Paving Asphalts
Highway Research Record No. 231, Highway Research Board, National Academy of Sciences, pp. 24-33
Lamb, C. W. and Couper, J. R.

66. Influence of Asphalt Composition on Its Rheological Behavior
Proc. of AAPT, Vol. 44 (1975), pp. 416-443
Marvillet, J.

67. Changes in Bitumen Composition Causing Changes in Viscosity
Highway Research Record No. 134, Highway Research Board
National Academy of Sciences, pp. 51-62
Tingle, E. D. and Green, E. H.

68. Use of HPLC and NMR Spectroscopy to Characterize Asphaltic Materials
Preprints Div. of Petrol. Chem., American Chemical Society, Vol. 26, No. 4, Sept. 1981, pp. 915-922

69. Chemical Composition of Commercial Asphalt Cement as Determined by High Pressure Liquid Chromatography
FHWA Report No. MT-7929, Dept. of Chemistry, Montana State University, Bozeman, Montana, December 1977
Jennings, P. W., et al

70. High Pressure Liquid Chromatography as a Method of Measuring Asphalt Composition
FHWA Report No. MTDOH-7930, Dept. of Chemistry, Montana State University, Bozeman, Montana, March 1980
Jennings, P. W., Pribanic, J., et al

71. Requirements for the Gel Permeation Mode (HP-GPC) of Asphalt Cement
Montana State Dept. of Highways Special Provision, No. 14, 1983

72. Differences in Distillation and Solvent Asphalt Residue
Ind. Eng. Chem. Prod. Res. Dev., Vol. 17, No. 4 (1978), pp. 342-346
Corbett, L. W., et al

73. An Examination of the Significance of the Oliensis Spot Test
Proc. of AAPT, Vol. 28 (1959), pp. 353-371
Heithaus, J. J. and Fink, D. F.

74. The Oliensis Spot Test as a Quality Test
Proc. of AAPT, Vol. 26 (1957), pp. 82-125
Oliensis, G. L.

75. A Qualitative Test for Determining the Degree of Heterogeneity of Asphalts
Proc. of ASTM, Vol. 33 (1933), pp. 715-728
Oliensis, G. L.

76. A Settling Test to Evaluate the Relative Degree of Dispersion of Asphaltenes
Proc. of AAPT, Vol. 48 (1979), pp. 351-374
Plancher, H., Hoiberg, A. J., Suhaka, S. C. and Peterson, J. C.

77. The Interrelationship Between the Density, the Composition, and the Properties of Bitumens
Khimiia i tekhnologiia topliv i masel, No. 9 (1979), pp. 41-44

Fryazinov, V. V., et al

78. Physico-Chemical Aspect of Asphalts
Proc. of AAPT, Vol. 5, (1933), pp. 40-53
Mack, C.

79. The Influence of Asphalt Composition in its Rheology
R. S. Winniford
ASTM, STP 294, 1960

80. Influence of Composition of Paving Asphalt on Viscosity, Viscosity-Temperature Susceptibility and Durability
Journal of Chemical Engr. Data 4, 349-54 (Oct. 1959)
R. L. Griffin, W. C. Simpson, T. K. Miles

81. Relationship of Asphalt Properties to Chemical Constitution
Journal of Chem. Engr. Data 6, No. 3, p. 426 (July 1961)
R. L. Griffin, T. K. Miles, W. C. Simpson

82. Investigation into the Plastic Properties of Asphaltic Bitumen
J. Inst. Petrol. Technologists 19 (1933) 176.
R. N. J. Saal and G. Koens

83. The Rheological Properties of Asphaltic Bitumens
J. Inst. Petrol. Technologists 22 (1936) 414
J. Ph. Pfeiffer and P. M. van Doormaal

84. The Relation Between Absolute Viscosity and Penetration of Asphaltic Bitumens
Physics 7 (1936) 408
R. N. J. Seal and J. W. A. Labout

85. Comparison of Various Methods for the Classification of Asphaltic Bitumens According to Their Temperature Susceptibility
Intern. Assoc. Testing Mater. Congr., London, April 1937
J. Ph. Pfeiffer and R. N. J. Saal

86. Rheological Properties of Asphaltic Bitumens
J. Phys. Chem. 44 (1940) 149
R. N. J. Saal and J. W. A. Labout

87. Physical Constants of Asphaltic Bitumens, I
J. Inst. Petrol. 26 (1940) 29; Shell Bitumen Reprint 2
R. N. J. Saal, W. Heukelom and P. C. Blokker

88. Physical Constants of Asphaltic Bitumens, II
J. Inst. Petrol. 26 (1940) 246; Shell Bitumen Reprint 2
R. N. J. Saal, K. Meinema and P. C. Blokker

89. The Determination of the Plastic Properties of Bitumen Aggregate Mixtures and the Influence of Variations in the Composition of the Mix
Proc. Assoc. Asphalt Paving Technologists 16 (1947) 203
L. W. Nijboer

90. Rheological Investigation of Asphaltic Bitumen in Connection with its Technical Applications
J. Inst. Petrol. 34 (1948) 69
R. N. J. Saal

91. Plasticity as a Factor in the Design of Dense Bituminous Road Carpets
Amsterdam, Elsevier Publ. Comp. Inc., 1948
L. W. Nijboer

92. The Colloidal Structure of Asphalt
J. Phys. & Coll. Chem. 53 (1949) 1195
H. Eilers

93. Representation of Rheological Properties of Bitumens in a Wide Range of Temperatures and Loading Times
Proc. Intern. Congr. Rheol., 2nd, Oxford, 1953, 331
C. van der Poel

94. A General System Describing the Visco-Elastic Properties of Bitumens and Its Relation to Routine Test Data
J. Appl. Chem. 4 (1954) 221; (in German) Kolloid/Z. 139 (1954) 101; Shell Bitumen Reprint 9
C. Van der Poel

95. The Microelastometer, A Micro Device for Measuring the Modulus of "Stiffness" of Small Samples of Thermoplastic Materials
Rheologica Acta 1958, 186
J. W. A. Labout

96. Durability of Bitumen in Theory and Practice
World Petrol. Congr., Proc., 5th, New York, 1959, Section VI; Shell Bitumen Reprint 14
P. C. Blokker and H. van Hoorn

97. Performance Requirements for Road Bitumens and Their Expression in Specifications
World Petrol. Congr., Proc., 6th, Frankfurt/Main, 1963, Section VI 145
(In German) Bitumen, Teere, Asphalte, Pecke 14 (1963) 399-401 and 450-453
Shell Bitumen Reprint 15
C. J. Krom and G. M. Dormon

98. Observations on the Rheology and Fracture of Bitumens and Asphalt Mixes
Proc. Assoc. Asphalt Paving Technologists 35 (1966) 358.
Shell Bitumen Reprint 19
W. Heukelom

99. Some Relations Between the Fracture of Asphaltic Bitumens and Their Rheology
Proc. Conf. Phys. Basis of Yield and Fracture, Oxford, (1966) 237
W. Heukelom

100. Characteristics of the Rheology of Bitumens
Proc. Assoc. Asphalt Paving Technologists, 38 (1969) 98
R. Jongepier and B. Kuilman

101. A Bitumen Test Data Chart for Showing the Effect of Temperature on the Mechanical Behavior of Asphaltic Bitumen
J. Inst. Petrol. 55 (1969) 404

102. The Effect of Temperature on the Mechanical Behavior of Some Canadian Asphalts as Shown By A Test Data Chart
Proc. 14th Annual Conference Canadian Techn. Asphalt Assoc. 14 (1969) 262
O. Kopvillem and W. Heukelom

103. The Dynamic Shear Modulus of Bitumens as a Function of Frequency and Temperature
Rheol. Acta 9 (1970) 102
R. Jongepier and B. Kuilman

104. The Sliding Plate Rheometer
Proc. 15th Annual Conference Canadian Techn. Asphalt Assoc. 15 (1970) 123
J. Fenijn and R. C. Krooshof

105. Viscosity of Dispersions as Governed by Concentration and Rate of Shear
Proc. Assoc. Asphalt Paving Technologists 40 (1971) 418
W. Heukelom and P. W. O. Wijga

106. Mechanical Testing of Asphaltic Bitumen
World Petrol. Congr., Proc., 4th, Rome, 1955, Section VI/A
R. N. J. Saal

107. A Study on the Significance of the Ductility Test for Bitumen
J. Appl. Chem. 5 (1955) 663
R. N. J. Saal

108. An Improved Method of Characterizing Asphaltic Bitumens With the Aid of Their Mechanical Properties
Paper presented at the Annual Meeting of the Assoc. Asphalt Paving Technologists, Houston, Texas, February 1973
W. Heukelom

109. Some Observations on the Molecular "Nature" of Petroleum Asphaltenes
Presented Div. of Petrol. Chem., American Chemical Society, Vol. 24, No. 4, pp. 910-923
J. G. Speight, et al, 1979

110. Asphaltenes in Petroleum Asphalts, Composition and Formation in Chemistry of Asphaltenes (Ed. J. W. Bunger, N. C. Li)
Advances in Chemistry Series 195, Chap. 7, American Chemical Society, Washington, D. C.
M. M. Boduszynski, 1981

111. The Concept of Asphaltenes
Div. of Petrol. Chem., American Chemical Society, Vol. 24, No. 4, pp. 891-900
R. B. Long, 1979

112. Fractionation of Asphaltenes by Gel Permeation Chromatography
J. of App. Polymer Science, Vol. 9, pp. 3389-3393
K. H. Altgelt, 1965

113. Rapid Method for the Determination of Malthene and Asphaltene Content in Bitumen, Heavy Oils, and Synthetic Fuels by Pyrolysis TLC
Journal of Chromatographic Science, Vol. 21, pp. 331-333
M. Poirier and E. G. Albert, July 1983

114. Effect of Asphaltenes on Asphalt Viscosity
Ind. Eng. Chem., Prod. Res. Develop., 14(4), pp. 240-6
K. H. Altgelt and O. L. Harle, 1975

115. The Structure of Petroleum Asphaltenes as Indicated by Proton Magnetic Resonance
ACS, Div. Fuel Chem., Prepr., pp. 21-32
R. S. Winniford and M. Bersohn, 1962

116. Asphalt Binder Hardening in the Michigan Test Road After 18 Years of Service
TRB Record 544, pp. 27-34
L. W. Corbett and R. E. Merz, 1975

117. Four Year Test Trends on the Michigan Bituminous Experimental Road
Proc. of AAPT, Vol. 28, pp. 295-315
W. K. Parr and P. J. Serafin, 1959

118. Michigan State Highway Experimental Bituminous Construction Project
Proc. of AAPT, Vol. 24, pp. 125-171
W. K. Parr, P. J. Serafin, and T. Humphries

119. Factors Relating Chemical Composition and Rheological Properties of Paving Asphalts with Durability
Proc. of AAPT, Vol. 28, pp. 280-294
B. M. Gallaway, 1959

120. Progress Report on the Zaca-Wigmore Experimental Asphalt Test Project
ASTM STP No. 277, pp. 3-46
F. N. Hveem, E. Zube, and J. Skog, 1960

121. The Effect of Asphalt Properties the Fatigue Cracking of Asphalt Concrete on the Zaca-Wigmore Experimental Project
Proc. of AAPT, pp. 39-60
R. J. Schmidt and L. E. Santucci, 1969

122. Correlation of the Microfilm Durability Test with Field Hardening Observed in the Zaca-Wigmore Experimental Project
ASTM STP No. 277, pp. 52-63
W. C. Simpson, R. L. Griffin, and T. K. Miles, 1960

123. Effect of Changes in Asphalt Properties on Pavement Performances: Zaca-Wigmore Test Road
Proc. of AAPT, Vol. 50, pp. 538-545
J. B. Skog, 1981

124. Results of Cooperative Test Series on Asphalts from the Zaca-Wigmore Experimental Project
ASTM STP No. 277, pp. 46-51
J. Skog, 1960

125. Final Report on the Zaca-Wigmore Asphalt Test Road
Proc. of AAPT, Vol. 38, pp. 1-38
E. Zube and J. Skog, 1969

126. Durability Study of Viscosity Graded AC-20 Asphalt in Pennsylvania
Pennsylvania Department of Transportation
P. S. Kandhal, D. B. Mellott, and H. R. Basso, April 1984

127. Significant Studies on Asphalt Durability: Pennsylvania Experience
Pennsylvania Department of Transportation presented at the Symposium of Asphalt Durability at the TRB Meeting
P. S. Kandhal and W. C. Koehler, January 1984

128. Low-Temperature Ductility in Relation to Pavement Performance in Low-Temperature Properties of Bituminous Materials and Compacted Bituminous Paving Mixtures
ASTM STP 628, pp. 95-106
P. S. Kandhal, 1977

129. Asphalt Characteristics in Relation to Road Performance
Proc. of AAPT, Vol. 39, pp. 575-613
E. H. Chipperfield, et al, 1970

130. Studies on the Relationship between the Properties of Road Bitumens and Their Service Performance
Proc. of AAPT, Vol. 36, pp. 421-488
E. H. Chipperfield and T. R. Welsh, 1967

131. Gel Permeation Chromatography Data on Asphalts Before and After Service in Pavements
Proc. of AAPT, Vol. 39, pp. 683-702
D. Bynum and R. N. Traxler, 1970

132. Asphalt Durability Tests and Their Relationship to Field Hardening
ASTM STP 532, pp. 100-122
G. R. Kemp, 1973

133. Laboratory Measurement of the Durability of Paving Asphalts
ASTM STP 532, pp. 79-99
R. J. Schmidt, 1973

134. "Setting" and Durability Studies on Paving Grade Asphalts
Proc. of AAPT, Vol. 36, pp. 387-420
J. Skog

135. The Hardening of Middle East Petroleum Asphalts in Pavement Surfacings
Proc. of AAPT, Vol. 49, pp. 30-64
E. J. Dickinson, 1980

136. A Comparison of Field and Laboratory Environments on Asphalt Durability
Proc. of AAPT, Vol. 50, pp. 492-537
G. R. Kemp and N. H. Predoehl, 1981

137. The Effect of Crude Source and Additives on the Long-Term Aging of Paving Asphalts
Proc. of AAPT, Vol. 50, pp. 560-571
L. E. Santucci, J. E. Goodrich, and J. E. Sundberg, 1981

138. Study of Physical Factors Affecting the Durability of Asphalt Pavements
Highway Research Record No. 231, Highway Research Board, National Academy of Sciences, pp. 1-23
Gotolski, Ciesielski, Smith and Kofalt, 1968

139. Durability of Asphalt Cements
Proc. of AAPT, Vol. 32, pp. 44-63
R. N. Traxler, 1963

140. Asphalt Hot-Mix Emission Study
Research Report 75-1A (RR-75-1A)
The Asphalt Institute, 1975

141. Exposure of Paving Workers to Asphalt Emissions
Research Report 80-1 (RR-80-1), The Asphalt Institute
V. P. Puzinauskas, 1980

142. Safe Storage and Handling of Hot Asphalt
Information Series 180 (IS-180)
The Asphalt Institute, 1981, Rev. 1984

143. Determing The Dispersion of Asphalt Emissions
Miscellaneous Series 76-2 (MISC-76-2)
The Asphalt Institute, 1976

144. Recycling of Substandard or Deteriorated Asphalt Pavements--A Guideline for Design Procedures
Proc. of AAPT, Vol. 46, pp. 496-526
D. D. Davidson, W. Canessa and S. J. Escobar, 1977

145. Role of Recycling Agents in the Restoration of Aged Asphalt Cements
Proc. of AAPT, Vol. 48, pp. 375-402
S. J. Escobar and D. D. Davidson, 1979

146. Recycling Conventional and Rubberized Bituminous Concrete Pavements Using Recycling Agents and Virgin Asphalt as Modifiers
Proc. of AAPT, Vol. 49, pp. 95-123
C. R. Gannon, et.al., 1980

147. Prototype Specifications for Recycling Agents Used in Hot-Mix Recycling
Proc. of AAPT, Vol. 49, pp. 177-199
W. J. Kari, et.al., 1980

148. Hot-Mix Recycling of Asphalt Pavements
Proc. of AAPT, Vol. 48, pp. 192-220
W. J. Kari, et.al., 1979

149. A Laboratory Study of the Effects of Recycling Modifiers on Aged Asphalt Cement
Paper presented at TRB
D. E. Newcomb, B. J. Nusser, B. M. Kiggundu, et.al., 1984

150. Chemical Aspects of Asphalt Pavement Rejuvenation
Proc. 26th Ann. Conf., CTAA, Vol. 26, pp. 84-96
E. A. Thompson, 1981

151. Flexible Pavement Mixture Design Using Reclaimed Asphalt Concrete
Research Report 84-2 (RR-84-2), The Asphalt Institute
Bernard F. Kallas, 1984

152. The Fatigue of Bitumen and Bituminous Mixes
Pro. 3rd Intern. Conf. Structural Design of Asphalt Pavements, London, I 354
W. van Dijk, H. Moreaud, A. Quedeville and P. Uge, 1972

153. Filler in Asphalt Mixtures
Research Report 69-2 (RR-69-2), The Asphalt Institute
V. P. Puzinauskas, 1969

154. Low-Temperature Mechanical Properties of Asphalt Concrete
Research Report 82-3 (RR-82-3) The Asphalt Institute
Bernard F. Kallas, 1982

155. The Role of Filler in Bituminous Mixes
Proc. Assoc. Asphalt Paving Technologists 34 396
Bitumen Reprint 17
W. Heukelom, 1965

156. The Engineering Properties of Bitumen--Their Measurement, Expression and Application in Design
RILEM Conf., Dresden, 16 pp.
G. M. Dormon and W. Visser, September 1968

157. The Modulus of Asphalt Layers at High Temperatures: Comparison of Laboratory Measurements under Simulated Traffic Conditions with Theory
Proc. 3rd Intern. Conf. Structural Design of Asphalt Pavements, London, I 430
A. Hofstra and C. P. Valkering, 1972

158. Permanent Deformation of Flexible Pavements Under Simulated Road Traffic Conditions
Proc. 3rd Intern. Conf. Structural Design of Asphalt Pavements, London, I 613
A. Hofstra and A.J.G. Klomp

159. Design Techniques to Minimize Low-Temperature Asphalt Pavement Transverse Cracking
Research Report 81-1 (RR-81-1)
Asphalt Institute, 1981

160. Effects of Field Aging on Fundamental Properties of Paving Asphalts
TRB Record 361, 1971.
B. A. Vallerga, and W. Halstead

161. Emulsified Petroleum Oils and Resins in Reconstituting Asphalts in Pavements
HRB Record 24, 1963
B. A. Vallerga

162. Changes in Fundamental Properties of Asphalt - During Service in Pavements
MR&D Inc. Final Report, for FHWA, Contract FH-11-6147, 1970
B. A. Vallerga, R. White and K. S. Rostler

163. Carbon Black as a Reinforcing Agent for Asphalt
Proceedings, Association of Asphalt Paving Technologists, Vol. 46, 1977
Rostler, F. S., R. M. White, and E. M. Dannenberg

164. Carbon Black Reinforcement of Asphalts in Paving Mixtures
American Society for Testing and Materials, STP 724, 1979
B. A. Vallerga, and P. V. Gridley

165. Characteristics and Performance of Asphalt-Rubber Material Containing a Blend of Reclaim and Crumb Rubber, TRB Record 821, 1981
B. J. Huff, and B. A. Vallerga

166. Applicability of Asphalt-Rubber Membrane in Reducing Reflection Cracking
Proceedings, Association of Asphalt Paving Technologists, Vol. 49, 1980
B. A. Vallerga, G. Morris, J. E. Huffman, and B. J. Huff

167. Pavement Deficiencies Related to Asphalt Durability
Proceedings, Association of Asphalt Paving Technologists, Vol. 50, 1981
B. A. Vallerga

168. Design and Specification Changes for Paving Mixes with Asphalt-Rubber Binders
Proceedings, National Seminar on Asphalt Rubber, FHWA, DOT, 1981.
B. A. Vallerga

TECHNICAL RESEARCH AREA 2

LONG-TERM PAVEMENT PERFORMANCE

Prepared for:

Pre-Implementation Activities for the
Strategic Highway Research Program (SHRP)
under Contract with the
Federal Highway Administration
of the
U.S. Department of Transportation

January 1986

Brent Rauhut Engineering Inc
10214 I.H. 35 North
Austin, Texas 78753

ERES Consultants, Inc.
P.O. Box 1003
Champaign, Illinois 61820

TABLE OF CONTENTS

	Page
LIST OF FIGURES	TRA 2-iii
LIST OF TABLES	TRA 2-iv
ABSTRACT	TRA 2-vi
ACKNOWLEDGEMENTS	TRA 2-vii
SECTION 1 STATEMENT OF THE PROBLEM	TRA 2-1
SECTION 2 GOALS AND OBJECTIVES OF THE PLAN	TRA 2-6
RELATIONSHIP BETWEEN OBJECTIVES AND EXPERIMENT DESIGN	TRA 2-6
LOAD EQUIVALENCE FACTORS	TRA 2-8
SUMMARY REQUIREMENTS	TRA 2-10
SECTION 3 FORMULATION OF THE PLAN	TRA 2-11
The LTPP Study Program	TRA 2-12
Model Building Process	TRA 2-19
Variability and Replication	TRA 2-23
Replications Versus "Repeats" for SPS	TRA 2-29
Allocation of Resourses	TRA 2-30
Data Collection and Management	TRA 2-30
Project Management	TRA 2-36
Summary of Background Information for Formulation of the Research Plan	TRA 2-37

SECTION 4 RECOMMENDED RESEARCH PLAN..... TRA 2-39

Experiment Design for General Pavement Studies.. TRA 2-39

Experiment Design for Specific Pavement Studies. TRA 2-55

SECTION 5 RESULTS TO BE ACHIEVED ..... TRA 2-96

Data Analysis..... TRA 2-97

Expected Major End Products and Results..... TRA 2-97

SECTION 6 IMPLEMENTATION OF RESULTS..... TRA 2-102

Implementable Results and Expected Benefits..... TRA 2-102

Expected Benefits for SHA Pavement Management Systems..... TRA 2-103

Implementation Issues for Future Consideration.. TRA 2-104

SECTION 7 SCHEDULE OF PROJECT TASKS SUB-TASKS..... TRA 2-106

SECTION 8 BUDGET..... TRA 2-114

Central LTPP Management..... TRA 2-114

Typical Regional Organization..... TRA 2-118

Total Estimated Cost to SHRP for a Five Year Program..... TRA 2-118

Estimate of State Highway Agency Work Effort.... TRA 2-127

LIST OF FIGURES

Figure No.	Title	Page No.
1.	Flow Chart for LTPP Activities	TRA 2-4
2	Candidate Study Programs	TRA 2-13
3	GPS: JPCP	TRA 2-15
4	GPS: AC With Granular Base	TRA 2-42
5	GPS: AC With Stabilized Base	TRA 2-44
6	GPS: JRCP	TRA 2-47
7	GPS: CRCP	TRA 2-48
8	GPS: AC With AC Overlay	TRA 2-50
9	GPS: AC Overlay of JCP	TRA 2-52
10	GPS: Bonded PCC Overlay of JCP & CRCP	TRA 2-53
11	GPS: Unbonded JCP OVerlay of JCP & CRCP	TRA 2-54
12	SPS: PCC Preventative Maintenance	TRA 2-59
13	SPS: PCC Load Equivalence Factors	TRA 2-62
14	SPS: PCC Restored JCP	TRA 2-64
15	SPS: PCC Subsurface Drainage	TRA 2-66
16	SPS: PCC Environmental Distress	TRA 2-68
17	SPS: High Strength PCC	TRA 2-71
18	SPS: CRCP Overlays	TRA 2-73
19	SPS: PCC With Non-Erodable High-Strength Bases	TRA 2-74
20	SPS: PCC Retrofit Shoulders	TRA 2-77
21	SPS: PCC Shoulder Design	TRA 2-79
22	SPS: Pre-Treated JCP With AC Overlay	TRA 2-81
23	SPS: AC Subdrainage	TRA 2-83
24	SPS: AC Hot Recycling	TRA 2-85
25	SPS: AC Cold Recycling	TRA 2-86
26	SPS: AC Preventative Maintenance	TRA 2-88
27	SPS: AC Low-Volume Roads	TRA 2-91
28	SPS: AC Load Equivalence Factors	TRA 2-93
29	SPS: AC Environmental Distress	TRA 2-95
30	Schedule for Specific Tasks and Subtasks for Long Term Pavement Performance Studies	TRA 2-110
31	Organization Chart for Central LTPP Management, Limited SHRP Staff and Primary Management by Contract	TRA 2-115
32	Organizational Chart for Typical SHRP Regional Organization	TRA 2-119

LIST OF TABLES

TABLE NO.	TITLE	PAGE NO.
1	"Wish List" of Specific Studies for Rigid Pavements	TRA 2-17
2	"Wish List" of Specific Studies for Flexible Pavements	TRA 2-18
3	Performance Results for 12 "Replicate" In-Service Sections in Illinois	TRA 2-24
4	Computed Coefficients of Variation for "Replicate" Pavement Sections	TRA 2-25
5	Required Replications for a Single Cell Result Over a Range of Values of Interest	TRA 2-28
6	Lane-Miles of Asphalt and Concrete-Surfaced Pavements in the United States (1985) in Broad Climatic Zones. (Source: FHWA HPMS Data Base)	TRA 2-31
7	Items of Inventory Data To Be Collected	TRA 2-33
8	Items of Monitoring Data To Be Colleted	TRA 2-35
9	Division of Responsibilities Between State Highway Agencies and SHRP Regional Contractors	TRA 2-38
10	Numbers of Test Sections by Pavement Type Selected for GPS Experiment Design	TRA 2-40
11	Numbers of Rigid Pavement Test Sections Selected for SPS Experiment Design	TRA 2-56

12	Numbers of Flexible Pavement Test Sections Selected for SPS Experiment Design	TRA 2-57
13	General Results and Products of LTPP	TRA 2-99
14	Identification of Specific Tasks and Subtasks for Long Term Pavement Performance Studies	TRA 2-107
15	Breakout of LTPP Central Staffing Expenses, Limited SHRP Staff and Primary Management by Contract	TRA 2-116
16	Breakout of Estimated Equipment Costs for Central Office, Limited SHRP Staff and Primary Management by Contract	TRA 2-117
17	Breakout of Regional Staffing Expenses for a Typical Regional Office	TRA 2-120
18	Breakout of Operating Expenses for a Typical Regional Office	TRA 2-121
19	Breakout of Estimated Equipment Costs for Typical Region	TRA 2-122
20	Breakout of Estimated Costs, Material Testing for Rigid Pavements	TRA 2-123
21	Breakout of Estimated Costs, Material Testing for Flexible Pavements	TRA 2-124
22	Estimated Cost for a Typical Regional Operation By Year	TRA 2-126
23	Estimated LTPP Cost for Five Year Program	TRA 2-128

ABSTRACT

This report presents the experimental designs for a broad program to study performance of inservice pavements on a national basis. These Long-Term Pavement Performance studies are to be conducted as part of the Strategic Highway Research Program, which is to be funded at approximately the 10 million dollar level per year for five (5) years. It is expected that funding will follow to continue the Long-Term Pavement Performance studies for an additional fifteen years. One major result of this data collection effort is to be a national data base, which can be analyzed to produce a variety of results.

The myriad of factors to be considered in the development of such an experimental plan have been discussed, and the experiment designs described. The experiment designs include the General Pavement Studies, which are broad studies of existing inservice pavements, and the Specific Pavement Studies, which are limited specific projects aimed at developing understanding of the effects on performance of a few specific factors.

The report also includes discussions of the anticipated results, recommendations for implementation, tentative organizational plans for conducting this massive data collection activity, schedules, and cost estimates.

ACKNOWLEDGEMENTS

This work represents the combined efforts of a research team from Brent Rauhut Engineering Inc, ERES Consultants, Inc., the FHWA, SHRP, and the SHRP Advisory Committee for Pavement Performance. The funding for contractor activities has been provided by the FHWA through contracts DTFH 61-83-C-00164, "Technical Support for the Long-Term Pavement Monitoring (LTM) Program", and DTFH-61-85-C-00093, "Development of Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) Implementation Plan".

The Co-Principal Investigators for the contractor team were Dr. J. Brent Rauhut, Chief Executive Officer of Brent Rauhut Engineering Inc; Dr. Michael I. Darter, Vice-President of ERES Consultants, Inc. and Professor of Civil Engineering at The University of Illinois; and Dr. Robert L. Lytton, Professor of Civil Engineering at Texas A&M University. Dr. Richard DeVor, Chairman of The Industrial Engineering Department of The University of Illinois, has made contributions to the experiment design through his statistical expertise. Other members of this research team that have contributed significantly are Mr. Dave Gendell, Mr. Roger Petzold, and Mr. Charlie Churilla with The Federal Highway Administration.

SECTION 1
TRA 2 STATEMENT OF THE PROBLEM

Substantial knowledge has been accumulated over the past century relative to the design and construction of highways in North America. A variety of materials have been employed in a variety of ways to reflect the perceptions of pavement engineers as to the best ways to support public transportation requirements as economically as possible. Numerous design procedures have been developed, each representing some form of "model" for pavement behavior and performance. Construction techniques and specifications have been developed and refined to reflect those attributes in the pavement materials and the finished product perceived to be advantageous. While the traveling public has generally been served, the service life expectations from the pavements constructed have often not been achieved and the successes have often been too costly. A lot has been learned, but not enough to predict with confidence how different designs will perform.

The emphasis for modeling pavements during the 1960's was on application of the empirical serviceability model developed from the AASHO Road Test Data, and on regional modifications to "calibrate" this model to other locales and conditions. At this same time, a revolution in mechanistic modeling was also underway and gaining momentum as computer applications expanded. By the end of the decade, elastic layer, finite element, and discrete element theories were in common research use for predicting pavement responses to wheel loads, and many pavement consultants were beginning to apply these pavement structure models in practical consulting and design.

There was a strong initiative during the 1970's to develop distress and performance models utilizing the predicted responses (primarily stresses and strains) from the mechanistic pavement structural models to predict the occurrence of distresses (such as cracking and rutting) and loss of serviceability. While some reasonable models with broad applicability to research were developed, their application for design and practical distress predictions has been limited by the difficulties in material characterizations required. As these difficulties do not appear to be subject to ready solution for practical applications, interest developed again in empirical models based on observed performance and in mechanistic-empirical models that utilize responses calculated with mechanistic models as input to empirical distress models.

The "pavement community," faced with rapid deterioration of pavements nationwide, recognized the critical need for better understanding of those parameters that affect pavement performance, especially those related to rehabilitated pavements. This situation led in the late 1970's to a broad acceptance that the only chance of success was to mount an organized

and massive study that could be continued for sufficient years to "let the pavements tell us how they perform" over their lifetime and over a diversity of environmental conditions, traffic, materials, designs, construction techniques and quality control, maintenance strategies, and other important parameters. In Section 506 of the Surface Transportation Act of 1978 (P.L. 95-599), the Congress of the United States directed the Secretary of Transportation to study and investigate "...the need for long-term or continuous monitoring of roadway deterioration to determine the relative damage attributable to traffic and environmental factors". This offered an opportunity to begin a serious initiative.

The FHWA Office of Planning developed concepts for a "Long-Term Pavement Monitoring (LTM)" Program, drawing strongly on the opinions and ideas from other offices of the FHWA. It was decided to approach LTM as a cooperative program between the FHWA, an AASHTO Advisory Panel, and participating State DOT's. In June 1981, a joint meeting of the Pavement Management Task Group, AASHTO Joint Task Force on Pavements and the FHWA was held to plan for pilot studies to assess the problems in building a national data base that could be used to develop improved pavement damage relationships, as well as to make a beginning in long-term monitoring of pavements. The initial pilot study was structured as a cooperative program between the FHWA, AASHTO, and eight selected States, and was implemented in 1982 to monitor selected pavements in those eight states.

Concurrent with the FHWA activities, the Transportation Research Board was conducting a study, called the "Strategic Transportation Research Study (STRS)", to develop a strategy for a major new research emphasis on key technological gaps with a potential for high payoff. The results of this study were published in TRB Special Report 202, "America's Highways, Accelerating the Search for Innovation". One of the primary recommendations from this study was long-term pavement monitoring of in-service highways. As it became clear that the major agencies involved in pavement design, construction, and management were recognizing the need for a national data base to include long-term data from highway monitoring, these agencies joined together to develop these plans mutually and in cooperation.

AASHTO approved the recommendations for STRS and established the "Strategic Highway Research Program (SHRP)" to carry it out. As a result of broad-based enthusiasm for such a program expressed at a National Workshop on Long-Term Pavement Monitoring sponsored by the FHWA in October 1984, the FHWA offered to fund "transition activities" to maintain the momentum until SHRP was approved by Congress and funded in its own right.

The proposed studies of "Long-Term Pavement Performance (LTPP)" are to be national in scope and twenty years in duration. The "problem" is then to plan these studies so that implementation could begin upon funding, anticipated in October 1986. The required plan must include:

- a design of the national experiment.
- a plan for information management.
- preliminary planning for organization management.

- establishment of the data elements to be collected.
- development of a general plan for data collection and selection of state-of-the-art field measurement equipment to optimize data quality and costs.
- establishment of working relationships between SHRP and the State Highway Agencies (SHA's).
- selection of an optimum set of test sections nationwide to meet the requirements of the overall experiment design.
- development of an overall implementation plan.

The planning for LTPP reported herein emphasizes the experiment design (as that was the primary objective of this work effort), but has necessarily included preliminary studies of organizational management, data requirements, data collection, measurement equipment, and instrumentation, materials testing, and the relative responsibilities of SHRP and the SHA's. This transition planning will continue through 1986 as a cooperative effort between SHRP, the SHRP Advisory Committee for Pavement Performance, the FHWA, the FHWA consultants (Brent Rauhut Engineering Inc, ERES Consultants, Inc., and Dr. Richard E. DeVor), and other interested parties.

Figure 1 provides identification of general activities planned for LTPP. The first box identifies "Pavement Management Needs" as the overall impetus for this study. This report primarily deals with those activities identified in the second box entitled "Research Plan" ("GPS" and "SPS" are study programs defined later). "Site Selection" is a primary activity to be undertaken by the SHRP/FHWA/Consultant team in 1986. "Data Collection" will not begin until 1987, but development of an Information Management System related to "Data Storage" is underway.

In years to come as sufficient data become available, "Analysis" is expected to be conducted by numerous interested agencies. The "LTPP Products" are expected to include better predictive models for use in design and pavement management, much better understanding of the effects of many variables on pavement performance, and new techniques for design and construction. These improved "tools" are then expected to result in Improved Pavement Management.

The dashed lines and arrows leading back to the Research Plan are intended to emphasize that the experiment designs reported herein are expected to undergo change, first when it is learned during site selection what cells can be successfully filled, and later as data collection experience is gained and field observations are made. This is particularly true for SPS, as it will be dependent upon the interests of the State Highway Agencies. Analysis of the data may also be expected to suggest new or revised experiments to be planned and implemented.

The planning for LTPP is expected to impact on that for other studies and vice-versa. This is especially true for other SHRP studies such as for asphalt, concrete, and maintenance cost-effectiveness; which the LTPP organization will be expected to support by conducting field experiments.

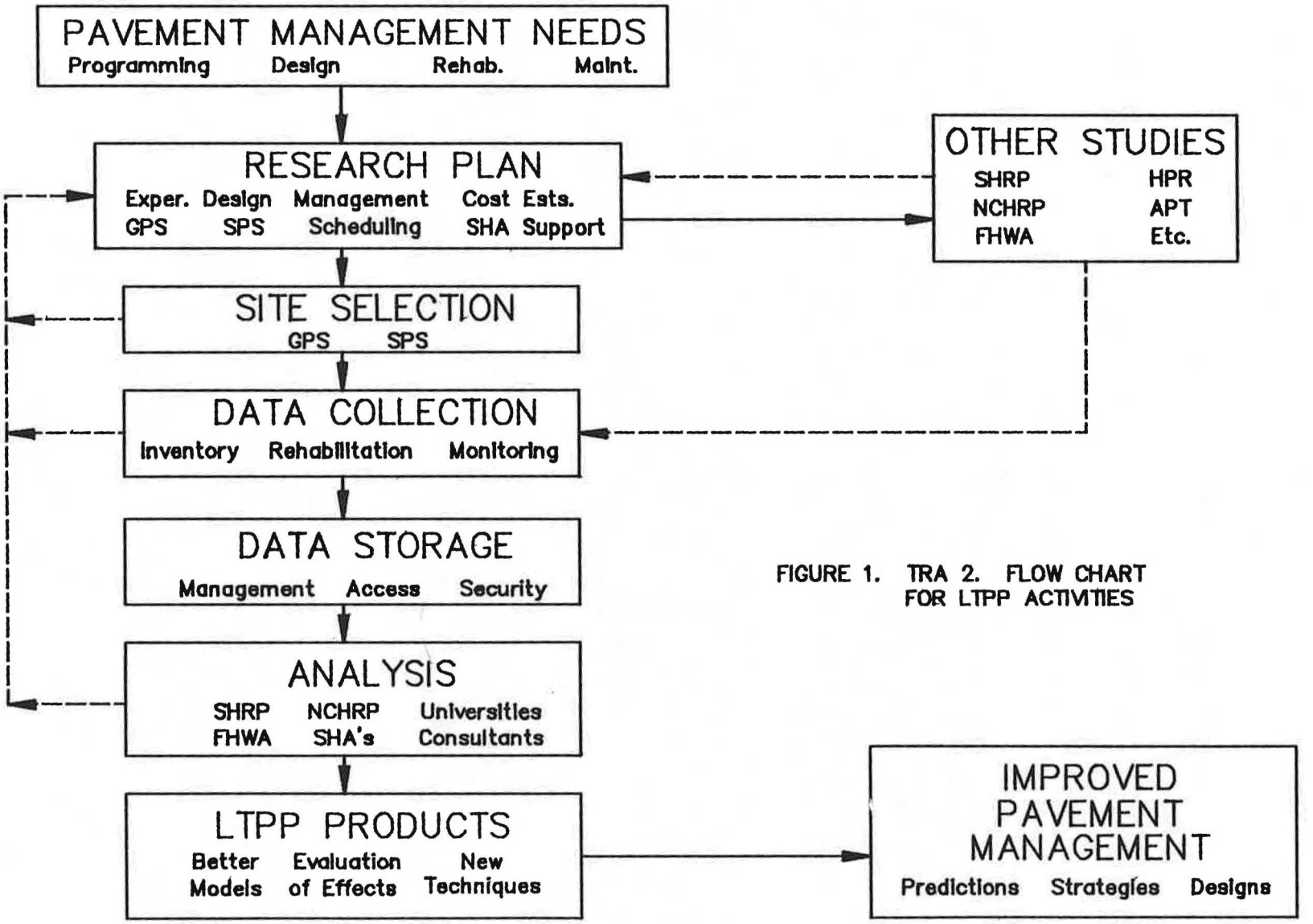


FIGURE 1. TRA 2. FLOW CHART FOR LTPP ACTIVITIES

These experiments are to be planned in coordination with SHRP staff representing those research interests. The needs for other studies may be expected to both impact on LTPP research planning and to introduce other data collection needs to be satisfied.

While Figure 1 offers a useful broad view of LTPP and how it will function, this framework is "fleshed out" with more detail in the remainder of this report.

SECTION 2
TRA 2 GOALS AND OBJECTIVES OF THE PLAN

GOAL AND OBJECTIVES

The objective for LTPP Studies established by the "Strategic Transportation Research Study" and adopted by the Advisory Committee for Pavement Performance as their goal was:

"To increase pavement life by investigation of various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices."

The specific objectives developed by the Advisory Committee are:

- Evaluate existing design methods.
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements.
- Develop improved design equations for new and reconstructed pavements.
- Determine the effects of (1)loading, (2) environment, (3) material properties and variability, (4) construction quality, and (5) maintenance levels on pavement distress and performance.
- Determine the effects of specific design features on pavement performance.
- Establish a national long-term pavement data base to support SHRP objectives and future needs.

It is expected that accomplishment of these objectives will resolve most of the difficulties currently experienced in implementing successful Pavement Management Systems.

RELATIONSHIP BETWEEN OBJECTIVES AND EXPERIMENT DESIGN

It is essential that the experimental designs be developed with clear relationship to the objectives. This subsection describes how a national data base may be utilized to attain each of the six objectives identified by the Advisory Committee. These are discussed separately below.

Evaluate Existing Design Methods

The procedures used for evaluation of existing design methods will depend on the nature of the design method itself. For instance, the equations to predict serviceability loss that appear in the AASHTO Design Guide may be evaluated through comparisons of their predictions for serviceability versus measured values of serviceability. No other performance measure or distress could be compared with this directly as there is no predictive equation in the method other than for serviceability. However, it would be possible to approach the evaluation by producing designs using the AASHTO method and then applying the predictive equations for key distress types obtained from the Long-Term Pavement Performance Studies to evaluate how well the design functioned over time and traffic.

There are a few design procedures (not in common use) that combine both a response model that predicts stresses or strains and distress models that predict area and/or severity of distresses in terms of the predicted stresses or strains. These models could be evaluated somewhat more directly. Using the materials data for stiffness and the measured and/or predicted traffic data, the models could be used to predict distresses. These distresses could then be compared to those actually measured. One problem with this will be the lack of some of the more sophisticated materials characterizations such as fatigue life potential and permanent deformation potential for the various material layers.

It can be seen then that most existing design procedures will be evaluated through application of the LTPP predictive equations to the pavement thickness designs that the methods produce. For those few design procedures that incorporate predictive equations directly, predictions may be developed for the actual pavement sections and comparisons made between the performance measures predicted by the model and those actually measured in the field.

Develop Improved Design Methodologies and Strategies for the Rehabilitation of Existing Pavements

Rehabilitation is a major interest at this time and will be for years to come. It is the topic for which we have the least understanding of performance and the numerous interactions between the condition of the existing pavement prior to rehabilitation, and the features of the rehabilitation itself. It is expected that predictive equations of various types will be developed from LTPP data and used as a basis for improved design methodologies and strategies for rehabilitation. It is also expected that specific studies utilizing specially constructed, rehabilitated, or maintained test sections will also yield much of the information that will be required for this objective.

With relation to experiment design, it will be critically important that the most promising combinations of existing pavements and rehabilitation techniques be included as major factors so that the data will exist for the development of the design methods and strategies.

Develop Improved Design Equations For New and Reconstructed Pavements

The needs for developing improved design equations for new and reconstructed pavements are very similar to those for evaluating existing design methods. The approaches are expected to include: 1) the development of predictive equations for the significant distress and performance measures, and 2) the "calibration" of mechanistic-empirical models for design. These new or calibrated models may be structured into a design procedure that will limit distresses and performance measures to acceptable levels. It is expected that information relative to the effects of design features and other information from specific studies on specially constructed sections will also be used in shaping these design procedures.

Determine the Effects of Significant Parameters On Pavement Distress and Performance

This objective involves the determination of the effects of (1) loading, (2) environment, (3) material properties and variability, (4) construction quality, and (5) maintenance levels on pavement distress and performance. The first two of these are major factors in the experiment design, and asphalt concrete quality (representing by asphalt concrete stiffness) is also included as a major factor for pavements with A.C. surfaces. Construction quality and maintenance levels are not presently planned as major site-selection factors because of the great difficulty in obtaining reliable data at the preliminary stage during which test section selections will be made (or indeed at any time); however, detailed data will be collected for test sections selected so that representative data is included in the data base for these important parameters.

As for the other objectives, the primary approach for determining the effects of the significant parameters will be the development of predictive equations and the statistical evaluation of the separate variables and their interactions with each other. Other useful information may be expected on a comparative basis from the pavement performance factorial and from specific studies.

Determine the Effects of Specific Design Features on Pavement Performance

It is expected that quite a bit of useful information will accrue from the studies of in-service highways, but it is expected that the primary source of information for this objective will be specific studies on specially constructed sections. The requirements of this objective were considered when structuring the general inservice-highway study factorial, but were emphasized in structuring the experiment designs for the specific studies on specially constructed sections.

LOAD EQUIVALENCE FACTORS

The load equivalence factors (LEF's) from the AASHO Road Test have been assumed by many persons to represent some physical fact with relation to damage to the highways. In fact, these load equivalence factors have no meaning outside the context of the equations from which they were derived, which are known to have many limitations and are based only on serviceability loss (not even the distress that generates most rehabilitation). These

limitations were recognized by the authors of TRB Report 202, and an important objective stated in that report was evaluation of the LEF's from the AASHO Road Test.

It is not difficult at all to develop LEF's from equations developed from data where axle loads have been controlled. However, if the model is based on data from in-service highways with mixed traffic, the development of LEF's requires some kind of assumption for sorting out these effects. This assumption drastically lowers the confidence level to be placed on the LEF's. Unfortunately, traffic on in-service highways is always mixed and the models developed must be based on equivalent single axle loads (ESAL's), so reliable LEF's may not be derived directly from these studies.

An approach utilized by the FHWA Consultants several years ago for developing predictive equations for pavement damage (also called pavement damage functions) for FHWA Cost Allocation studies for flexible pavements is described below. This approach involved the use of the mechanistic-empirical VESYS III-B model to predict fatigue cracking, rutting, and serviceability loss on real pavement sections and calibration of the results to approximate the actual experience. These models were then applied with the calibration multipliers to generate a "computer road test", which included 216 "test sections" for each of four environmental regions (for a total of 864). The factors in this experiment included four environmental regions, three levels of subgrade resilient moduli, three surface thicknesses, three structural numbers, and eight load levels (four single and four tandem axle loads).

Multiple regression statistical techniques were then applied to the data base generated to develop predictive equations for fatigue cracking, rutting, and serviceability loss. These equations were of the same form as those from the AASHO Road Test, but the dependent variables ρ and β were found to depend on axle load, axle code, structural number, thickness of the asphalt concrete layer, thickness of the granular base layer, and subgrade modulus of elasticity.

The calculation of the LEF's for the three separate distress types was rather direct. The load equivalence factors were simply the ratio of the ρ for the standard axle to the ρ for the axle of interest.

While the expeditious nature of this project and the limited field data for calibration limited the opportunity for accurate calibrations of the mechanistic-empirical models, a more sophisticated approach was developed using calibration functions, which were themselves the result of regressions considering significant variables. This calibration approach was later applied successfully to AASHO Road Test data, resulting in an equation for serviceability loss and LEF's different from those in use, but with approximately the same predictive accuracy.

When comparing predictions from equations using different sets of LEF's, it is found that differences in predictions do not usually reflect the magnitudes of the differences in the LEF's. This is because relative increases in LEF's for heavy axles is generally accompanied by relative decreases in the LEF's for the more numerous light axles, thus compensating differences reduce the effect of the differences in the LEF's for typical mixed traffic streams.

SUMMARY REQUIREMENTS

The primary requirements to be satisfied during experiment design are:

- Selection of the most significant types of original and rehabilitated pavements for study (funding will not be sufficient to study all types).
- Selection of major site-selection factors to insure adequate distributions of data element values for the most significant variables.
- Statistical design to insure adequate data is available to build or "calibrate" the required models, and that test sections in excess of needs are not included (utilize funding for other studies).
- Identification and collection of all data elements that are significant to pavement performance. This must include data elements such as resilient moduli of materials to support use, further development, and "calibration" of mechanistic models.
- Provide for field verification and other studies to support needs of other Technical Research Areas (Primarily "Asphalt", "Maintenance," and "Concrete").
- Through "Specific Pavement Studies", provide for study of specific design and construction features using specially constructed sections.

While there are many other considerations to be satisfied, close attention to the six requirements listed above may be expected to lead to adequate experiment designs.

SECTION 3
TRA 2 FORMULATION OF THE PLAN

The FHWA/Contractor Staff had been involved in the Long-Term Pavement Monitoring initiative for over three years when the decision for FHWA support of SHRP in Long-Term Pavement Performance Study planning was made. Much of the work required for SHRP was already underway or planned. The proposed LTPP transition activities were undertaken through increased scope and revision of the ongoing LTM contract.

An AASHTO Task Force for the Strategic Highway Research Program was appointed, and Advisory Committees subsequently established for each of the six technical research areas in SHRP. The Advisory Committee on Pavement Performance included a broad range of representatives from State Highway Agencies, industry, academia, FHWA, a city and a county. Byron Blaschke was appointed as Chairman and Brooks Nichols as Vice Chairman. This Advisory Committee first met in early February 1985. They were briefed by Mr. Gary Byrd, Interim Director for SHRP, on SHRP planning, by the FHWA on the transition plan, and by the contractors relative to their proposed approach to experiment design. Mr. Brooks Nichols highlighted the findings and recommendations from the Long-Term Monitoring (LTM) Workshop held in Alexandria, Virginia in October 1984. The Advisory Committee discussed issues, developed a set of objectives, made tentative decisions on management of the program, what types of pavements should be studied, what portions of the transition plan they supported, and on other issues as guidance for the FHWA/Contractor team.

A procedure was developed at this meeting for iterative review and guidance, with Advisory Committee meetings occurring approximately every two months. The approach was for the FHWA/Contractor team to proceed with the experimental design and other assignments, and to present the results of these studies to the Advisory Committee. The Advisory Committee would then discuss these presentations and whatever other issues had developed, and provide decisions and guidance for the team to follow as the work progressed to the next check point. This became a very effective means of gaining the input of the highway community and guidance from those selected to supervise the development of the LTPP study planning.

The fifth meeting of the Advisory Committee was held at the end of October 1985 to finalize the research planning for presentation to the AASHTO Task Force on SHRP. The resultant plan was presented to the AASHTO Task Force on November 7, 1985 and received unanimous approval. This plan is discussed in detail in Section 4, while the remainder of this section provides detailed description of the studies leading to the research plan.

THE LTPP STUDY PROGRAM

The research team and the Advisory Committee drew heavily on the previous work and planning on the Long-Term Pavement Monitoring Program to develop an overall LTPP Study Program with three potential types of studies. These include General Pavement Studies (GPS), Specific Pavement Studies (SPS), and Accelerated Pavement Testing (APT). The General Pavement Studies involve a very large experiment that embraces a large array of site selection factors, and is expected to produce a broad range of products and results. The Specific Pavement Studies will have their own set of more limited goals, construction needs, and experimental approaches; and are generally aimed at more intensive studies of a few independent variables for each of a number of study topics. The other category of studies, which is to be considered for future adoption, is the Accelerated Pavement Testing Program. The APT could include either road tests (not now under consideration) or an accelerated loading facility (ALF), currently under development by the FHWA and scheduled for availability in 1987. It may be seen from Figure 2 that both the GPS and SPS are to be conducted on inservice pavements using only the normal traffic.

The great majority of test sections for the GPS will be selected from existing highways, but it is expected that most of the test sections used in the SPS will be specially designed and constructed pavements having characteristics needed for the specific studies. The majority of sections for a specific study will usually be built at a single location, except where environmental variations are desired. The reason for selecting a single location is to maintain as much uniformity as possible, such as in subgrade, traffic, and environmental factors.

There will be a number of specially designed and constructed sections for the GPS to fill important cells for which existing highway sections are not available.

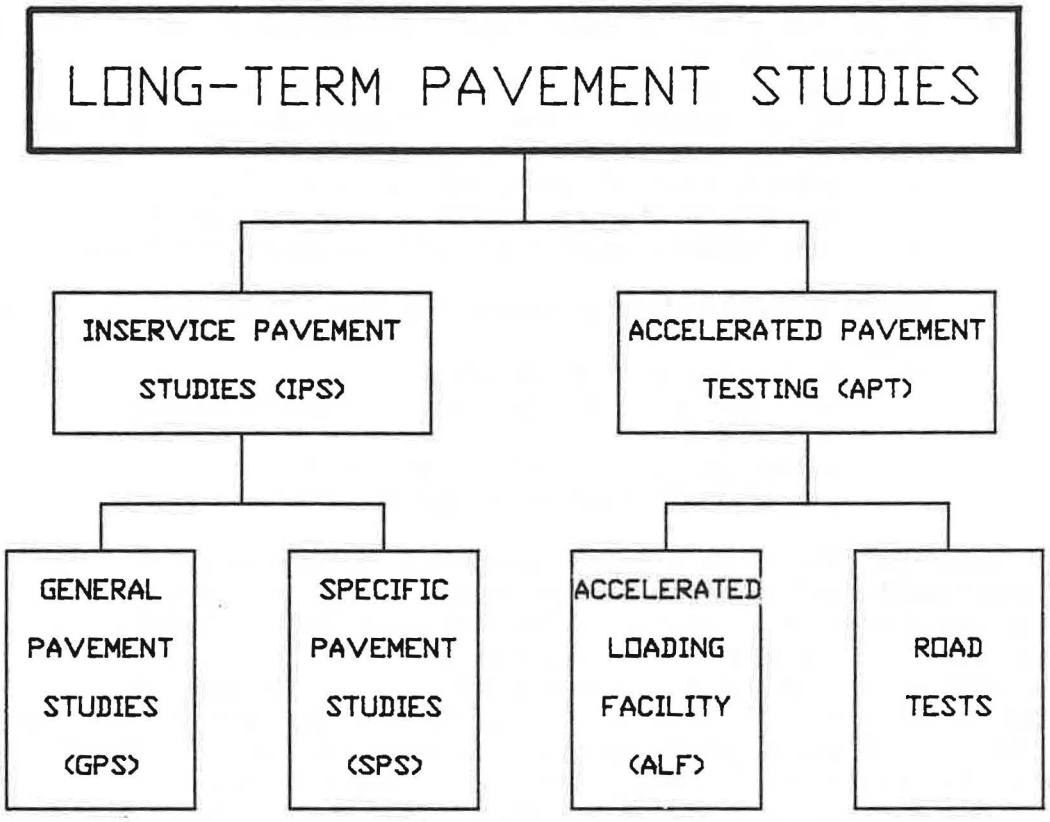
While considered separately for clarity of understanding and planning, it should be noted that the results from GPS, SPS, and APT (if a decision is made later to employ it) will be very interactive and some of the test sections will be shared between experiments. These separate study resources are discussed in detail below.

General Pavement Studies (GPS)

The primary goal of the GPS experiment design is to structure an experiment, using primarily existing inservice pavement sections that have a suitable range of characteristics to develop a national data base that will provide the needed data to meet the objectives of LTPP (other than those met by SPS). This was done by identifying major factors of known significance (such as environment, pavement type, traffic, etc.) and suitable levels (or magnitudes), and combining them into a factorial experiment. These factors are to be used in selecting test sections so that suitable representation of the significant characteristics and their effects on performance are attained. While a great number of such characteristics (or independent variables) were considered, only those major factors discussed subsequently were selected, as it would not be practical to attempt to locate hundreds of

FIGURE 2. TRA 2

CANDIDATE STUDY PROGRAMS



existing test sections, each having more than six to eight specific attributes.

The first and most obvious factor to be considered is type of pavement. For practical reasons, it is necessary to develop and analyze separate factorial experiments for each type of pavement considered. For budgetary reasons, the number of pavement types was limited to the following nine:

- Five "original pavement types" (pavements in their first performance period):
  - asphalt concrete (AC) on granular base.
  - AC on stabilized base (with cold mix asphalt or portland cement as a stabilizing agent).
  - jointed plain concrete pavements (JPCP).
  - jointed reinforced concrete pavements (JRCP).
  - continuously reinforced concrete pavements (CRCP).

- Four rehabilitation techniques applied to specific pavement types:
  - AC overlay over AC pavement.
  - AC overlay over jointed concrete pavement (plain or reinforced).
  - bonded JCP overlay of JCP and CRCP.
  - unbonded JCP overlay of JCP and CRCP.

Each of the nine types of pavements is considered to be an individual experiment, and a detailed experimental design was developed for each one. Two approaches were considered for the experimental design. The first approach was to use one large nationwide factorial for each of the nine types of pavements under study to investigate how performance is affected by major design factors. The major problem with this approach is that the levels of several of the major factors will need to vary across climatic zones due to differences in pavement design and traffic levels (e.g., traffic loadings vary considerably across the nation, as do thicknesses of bases and subbases in frost and non-frost areas).

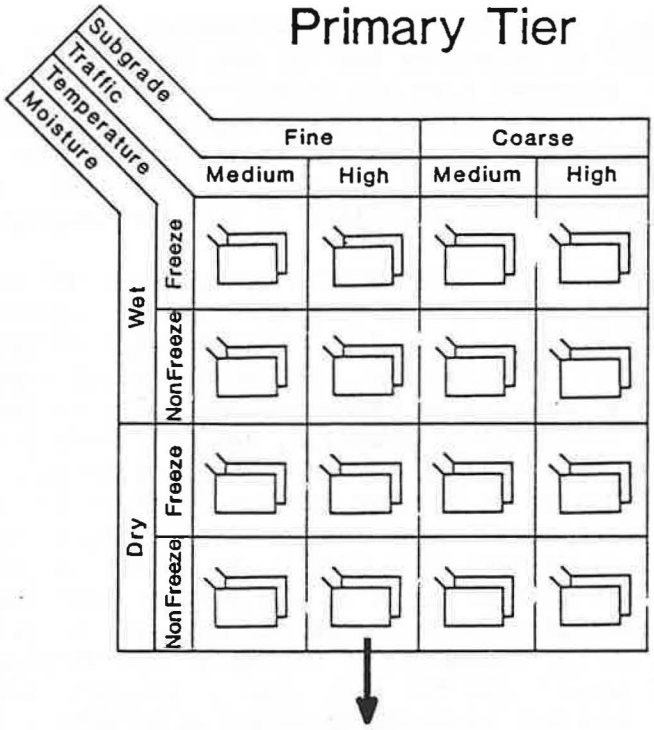
The second approach to the experimental design was a tiered factorial approach. For each pavement type, the key factors of traffic, climate (moisture and temperature) and subgrade soil were selected in common for the primary tier factorial as shown in Figure 3. Traffic was divided into medium and high levels. Climate was divided into "freeze" and "non-freeze" temperature levels and "wet" and "dry" moisture levels. Subgrade soil was divided into "coarse" and "fine-grained" soils. Thus, pavements located in any one of these sixteen primary tier cells have approximately the same traffic, climate and subgrade soil. These four factors basically describe the forces that act on a pavement structure in a given geographic location.

The "traffic" factor has been tentatively defined in terms of rate (i.e., 18-kip ESAL per year) rather than accumulated ESAL, because using the rate may be expected to provide a good distribution of pavement age as well as traffic. It is possible to have a low level of accumulated ESAL on a heavily-trafficked pavement simply because it is relatively new, but rate is

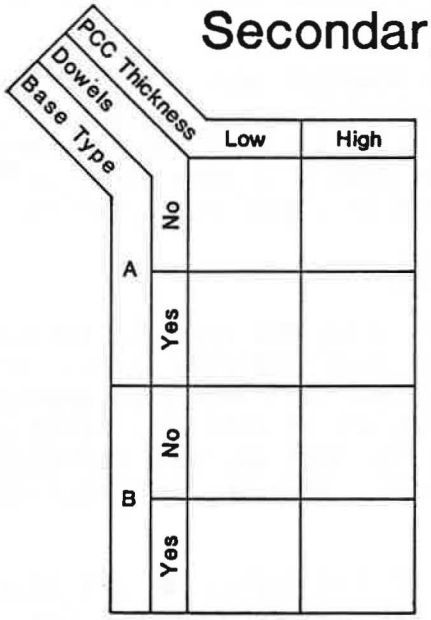
FIGURE 3. TRA 2

GPS: JPCP

Primary Tier



Secondary Tier



16 Primary Cells x 8 Secondary Cells x 2 Replications = 256 Total Sections

dependent on age only to the extent that it changes over time. The use of a rate will tend over the long term to ensure that the desired levels of accumulated ESAL will occur over a range of pavement ages as expected. Age will be reviewed during screening of candidate test sections, especially to insure enough older sections to allow development of early results.

A secondary tier factorial experimental design is then set up in each primary tier cell by selecting the factors that are of greatest concern for that particular pavement type and selecting factor levels that are most relevant to it. Figure 3 provides an example of a secondary tier factorial. The tiered approach was selected as it provides maximum flexibility for analyzing all or portions of the data, and thus will be responsive to the specific needs and resources available in a given geographic area.

To illustrate the relationship between the primary and secondary tier factorials, consider Cell 2 (top row, second column) in the primary tier and the Secondary tier shown for "Jointed Plain Concrete Pavement" in Figure 3. The intent will be to locate and select eight test sections having the correct attributes to represent the cells in the secondary tier factorial; each on a fine-grained subgrade, having a high traffic level, and located in a "cold climate" that experiences relatively high amounts of precipitation. As we wish to have two "replicates" for statistical purposes, we will need to have two very similar test sections representing each of the eight cells in Primary Tier Cell 2, or a total of sixteen JPCP test sections. As there are sixteen cells in the primary tier factorial, we will need to find 256 test sections with the correct sets of seven characteristics (subgrade, traffic, temperature, moisture, PCC thickness, dowels provided or not, and base type) for this type of pavement alone. These test sections will be located through cooperative efforts with participating State Highway Agencies (SHA's).

It is important to remember that the major factors described above are those for which characteristics are to be enforced during site selection. The actual data collection for test sections selected and implemented into the study will include dozens of data elements for each test section, including all of those believed to significantly affect performance.

Specific Pavement Studies (SPS)

As discussed previously, the specific pavement studies are generally limited factorials for very intensive studies of the effects of a few factors. The highway sections will mostly be specially designed and constructed through a cooperative effort with interested State Highway Agencies (SHA's), frequently with the test sections collocated to ensure the same subgrade, climate, and traffic. However, some studies may utilize existing pavements directly.

The development of the topics for SPS began with invitations to the industry representatives on the Advisory Committee to develop "wish lists" for research projects. The resulting wish lists were combined and reviewed, resulting in long lists of general topics for rigid and flexible pavements (Tables 1 and 2). Continued study and committee review with consideration of budgetary limitations has resulted in the reduced lists of flexible and rigid pavement topics described in Section 4. However, the

TABLE 1
TRA 2 "WISH LIST" OF SPECIFIC STUDIES FOR RIGID PAVEMENTS

Effects of Subsurface Drainage of various kinds

General Study of CRCP

General Study of Prestressed Concrete Pavements (slab design & thickness, prestressing amount, joint detail)

Effects of Shoulder Design on Pavement Performance

Effects of Tied Concrete Shoulder on Pavement Performance

Effects of Joint Spacing on JRCP

Effects of Maintenance on Pavement Performance

Effects of Joint Spacing on JPCP

Effects of Using Non-erodible, High-Strength Subbases

Effects of Dowel Type on Pavement Performance (Materials, Coatings, Shape)

Evaluate Innovative Design Techniques

Retrofit of Existing PCC Pavements with Tied Concrete Shoulders

Relative Effects of Implanted Dowels vs. Placement in Baskets

Use of Porous Concrete as a Drainage Medium

Effects of Variations in Material Properties

General Studies of the Effects of Quality of Construction (Consistency of Materials, Construction Details, Specifications, Inspection, Testing, etc.)

Recycled Concrete Pavement

Use of Fewer Nonuniformly Spaced Dowels

PCC Overlays over Existing A.C. Pavements (resurfacing, in-lays)

Evaluate Innovative Construction Techniques

Use of Higher Strength Concrete-Effects on Numbers of Cracks for JRCP, Reduction in Surface Defects, etc.

Effects of Swelling Soils on Pavement Performance

Effects of Frost Heave on Pavement Performance

Need for Doweled Joints to be Skewed

Evaluate Performance of Novel Mat'ls

TABLE 2
TRA 2 "WISH LIST" OF SPECIFIC STUDIES FOR FLEXIBLE PAVEMENTS

Effects of Subsurface Drainage

Recycled Asphalt Pavement (Exposed wearing Course and Inter-layer-Batch Plant, Drum Plant, Microwave)

Evaluate Innovative Design Techniques

Various Thicknesses of A.C. Overlay on Jointed Rigid Pavements:
- With Cracking and Seating
- Without Cracking and Seating
- With and Without Undersealing

Evaluate Assumptions in Revised AASHTO Guide

Various Thicknesses of A.C. Overlay on CRCP

Effects of Preventive Maintenance on Performance

Evaluate Innovative Construction Techniques

Effects of Subgrade Stabilization

Effects of Variations in Material Properties

Evaluate Performance of Novel Materials

General Studies of the Effects of Quality of Construction (Consistency of Materials, Construction Details, Specifications, Inspection, Testing, etc.)

General Studies of Sulphur/Asphalt Pavements (Sulphlex, SEA, & SAS)

Performance of Full-Depth HMAC Pavements

Performance of Staged Construction

Performance of Purposely Weakened Section

great majority of the general topics appearing in Tables 1 and 2 represent valid research needs, and those not included in SPS should be considered by other agencies for funding. The factorial experiments for these topics are tentative and additional study will be required to refine them to final form.

Accelerated Load Testing

This type of testing is generally applied when the relative effects of specific axle-load levels are required for establishing load equivalence factors, cost allocation studies, or applying load limits. This has generally been accomplished in the past through carefully designed experiments utilizing specially designed, constructed, and loaded test roads. Although this approach may be selected for LTPP at a later date (probably utilizing existing test tracks), it is not presently planned.

The Accelerated Loading Facility (ALF) under development by the FHWA is a mobile test facility that may be used on existing or specially constructed pavements. It will apply dual truck tire wheel loads ranging from 9,000 to 22,500 lbs. at a rate of approximately 8500 load applications per day over a test pavement length of 30 feet in one direction. An individual testing sequence or experiment will last from four to six months.

Plans and supporting design documentation were acquired for the Australian ALF, and contracts have been awarded for its fabrication and operation. The FHWA expects to start its first series of tests in January 1987 at Turner-Fairbank Highway Research Center in McLean Virginia. SHRP will be kept informed by FHWA of the progress in the ALF testing program, so that its potential for serving the LTPP and Asphalt Properties study areas may be defined.

MODEL BUILDING PROCESS

The major technical objective of this overall experiment is to measure the effects of significant factors (such as material properties, design, environment, subgrade and traffic) on long-term performance (e.g., distresses, roughness, maintenance, serviceability) of pavements. In order to successfully structure an experiment, it is essential to understand how the experimental results are to be employed. As the classical approach to evaluating the effects of the significant parameters in an experiment is through development of mathematical models and their statistical analysis, it was necessary for the project team and the Advisory Committee to carefully examine the potential model building processes.

Approaches to Model Building

Two completely different major approaches could conceivably be used for the development of predictive models for in-service pavement performance:

- Random selection of in-service pavements and construction of new design sections over a wide range of climates and geographical areas, or

- Use of a statistically designed plan for the selection of pavement sections.

The following are some of the many reasons for choosing a statistically designed plan for the selection of the pavement sections:

- An ordered plan (such as a factorial design) provides the most economical and effective approach to experimental design. This approach permits the determination of the effect of each individual main factor, and also the way in which each factor effect depends on the levels of the other factors (i.e., the interactions).

- The ranges of factors of interest are limited by past design practice (for example, thickness of pavements is directly related to traffic level and subgrade support), and thus it may be necessary to construct sections to fill out missing design cells/combinations to ensure a complete and relevant range of sections.

- A factorial design plan permits identification and consideration of semi-confounding of effects. A change in one variable is often accompanied by a corresponding change in another (such as the increase in traffic loadings with age).

- A factorial design plan offers opportunity to avoid confusion of correlation with causation: many variables may be found to be correlated when analyzing randomly selected data, but this does not prove that a change in one causes the others to change. The development of models which show causation between, for example, cracking and design variables such as thickness and stiffness is essential for use in pavement design.

Factorial designs are extremely useful for avoiding problems such as those discussed above. These designs and the fractional designs derived from them are economical and can provide a large amount of valid information about long-term pavement performance. The experimental design of the AASHO Road Test utilized a factorial arrangement of factors.

Mechanistic and Empirical Models

Improved design procedures, which are one of the principal objectives of the SHRP LTPP study, will be developed from predictive models that come from this study. A predictive model is a mathematical representation of the relationships under consideration. There are basically three different types of models: empirical, mechanistic-empirical and mechanistic.

Empirical models are developed from measured data using mathematical "French curve" type equations such as graduating polynomials. They do not necessarily represent the theoretical mechanisms of the pavement response. An example of an empirical model is:

$$Y = B_0 + B_1 * X_1 + B_2 * X_2^{B_3} + B_4 * X_1 * X_2$$

where:

Y = a dependent variable (cracking, rutting, joint deterioration, etc.)

X_i = independent variables (design, climate, soils, materials, traffic, maintenance, etc.)

B_i = coefficients determined from regression

Mechanistic models have a form derived from consideration of the conceptual mechanism (e.g., F = ma). Pure mechanistic models in the pavement design field exist only for responses such as stress, strain and deflection (e.g., elastic layer theory, Westergaard's theory). They do not exist for fatigue cracking, rutting, joint faulting, etc.

Mechanistic-empirical models may be developed by employing theoretical models and empirical data together. The form of the model and the variables included may be based on theoretical knowledge, but the coefficients are determined from regression analysis with measured data (sometimes called "calibration"). This type of model gives a closer representation of the response over a wider region than is usually possible with a purely empirical model. The following is an example of a very simple mechanistic-empirical model for joint faulting:

$$\ln(F + 1) = \ln(ESAL + 1)[-9.1 \times 10^{-2} + 1.394 \times 10^{-4} \text{ BSTRESS}]$$

where:

F = joint faulting, inches.

ESAL = cumulative 18-kip equivalent single-axle loads, millions.

BSTRESS = maximum bearing stress of dowel bar on PCC, psi.

Each of these three types of models has important applications. Empirical models are extremely useful when the theoretical mechanisms are not well understood (e.g., raveling, joint deterioration). Empirical models may be very useful for prediction of performance for many types of rehabilitation techniques. Mechanistic models are especially useful as "response models" for predicting responses such as stress and strain in a pavement due to axle loadings. The stresses and strains can then be utilized for prediction of distress by developing "distress models" of a mechanistic-empirical nature. Also, empirical data can be used to "calibrate" mechanistic responses, thus allowing mechanistic models to generate data over a broad range of variables; this data then can be employed to develop very useful mechanistic-empirical models.

It is very important to understand that there are no purely mechanistic models for predicting distress or other performance measures for pavements. Some confusion arises from the availability and widespread use of mechanistic response models. However, if one wishes to predict the actual distress or performance measures (such as ride quality and skid

resistance), one must either use an empirical model or utilize the responses calculated from a mechanistic model in some purely empirical or semi-theoretical distress or performance model that relies on empirical coefficients and/or exponents. The determination of the coefficients and exponents has been the primary source of difficulty to date in the use of mechanistic-empirical models to predict distress and performance for pavements.

The experiment and the resultant data base should be structured so that sufficient data is available for both (1) building empirical models and (2) calibrating or improving mechanistic-empirical models. This experiment is too important to attempt an advance decision as to which will be the most useful. Both approaches to predictive model development are possible with the data that will be in the data base as presently planned. The cost will not be substantially greater to collect the data for both purposes, since only the amount of one-time inventory data is in question.

The mechanistic response models are generally reasonably accurate, and the material properties required for them will be collected. The "calibration" will primarily be applied to the empirical or semi-empirical "distress models." This calibration may be applied in several ways, as described below:

- The mechanistic response model may be used to predict stresses or strains for an eighteen-kip equivalent single axle load, and these stresses or strains may then be included directly as independent variables in multiple regression analyses to develop empirical distress models. The end result is a mechanistic-empirical model that uses responses calculated by a suitable mechanistic model as independent variables in an empirical distress model.

- Models such as the VESYS models developed by the FHWA for predicting distress and serviceability loss for flexible pavements are dependent on very sophisticated and costly test procedures to produce fatigue life characterizations for asphalt concrete and permanent deformation characterizations for all materials in the pavement structure. A series of tests are required in all cases because the characterizations are functions of temperature and stress state for asphalt concrete and stress state and moisture content for other materials. Appropriate "shift factors" must also be applied to transpose the results from laboratory to field conditions. The possibilities for calibration are at least twofold:

  - studies may be conducted to modify the material characterizations to produce better predictions, or

  - calibration functions may be used to improve the final predictions (discussed below).

- "Calibration functions" may be used to improve the predictions for either empirical or mechanistic-empirical models. The approach is to apply the model to predict the occurrence

of distress or serviceability loss for specific pavements. The measured values are then divided by the calculated values to obtain a set of multiplying "constants" that then may be used to transform predicted values to measured values. These multiplying constants are then regressed with various combinations of independent variables to arrive at "multiplying functions" to transform predictions from the existing models to more accurate predictions.

VARIABILITY AND REPLICATION

The development of the experimental design factorials for site selection is the first phase of experiment design. Once this is done, an essential second phase can be undertaken to develop: (1) field layout randomization procedures, (2) replication of test section needs and (3) the inference space desired for each experiment. The field layout procedures will include for example, possible use of inner/outer lanes for "medium" and "high" levels of traffic and guidelines for selection and location of replicate test sections. The primary technique for the development of these results will be "dummy analyses" similar to those expected for the real data, except using existing or simulated data within reasonable ranges of variability.

Variability In Pavement Performance

Pavements are known to show highly variable performance. However, very little data is available to quantify the extent of variability in pavement performance. A considerable amount of data is available from the AASHO Road Test on pavement performance; however, because of the extremely tight construction controls, the short performance period (only two years), and the very short sections of pavement, these results are not likely to be representative of actual pavements after many years of service. It is important to obtain estimates of the variation in actual in-service pavement performance for use in the design of the experiment to help determine the number of replications needed.

To illustrate the significance of variability in pavement performance, an analysis was conducted using data from the NCHRP Project 1-19 (COPES) data base for JPCP and JRCP located in six states. Several of the pavement sections in each state could be roughly considered as "replicate" sections having approximately the same design, subgrade soils, traffic, age, and no "D" cracking. Table 3 shows an example of the performance of 12 "replicate" JRCP sections in Illinois. These sections are not "identical" in all ways in that they were not necessarily located adjacent to each other, did not have the same contractor, did not likely have the same maintenance or same drainage, and probably differed in several other ways (i.e., topography). An examination of the performance of these sections reveals a large variability for some of the distresses. The coefficient of variation was computed and ranges from 15 percent for PSR to 115 percent for joint deterioration.

This same analysis was repeated for other combinations of age and ESAL in Illinois and five other states. The results in Table 4 show quite

TABLE 3

TRA 2 PERFORMANCE RESULTS FOR 12 "REPLICATE" IN-SERVICE PAVEMENT SECTIONS IN ILLINOIS

Section	Age (years)	ESAL (millions)	PSR	Faulting (inches)	Cracking (feet/mile)	Deteriorated Joints (no./mile)
1	18	5	4.2	0.11	0	0
2	18	5	4.0	0.05	0	0
3	18	5	3.4	0.25	0	0
4	22	5	3.8	0.06	950	1
5	22	5	3.6	0.10	1162	0
6	19	8	3.1	0.26	1214	0
7	19	8	2.5	0.39	1478	0
8	22	6	3.3	0.24	106	5
9	22	7	3.3	0.16	106	9
10	20	6	3.8	0.19	0	0
11	17	7	3.2	0.33	106	9
12	18	8	2.6	0.32	1426	18
Mean	19.4	6.3	3.4	0.20	545	4
COV	10	20	15	54	116	115

Pavement: JRCP, 10-inch slabs, 100-foot joint spacing, fine-grained subgrade, no "D" cracking, age between 17 and 22 years, ESAL between 5 and 9 million in design lane.

TABLE 4
TRA 2 COMPUTED COEFFICIENTS OF VARIATION FOR "REPLICATE" PAVEMENT SECTIONS

State	Pavement Type	Number of Replicates	PSR	Faulting (inches)	Cracking (feet/mile)	Deteriorated Joints (number/mile)
IL	JRCP	16	5	49	183	---
		18	9	58	227	178
		3	21	81	151	86
		18	16	45	110	158
		7	11	41	52	137
		19	12	37	116	173
MN	JRCP	4	6	60	111	129
		3	3	22	53	15
LA	JRCP	15	8	38	273	154
		13	6	50	123	77
		2	2	70	54	7
GA	JPCP	5	7	31	121	142
		5	9	13	88	157
		6	13	41	81	94
CA	JPCP	7	5	41	97	171
		4	6	17	30	200
		5	6	17	70	224
		3	9	45	104	173
		9	13	38	77	133
UT	JPCP	2	7	71	141	0
		15	4	33	107	195
		5	7	34	149	129
MEAN			8	42	115	130

large variabilities for distresses such as joint deterioration and cracking and lower variabilities for PSR and faulting.

Further analyses were conducted by considering only "within-project variability". Means and coefficients of variation were computed from distress results obtained from 0.1 mile sections along selected projects. These sections did have the same material sources, contractor, topography, etc. The resulting mean coefficients of variation, as expected, were somewhat lower than those shown in Table 4.

These results are for rigid pavements. However, there is no reason to believe that distresses associated with flexible pavements (e.g., cracking, rutting, and serviceability) will be substantially different.

Effects of Variability and Replication

When mathematical models used to predict phenomena of interest are developed from experimental data, the questions of model adequacy and model predictive precision are central to the model building effort. The techniques of statistical design of experiments help to deal with these issues. In particular, the use of replication is important for at least two fundamental reasons:

1. Replication provides an estimate of experimental error independent of the model form being pursued. As a result, model inadequacies can more readily be identified; and

2. Replication provides a means to reduce the sampling error associated with the model, and to thus improve the predictive precision of the model.

The important issue that remains, then, is to determine how much replication is desirable in any situation. Fortunately, the answer to this question can be formulated in precise mathematical terms. The amount of replication required is influenced by several important factors.

Factors Which Influence Replication Requirements One important use of a mathematical model based on observed data is to predict the phenomenon it is representing, e.g., stress, serviceability, pavement distress. It is desirable to be able to make statements such as:

"I am 90 percent confident that the amount of cracking (feet per mile) present under this particular set of conditions will be 350 ± 150; that is, between 200 and 500 feet per mile."

It is of interest here to review just exactly what governs how large the confidence interval will be for the true or actual cracking. In the above example it is ± 150 feet per mile. What could be done to reduce it to ± 75 feet per mile?

An examination of the mathematical equation which is used to construct the interval described above will show that there are five factors

which influence the size of the confidence interval (in other words, the predictive precision associated with the model prediction). These are:

- The form of the predictive equation; i.e., number of variables, nature of the terms, etc.;
- The placement of the tests used to collect data and fit the model; i.e., the experiment design;
- The number of tests in the experiment design; in particular, the amount of replication;
- The amount of confidence that is desired on the interval statement; i.e., 80 percent, 90 percent, 95 percent; and
- The level of inherent variability in the phenomenon under study.

Generally, the greatest amount of control over the size of the confidence interval (i.e., the percent prediction error) can be exercised via the third item listed above, the amount of test replication. The second item, the experiment design structure, is within control as well, but the decision as to the experiment design is influenced by other factors. Only limited control exists over the model form, as this depends on the state of knowledge and the inherent complexity of the phenomenon under study.

The level of confidence that is chosen is primarily an economic decision. For example, what is the cost associated with predicting that the true response is within the confidence interval when it is really not within the interval? The level of inherent variability in the phenomenon under study is not generally something that can be controlled directly. However, as was discussed previously, the selection of replicate sections is a crucial process which can greatly influence the ultimate predictive precision of the models that will ultimately be built.

Analysis of Replication Requirements The results of an analysis are presented in Table 5 that demonstrated experiment design replication requirement as a function of the model employed (analysis type), coefficient of variation (inherent variability), percent prediction error required (e.g., ± 10 percent, 20 percent), and the level of confidence placed on the interval. Table 5 essentially shows that even for moderately high coefficients of variation, say in the range of 0.40 to 0.50, replication requirements need not be excessive if we can be satisfied with a predictive capability of ± 30 percent, which is a reasonable expectation. In fact, it may not be unreasonable to think that a predictive precision of ± 40 or 50 percent may be acceptable, given the phenomena under study and the purposes for which we seek decision-making guidance from the models that are being developed. Under such situations, an acceptable predictive precision may be achieved by having two observations (replications) per cell in a factorial-type experiment design. This tentative conclusion will be evaluated in the "second phase" of the experiment design.

TABLE 5
TRA 2 REQUIRED REPLICATIONS FOR A SINGLE CELL RESULT OVER A RANGE OF VALUES OF INTEREST

Permissible Error in the Estimate, Prop. of Mean (e)	Coefficient of Variation (K)	Replication, n Level of Confidence 90%	80%
0.10	0.75	152	92
	0.50	68	41
	0.40	43	26
	0.30	24	15
	0.20	11	7
	0.10	3	2
0.20	0.75	38	23
	0.50	17	10
	0.40	11	7
	0.30	6	4
	0.20	3	2
	0.10	1	1
0.30	0.75	17	10
	0.50	8	5
	0.40	5	3
	0.30	3	2
	0.20	1	1
	0.10	1	1
0.50	0.75	6	4
	0.50	3	2
	0.40	2	1
	0.30	1	1
	0.20	1	1
	0.10	1	1

$n = (ZK/e)^2$
Z = 1.645 for 90 percent confidence level
Z = 1.28 for 80 percent confidence level

Placement of the Replications in the Experimental Design Structure Generally in a factorial-type experimental design, replications are placed more or less uniformly across all cells. This may not be (1) practical if large differences in testing costs exist from cell to cell, or (2) appropriate if well-established a priori information suggests significant (and known) differences in error variation from cell to cell. But unless such conditions are present, equal replication in all cells is generally the practice.

In the context of these experiments, equal cell replication may be desirable for several reasons:

- The data base under development will likely be used for many purposes; hence, equal replication may provide maximum flexibility in regard to the types of analyses which may be performed and the application of less restrictive assumptions. It is expected that many "local" models will be developed from the data for say an individual state with one climatic zone.

- By having replication in all of the cells, more comprehensive variability analysis can be performed within individual cells and across one or more cells. This will also allow for testing certain variation assumptions made during model building or for performing more involved analysis/estimation if the normal assumptions are violated.

- A highly unbalanced replication distribution may become more costly if many replicate sections are required of a certain type.

At the time of this report, the complete dummy analyses have not been conducted, so two replications have been assumed for structuring the experiments described in Section 4.

REPLICATIONS VERSUS "REPEATS" FOR SPS

The limited nature of the SPS projects and their emphasis on a few specific variables introduce some potential differences in approach from the much broader GPS experiments. For GPS studies, the advantages of independent random replication are obvious in terms of a broad inference space. For SPS studies, random selection of locations will be difficult as selections will depend most heavily on SHA construction planning, interests, and willingness to participate.

The choices are replication at separate locations or repeated sections at a single location. The former lends itself to expanding the inference space, but also involves more variations in important parameters although selected as a replicate. The latter tends to limit the sources of variation (i.e., essentially the same traffic, environment, subgrade, construction contractor, prior maintenance practice, etc.) and the inference space. Use of repeats at the same location has been tentatively selected for this report as a basis for identifying SPS test locations for cost estimating. However, the final selections must be made on the basis of careful

consideration of specific project needs as these tentative experiments are further developed.

ALLOCATION OF RESOURCES

This subsection discusses the problem of allocating available research funding and resources to each of the nine major GPS experiments and the SPS program. It is very likely that any one of the nine major GPS experiments could utilize a majority of the anticipated funding, and the SPS program could as well. Some important factors to be considered in this allocation are as follows:

- Existing mileage of the different types of pavements in the United States. Table 6 shows statistics relative to the existing (1985) mileages of concrete and asphalt-surfaced pavements in different climatic zones of the United States, obtained from the FHWA HPMS data base.

- The current level of technology to design and rehabilitate each type of pavement. If a lack of technology exists for a particularly promising type of pavement or rehabilitation procedure, it should be included in more detail in the experiment.

- The predominant types of pavements and rehabilitation techniques that will likely be constructed in the future should be given more emphasis.

Similar considerations apply for the selection of SPS topics and the development of individual experiment factorials.

The allocation of resources has been the subject of numerous letters and discussions as this experiment design has evolved. Those having a vested interest in asphalt concrete pavements stress that roughly 96 percent of all paved roads and streets in the United States are surfaced with asphalt concrete; or that some 71 percent of interstate, other freeways and expressways, and other primary arterials are surfaced with asphalt concrete. Those interested in portland cement concrete pavements stress that there is as much rigid as flexible pavements on the interstate system, and that PCC would dominate in terms of vehicle-miles traveled. Similarly, some parties are especially eager for studies of certain design features such as types of drainage, maintenance procedures, etc. The approach taken has been to offer the highway community at large ample opportunity to express their opinions fully (SHRP National Workshop, Advisory Committee Meetings, correspondence, etc.), and to develop programs to achieve a reasonable balance in content and emphasis.

DATA COLLECTION AND MANAGEMENT

The data items tentatively recommended for collection appear in a May 1984 document, entitled "Long-Term Pavement Monitoring Program Data Collection Guide", prepared by the consultants for the FHWA. While subject to revision as the LTPP Program is further developed (especially to add more rehabilitation details), this data collection guide provides a standardized

TABLE 6

TRA 2 LANE-MILES OF ASPHALT AND CONCRETE-SURFACED PAVEMENTS IN THE UNITED STATES (1985) IN BROAD CLIMATIC ZONES. (SOURCE: FHWA HPMS DATA BASE)

TYPE OF HIGHWAY	CLIMATIC ZONE	LANE-MILES (PERCENT) ASPHALT-SURFACED**	CONCRETE SURFACED
Interstate			
	Wet-Freeze	24,793 (39)	38,083 (61)
	Wet-Nonfreeze	18,714 (51)	18,163 (49)
	Dry-Freeze	23,904 (57)	18,255 (43)
	Dry-Nonfreeze	20,622 (62)	12,715 (38)
	Total	80,033 (48)	87,216 (52)
Interstate, Other Freeways and Expressways, Other Primary Arterials			
	Wet-Freeze	106,992 (56)	83,073 (44)
	Wet-Nonfreeze	107,110 (79)	27,755 (21)
	Dry-Freeze	94,658 (78)	26,963 (22)
	Dry-Nonfreeze	87,455 (78)	24,166 (22)
	Total	398,215 (71)	161,957 (29)

** Asphalt-surfaced includes all types of flexible pavements plus asphalt overlays of concrete pavements.

procedure and data sheets for collection of data elements believed to be significant for future data analysis needs.

The data items recommended for collection are considered in two broad categories. The first is basic inventory data, which includes those items that remain constant over the monitoring period. The second is monitoring data, which includes those items that will change with time and will require periodic measurements or updating during the monitoring period.

The basic inventory data (See Table 7 for general data elements) includes that data necessary to: 1) identify the test section, 2) describe the geometric details of its construction and the material properties of its structural constituents, 3) describe the environment in which the pavement test section exists, 4) identify the accumulated traffic and axle-load data prior to the long-term monitoring effort, 5) identify previous maintenance activities, 6) identify previous resurfacing or rehabilitation, and 7) identify construction costs and costs of subsequent maintenance and repair prior to the long-term monitoring effort. All of this data should remain constant throughout the monitoring period unless the pavement is resurfaced or rehabilitated. In the latter case, the test section becomes for practical purposes a new pavement structure with new surface conditions, so the basic inventory data must be revised to describe these new conditions, while retaining the original data for reference in long-term cost analyses and studies of the effects of rehabilitation on deterioration rates.

The monitoring data (See Table 8) includes: 1) distress, serviceability, and skid measurements; 2) traffic and axle load data; 3) skid testing results; 4) deflection testing results; 5) identification of pavement maintenance and its costs; and 6) identification of restoration and rehabilitation and their costs during the monitoring year. This data is to be collected on a periodic basis (expected to vary from four times a year for traffic data to perhaps once every three years for deflections) to provide a historical data base for developing relationships between distress, performance, traffic and axle loads, age, maintenance, and costs.

One of the strongest conclusions from the pilot studies and all meetings in the past four years relative to long term monitoring of pavements has been the absolute necessity for uniformity and consistency in data collection. This means careful training of data collection personnel nationwide, use of essentially identical procedures and equipment, and close quality control on data collection activities.

State-of-the-art automated data collection will be applied. This is expected to include the following:

- Automated photographic collection of distress data with simultaneous direct measurement of rutting.
- Some type of profilometer will likely be used rather than a response-type roughness meter.
- Deflection measurements will be made with the falling weight deflectometer.

TABLE 7
TRA 2 ITEMS OF INVENTORY DATA TO BE COLLECTED

1. Test Section Identification:

State Code	Urban or Rural
Project ID	Lanes Included
County	Functional Class
HPMS Identification	Location of Test Section
Highway Number	Direction of Survey

2. Geometric Details and General Information

Lane Widths	Joint Spacing
Number of Lanes	Dowel Bar Diameter
Type of Construction	Dowel Bar Spacing
Adequacy of Drainage	Method Used to Install Dowels
Underdrains Provided	Year and Details if Roadway Widened
Width of Shoulders	Tie Bar Diameter, Length, and Spacing
Year Originally Constructed	Type of Shoulder - Traffic Lane Joint
Year Opened to Traffic	Identification of Layer Materials

Thickness of Layers and Material Types
Years When Overlays or Reconstruction Occurred
Identification of Materials Used in Overlay or Reconstruction
Thicknesses of Overlays or Final Layer Thicknesses After Reconstruction
Type of Load Transfer (Aggregate Interlock or Dowels)
Method Used to Form Transverse and Longitudinal Joints
Joint Sealant Used in Transverse and Longitudinal Joints
Depth and Width of Transverse Joint Sealant Reservoir
Diameter, Length, and Spacing of Shoulder - Traffic Lane Joint Tie Bar
Transverse and Longitudinal Bar Diameter, Spacing, and Yield Strengths
Depth to Reinforcement from Slab Surface and Method Used to Place Rebar
Length of Steel Laps at Construction Joints

3. Environmental Data for Prior Years:

Number of Freeze-Thaw Cycles per Year	Freeze Index
Average Maximum Monthly Temperature	Lowest Mean Solar Radiation
Average Minimum Monthly Temperature	Highest Mean Solar Radiation
Average Monthly Precipitation	Latitude and Elevation
Average Annual Deicing Salt Application	

General Type of Environment (Dry-Freeze, Wet-No Freeze, etc.)

4. Accumulated Traffic and Axle-Load Data Prior to Long-Term Monitoring Effort:
Mean of AADT for Prior Years
Accumulated 18-Kip ESAL (AASHO Equivalencies)
Lane Distribution and Percent Trucks for Prior Years
Accumulated Number and Distribution of Tandem Axles
Accumulated Number and Distribution of Single Axles

5. Material Properties:
   a. Subgrade Soil:

Soil Type and Classification	Liquid Limit and Plasticity Index
Percent Passing No. 200 Sieve	Type of Laboratory Compaction Test
CBR	Subgrade Resistance (R-Value)

TABLE 7
TRA 2. ITEMS OF INVENTORY DATA TO BE COLLECTED (continued)

a. Subgrade Soil: (continued)
Modulus of Subgrade Reaction (k-Value)
Optimum Dry Density and Moisture Content
Dry Density and Moisture Content, Percent
Resilient Modulus and Load Duration
Type Test and Results to Predict Swell Potential
Type Test and Results to Predict Frost Susceptibility

b. Base and Subbase Layers

Type of Base or Subbase (Stabilized or Unstabilized)
Soil Type and Classification
Dry Density
Percent Modified AASHO Compaction
Percent of Stabilizing Agent
Percent Passing No. 200 Sieve
Percent Passing No. 40 Sieve
Resilient Modulus and Load Duration
Type of Laboratory Compaction Test
Type of Treatment (Cement, Lime, etc.)
Percent Dry Density and Moisture Content In Situ

c. Asphalt Concrete Layers:

Percent Passing No. 200 Sieve
Type of Coarse Aggregate
Source of Coarse Aggregate
Softening Point of Asphalt
Type of Fine Aggregate
Source of Fine Aggregate
Asphalt Grade
Source of Asphalt Cement
Asphalt Content
Density
Marshall Stability
Marshall Flow
Hveem Stability
Percent Air Voids
Dynamic (Resilient) Modulus
Permanent Deformation Properties
Tensile Properties
Fatigue Behavior
Penetration of Asphalt at 77 F
Viscosities of Asphalt at 140 and 275 F
Ductility of Asphalt at 140 and 275 F

d. Rigid (PCC) Pavement Layers:

Mix Design
Modulus of Rupture
Slump
Type of Cement
Alkali Content of Cement
Percent Entrained Air
Additive Other Than Air Entrainer
Maximum Size of Coarse Aggregate
Type of Coarse Aggregate
Source of Coarse Aggregate
Type of Fine Aggregate
Source of Fine Aggregate
Type of Paver Used
Method Used to Cure Concrete
Elastic Modulus and Test Method Used
Method Used to Finish Concrete
Compressive Strength of In-Place Concrete
Durability and Type Durability Test Used
Geologic Classification of Coarse Crushed Stone Concrete Aggregate
Indirect Tensile Strength of In-Place Concrete

6. Maintenance Data by Year:
(Details not yet developed).

7. Cost Data by Year
(Details not yet developed)

TABLE 8
TRA 2 ITEMS OF MONITORING DATA TO BE COLLECTED

1. Distress and Performance Measurements:

   a. Flexible Pavements (With or Without Overlays):

Alligator Cracking (Fatigue)	Rut Depth
Roughness	Raveling
Lane/Shoulder Separation	Potholes/Pothole Patching
Lane/Shoulder Dropoff or Heave	Bleeding
Low-Temperature Block Cracking	Reflection Cracking
Skid-Resistance (To Monitor Reductions)	
Low-Temperature Transverse or Longitudinal Cracking	

   b. Rigid Pavements:

Slab Cracking	D-Cracking
Joint Faulting	Pumping
Lane/Shoulder Separation	Lane/Shoulder Dropoff or Heave
Roughness	Blow-ups
Deterioration of Transverse Joints	Joint Spalling
Skid-Resistance (To Monitor Reductions)	

   c. Rigid Pavements with Flexible Overlays:

Reflection Cracking	Rut Depth
Pot Holes in Overlays	Raveling
Roughness	Bleeding
Lane/Shoulder Separation	Lane/Shoulder Dropoff or Heave
Skid-Resistance (To Monitor Reductions)	

2. Traffic and Axle Loads:

AADT	Percent Trucks
18-KIP ESAL for Year	Accumulated 18-KIP ESAL
Truck Lane Distribution	
Number and Distribution of Single Axle Loads	
Number and Distribution of Tandem Axle Loads	

3. Deflection Testing Results:

Type of Deflection Device	Test Load Frequency
Date of Measurement	Air Temperature
Deflections for each Sensor (One set for each of four locations for each of ten subsections)	

4. Environmental Data:
   Same as for Inventory Data, Except for Monitoring Period Only

5. Maintenance Data:
   (Details not yet developed)

6. Restoration and Rehabilitation and Its Costs
   (Details not yet developed)

- New equipment for traffic counting, vehicle classification, and axle weighing in motion is being developed at greatly reduced costs.

It is expected that numerous permanently installed induction loop systems with telemetry tied to central data control will be used for vehicle classification and counting. Promising and much more economical weigh-in-motion (WIM) systems using piezoelectric cables or capacitance strips are expected by 1988, and will be installed when available. Their installation will provide both automated vehicle classification (AVC) and axle weight measurements for each GPS test section and each SPS location. The AVC/WIM equipment purchase may be shared between SHRP and the SHA's, but this equipment will be operated by the SHA's as part of their traffic monitoring activities.

Coring and boring of all sections will be required. The material testing on these samples will include relatively sophisticated tests to measure resilient moduli of pavement layers. Both the material sampling and testing will be accomplished by the SHRP regional contractors or by subcontracts, while the SHA's will be requested to provide traffic control during coring and boring operations. As a portion of a structured experiment, some coring and testing of AC materials will be conducted periodically to study effects of AC aging.

The data will be entered into the data base on an automated basis wherever possible. Any manual data entry will be made (generally by SHRP Contract Staff), using a full-screen data entry and editing system, into a data base for micro-computers. The data base for a particular SHA will be processed directly to them, but will also be processed into the National Data Base for primary analysis. The National Data Base will be generally accessible, but on a "read only" basis. The security details have not yet been developed.

PROJECT MANAGEMENT

There has been an ongoing interaction during formulation of the research plan between estimated costs for managing and conducting the program, purchasing equipment, and material testing; numbers of GPS sections to be monitored; and numbers of SPS topics that can be studied. The primary constraint is, of course, the anticipated budget, which is estimated as ten million dollars per year in 1986 dollars.

The SHRP Advisory Committee on Pavement Performance has recommended that:

- Central management should consist of a combination of SHRP and contractor personnel. The SHRP contractor at the national level would be responsible for managing and implementing the experimental design plans, and to some extent for data bank development and management.

- Data should be collected on a regional basis by four regional contractors in cooperation with State Highway Agencies.

- SHRP funds should be used to purchase most needed equipment for regional operations in order to provide uniformity.

Most of the GPS test sections are expected to be implemented the first year and the rest the second year. The implementation planning, including selection of equipment to be used; selection of test sections; and development of plans for data collection, data base development and management, and management of the entire program are expected to be completed by the FHWA/Consultant team during 1986 under the guidance of SHRP and the Advisory Committee. Consequently, contracts can be executed and the program implemented fairly rapidly after funding is available late in 1986.

The SPS will take longer to implement in general because the majority of studies will require special design and construction in coordination with State Highway Agencies. Therefore, implementation for SPS, except for studies involving primarily inservice highways, may take two to four years.

In order to prepare the cost estimates required for the iterative development of the research plan, it has been necessary also to reach an agreement on the division of responsibilities between the regional contractors and the State Highway Agencies. The division of responsibilities approved by the Advisory Committee and AASHTO Task Force for SHRP appears in Table 9.

SUMMARY OF BACKGROUND INFORMATION FOR FORMULATION OF THE RESEARCH PLAN

The national scope of the LTPP studies and the almost infinite variety of possibilities for applying the expected funding necessitated an iterative approach of structuring the program, estimating costs, presentations to the Advisory Committee and obtaining their guidance, considering new input on relative priorities, and revising the program. The common intent for development of both the GPS and SPS experiment designs was to attain an appropriate balance between the broad statistical studies in GPS and the more limited SPS directed toward study of a few specific independent variables for each topic identified. The concept of the GPS had been under development by the FHWA and AASHTO for several years, whereas that for SPS first appeared as "Designed Highway Sections" at the International Pavement Testing Conference in early 1984. Consequently, the planning for SPS has always lagged that for GPS. The experiment design for GPS is considered to be quite close to that to be finally implemented, whereas the experiment designs for SPS topics are considered tentative (although necessary for cost estimating and adequate for that purpose).

The previous text described much of the background information that had to be considered in formulating the research plan. The resulting research plan, expected outputs, recommendations for implementation, schedules, and cost estimates appear in subsequent sections.

TABLE 9
TRA 2 DIVISION OF RESPONSIBILITIES BETWEEN STATE HIGHWAY AGENCIES AND SHRP REGIONAL CONTRACTORS

PROPOSED STATE FUNCTIONS	PROPOSED SHRP FUNCTIONS
1. IDENTIFICATION OF CANDIDATE SITES	1. CORING & BORING
2. INVENTORY DATA CONTROL	2. DEFLECTIONS
3. ASSIGN A SHRP COORDINATOR	3. PROFILE/ROUGHNESS
4. MAINTENANCE DATA	4. DISTRESS
5. REHABILITATION/RECONSTRUCTION DATA	5. QUALITY CONTROL ON DATA COLLECTION/CALIBRATION
6. TRAFFIC COUNT, AVC, WIM (PARTIAL EQUIPMENT FUNDING BY SHRP)	6. DATA MANAGEMENT
7. SKID RESISTANCE DATA	7. ENVIRONMENTAL DATA
8. TRAFFIC CONTROL	8. MATERIALS TESTING
9. CONSTRUCTION OF SPECIAL SECTIONS	9. TRAINING

SECTION 4
TRA 2 RECOMMENDED RESEARCH PLAN

The overall recommended research plan, consisting of the General Pavement Studies (GPS) and the Specific Pavement Studies (SPS), is presented in this section. The experimental designs are based upon current knowledge of in-service pavements, and several designs will likely need to be modified during the section selection process when actual in-service designs become known. Also, the SPS designs are very tentative and require further study and development.

EXPERIMENT DESIGN FOR GENERAL PAVEMENT STUDIES

Table 10 identifies five original (or reconstructed) and four rehabilitated pavement types included in the General Pavement Studies. It also shows the numbers of test sections expected for each pavement type.

It should be noted that five of these separate experiments (one for each pavement type) do not include all sixteen of the primary tier cells. In some cases, this was because some types of pavements are not used extensively in all environmental zones. In others, compromises were made to consider most prevalent or critical cases because of budget restrictions. Consideration may be given later to filling some of the primary tier cells omitted, depending on the availability of sections and funding considerations.

A summary of the number of test sections included in all of the GPS experimental designs is also given in Table 10. A total of 1560 test sections are included, 960 of which are original pavements in their first performance period (before they have been rehabilitated the first time) and 600 are rehabilitated pavements. Two replicates appear as reasonable average estimates in all GPS experiment designs and calculations for members of test sections, pending the results of replication studies. (See Section 3).

It should be noted that each of these 1560 test sections represents a separate monitoring location, as replicates must be selected randomly for statistical purposes.

The specific experiment designs for each pavement type appear subsequently and include detailed descriptions.

TABLE 10
TRA 2 NUMBERS OF TEST SECTIONS BY PAVEMENT TYPE
SELECTED FOR GPS EXPERIMENT DESIGN

Pavement/ Rehabilitation Type	Primary Tier Cells	Secondary Tier Cells	Replications Per Cell	Total Sections
Original Pavements				
AC over Granular Base	16	12	2	384
AC over Stabilized Base	4	16	2	128
Jointed Plain Concrete	16	8	2	256
Jointed Reinforced Concrete	12	4	2	96*
Continuously Reinforced Concrete	12	4	2	96*
Rehabilitated Pavements				
AC Overlay of AC	16	8	2	256
AC Overlay of Jointed PCC (JCP)	16	8	2	224*
Bonded JCP Overlay of JCP and CRCP	8	6	2	80*
Unbonded JCP Overlay of JCP and CRCP	4	6	2	40*
Total GPS Sections				1560
Total Original Sections				960
Total Rehabilitated Sections				600

* JRCP and CRCP not included in Dry Nonfreeze zone.

GPS Experimental Design for Asphalt Concrete Pavement with Granular Base (Original Design)

Pavement Type Definition This type of pavement is specifically defined as a layer of asphalt concrete (AC) material placed over untreated granular base and subbase layers. All of the asphaltic concrete material in the pavement will be hot mixed and dense graded. This pavement includes the traditional "flexible" type of pavement utilized throughout the United States on all types of highways. It also includes "full-depth" asphalt concrete pavements as one case of high AC thickness and low SN of base and subbase.

Main Experimental Design Factors The primary tier of the experiment includes these main factors (same for all GPS experiments):

- Traffic (rate of 18-kip equivalent single-axle loads (ESAL) per year).
- Subgrade.
- Moisture.
- Temperature.

as shown in Figure 4. Within each of the 16 cells, a second tier factorial design will be conducted. The following main factors to be used for flexible pavement with granular bases are recommended:

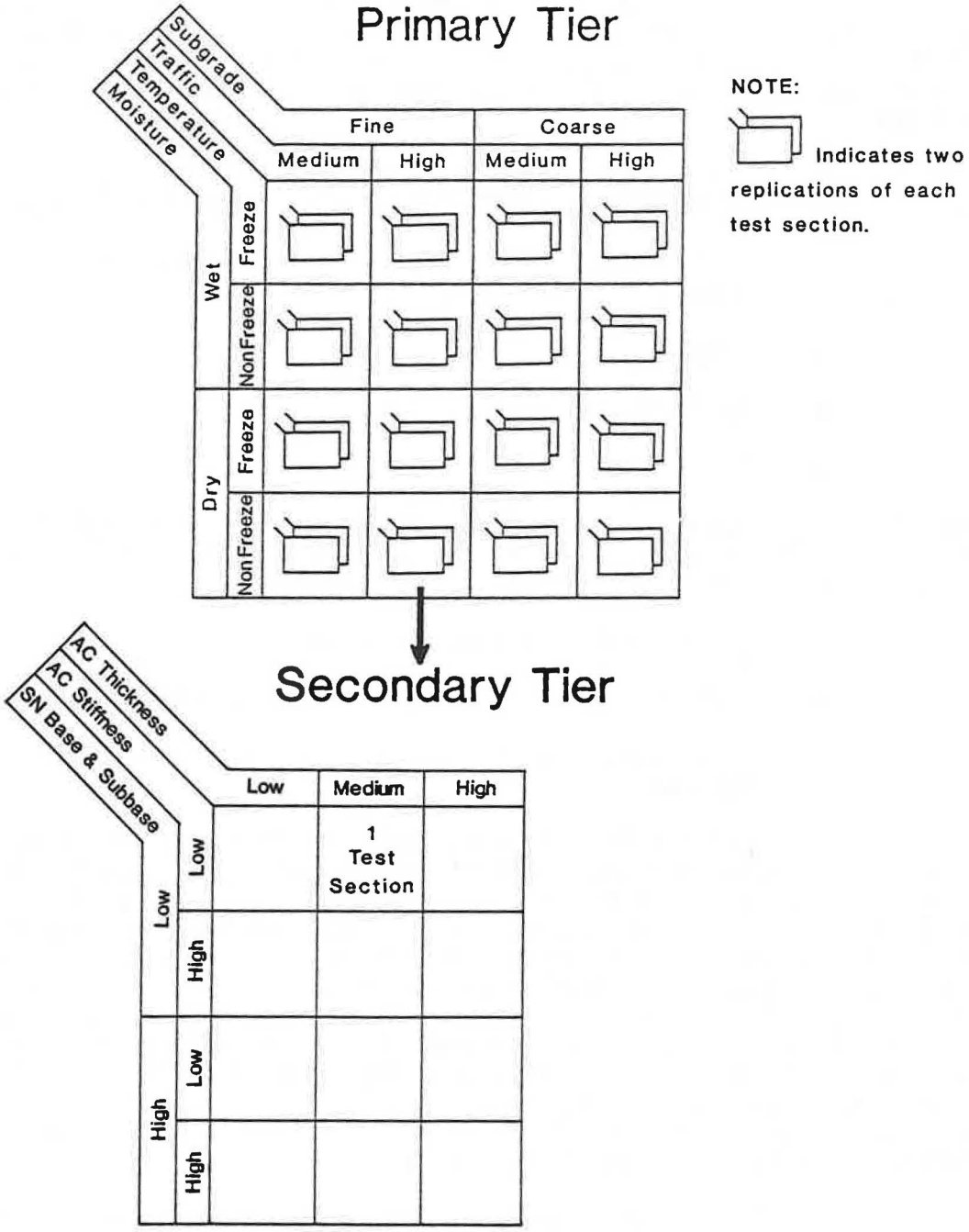
- Asphalt concrete material thickness.
- Asphalt concrete material initial stiffness.
- Structural number of the granular base and subbase.

The purpose for including either stiffness or air voids as a major factor is to encourage a distribution in quality of asphalt concrete surfaces. Air voids (in the opinions of a number of reviewers) is a more significant parameter than stiffness and should have been used instead.The site selections occur before coring and testing, so the data for calculating either stiffness or air voids will not usually be available. Initial stiffness was selected because it can be calculated approximately with limited information and appears to represent more mix parameters than air voids, which relate primarily to the compaction achieved. Although stiffness does increase with age at rates that cannot be readily predicted, it is logical to expect that the relative stiffnesses in time will be correlated with those mix properties that affect initial stiffness.

In discussions with the advisory committee membership, it was concluded that stiffness was a reasonable "placeholder" for mixture quality in place, but that other approaches might be required when site selection is undertaken. If the simplistic calculations of initial stiffness may not be made for lack of data or appear erratic and therefore not significant, judgement may be applied or some other procedure developed. Another ap-

FIGURE 4. TRA 2

GPS: AC WITH GRANULAR BASE



16 Primary Cells x 12 Secondary Cells x 2 Replications = 384 Total Sections

proach yet to be explored is to develop simple plots or equations from available mixture data to get rough correlations of quality to such more readily available parameters as asphalt content, density at construction, asphalt cement viscosity, etc.

Number of Sections Flexible-type pavements are located throughout the United States. There are more miles of this type of pavement than any other type of pavement, so it is recommended that full secondary-tier factorial designs be carried out in all of the 16 primary cells shown in Figure 4. Existing in-service pavements having the desired characteristics should be available for the great majority of the test sections required. Total number of GPS sections of AC pavement with granular base = 16 primary cells x 12 secondary cells x 2 replications = 384.

Experimental Design for Asphalt Concrete Pavement with Stabilized Base (Original Design)

Pavement Type Definition This type of pavement is specifically defined as a layer of asphalt concrete material placed over a stabilized base layer. Two types of stabilized base are included: asphalt and cement. The asphalt-stabilized base may be stabilized with either liquid asphalt cutback or emulsion. The Portland cement-stabilized base may include either cement-treated granular material or lean concrete material. This type of pavement is much less prevalent than the "flexible" type (estimated 85 percent flexible versus 15 percent stabilized base), but there is a significant number of these pavement sections in many states.

Main Experimental Design Factors

The following secondary-tier main factors are recommended:

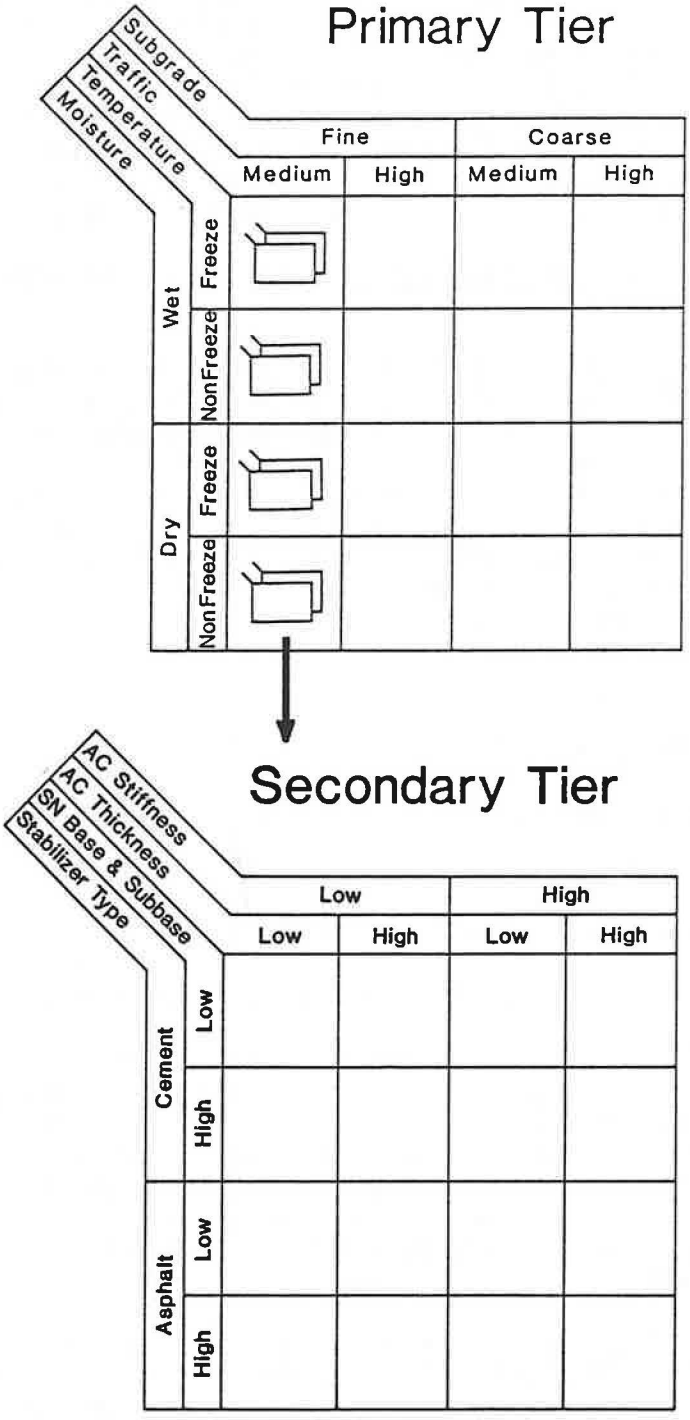
- Asphalt concrete material thickness.
- Asphalt concrete material initial stiffness.
- Structural number of the stabilized base.
- Type of base (asphalt or cement stabilizer).

Initial AC stiffness can be estimated from the asphalt content, density, and the viscosity grade or penetration of the asphalt cement using Van der Poel's or MacLeod's nomograph. The factorial stiffness levels should be "low" and "high." The stabilized base course structural number should have "high" and "low" factorial levels. Two base types are included: liquid asphalt-stabilized and cement-stabilized granular material. It is desired to utilize lean concrete base instead of cement-stabilized if an adequate number of sections can be located.

Number of Sections Asphalt-surfaced pavements with stabilized bases are located in most areas of the United States. However, they may not be found in significant numbers in all climatic or subgrade soil regions or at all traffic levels.Thus, it is recommended that full secondary-tier factorial designs be carried out in 4 of the primary cells as shown in Figure 5. Most of these sections should be found on existing in-service pavements.

FIGURE 5. TRA 2

GPS: AC WITH STABILIZED BASE



4 Primary Cells x 16 Secondary Cells x 2 Replications = 128 Total Sections

Total number of sections of asphalt concrete pavement on stabilized base = 4 primary cells x 16 secondary cells x 2 replications = 128.

GPS Experimental Design for Jointed Plain Concrete Pavement--JPCP (Original Design)

Pavement Type Definition This type of pavement is specifically defined as a nonreinforced Portland cement concrete slab placed over any number of base or subbase layers. The joints may or may not include dowel bars (as specified in the experiment design). Joint spacing ranges from 10 to 20 feet. JPCP is used throughout most of the United States, and is presently the predominant type of rigid pavement constructed in the West and Southeast. A substantial number of JPCP sections exist in many states.

Main Experimental Design Factors The following main secondary-tier factors are recommended:

- Concrete slab thickness.
- Presence of dowels at transverse joints.
- Type of base.

Two levels for concrete slab thickness are recommended. The "low" level will likely include thicknesses in the range of 7 to 9 inches (where significant fatigue damage occurs), and the "high" level will include thicknesses of 10 inches and greater (where very little fatigue damage occurs). Pavements both with and without dowels in the transverse joints will be included in the experiment. Two base types will be identified during the search for test sections (e.g., untreated granular, cement-treated granular, asphalt-treated granular).

Number of Sections Jointed plain concrete pavements are located in most areas of the United States. It is recommended that secondary-tier factorial designs be carried out in all of the 16 primary cells as shown in Figure 3 (See Section 3). Most of these sections should be found on existing in-service pavements. Total number of JPCP sections = 16 primary cells x 8 secondary cells x 2 replications = 256.

GPS Experimental Design for Jointed Reinforced Concrete Pavement--JRCP (Original Design)

Pavement Type Definition This type of pavement is specifically defined as a reinforced Portland cement concrete slab placed over any number of base or subbase layers. The joints must contain dowel bars. Joint spacing should range from 25 to 60 feet. JRCP is fairly prevalent throughout the central and eastern United States, but only very few have been constructed in the dry, warm climate of the Southwest. A substantial number of JRCP sections exist in many states.

Main Experimental Design Factors The following main secondary-tier design factors are recommended:

- Concrete slab thickness.
- Transverse joint spacing.

Since the predominant base type for JRCP is untreated granular material, it is recommended that this factor be held constant. Pavements with both shorter (25 to 30 ft) and longer (40 to 60 ft) transverse joint spacings will be included in the experiment.

Number of Sections Jointed reinforced concrete pavements are located in most areas of the United States. However, they may not be found in substantial numbers in all climatic (i.e., dry nonfreeze), subgrade soil regions or traffic levels. Thus, it is recommended that full secondary-tier factorial designs be carried out in 12 of the 16 primary cells shown in Figure 6. Total number of JRCP sections = 12 primary cells x 4 secondary cells x 2 replications = 96.

GPS Experimental Design for Continuously Reinforced Concrete Pavement -- CRCP (Original Design)

Pavement Type Definition This type of pavement is specifically defined as a continuously reinforced Portland cement concrete slab placed over any number of base or subbase layers. CRCP has been constructed extensively in a few states and to a more limited degree in many other states. A substantial number of CRCP sections exist in a few states.

Main Experimental Design Factors The main secondary-tier design factors are recommended as follows:

- Concrete slab thickness.
- Type of base.

Since the need for good foundation support is well established for CRCP and the predominant base types for CRCP are asphalt- and cement-treated granular material (or lean concrete), it is recommended that untreated bases not be considered. Specific types of base to be included will be determined during the search for test sections.

Number of Sections Continuously reinforced concrete pavements are located in several areas of the United States. However, they may not be found in substantial numbers in all climatic or subgrade soil regions or at all traffic levels. Thus, it is recommended that full secondary-tier factorial designs be carried out in 12 of the 16 primary cells as shown in Figure 7. Total number of CRCP sections = 12 primary cells x 4 secondary cells x 2 replications = 96.

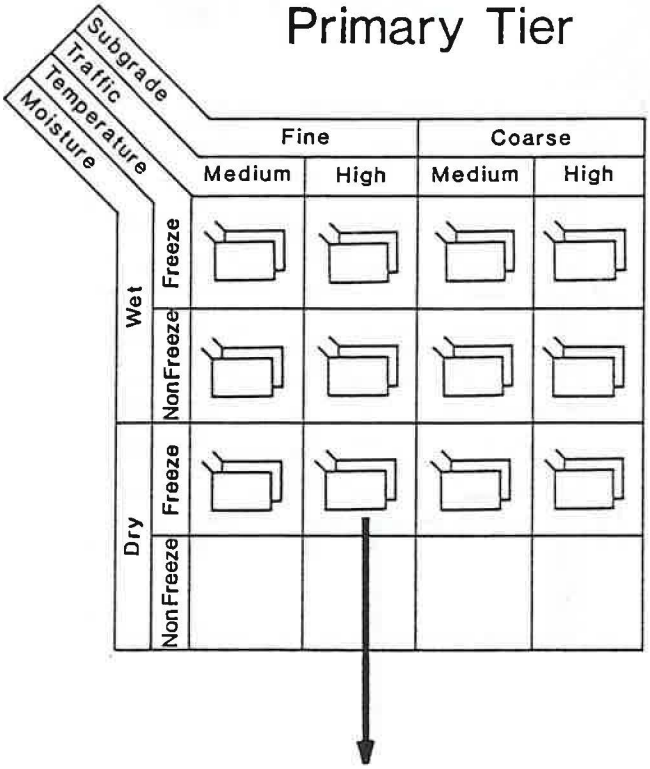
GPS Experimental Design for AC Overlay of Flexible Pavement

Pavement Type Definition This type of pavement is specifically defined as an AC overlay over the traditional type of "flexible" pavement that is utilized throughout the United States on all types of highways.

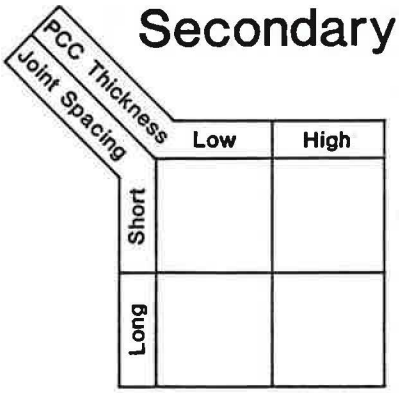
FIGURE 6. TRA 2

GPS: JRCP

Primary Tier



Secondary Tier

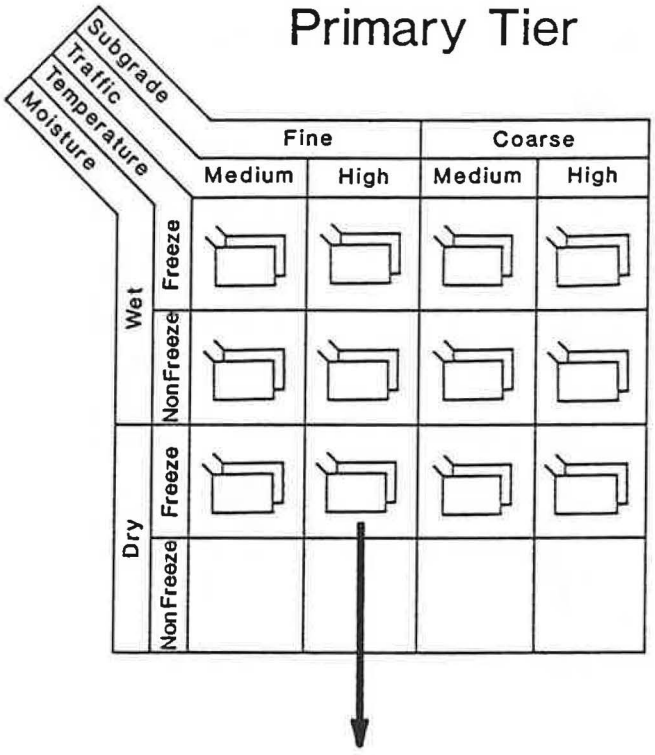


12 Primary Cells x 4 Secondary Cells x 2 Replications = 96 Total Sections

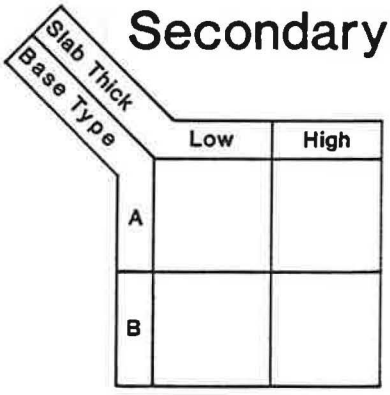
FIGURE 7. TRA 2

GPS: CRCP

Primary Tier



Secondary Tier



Primary		Secondary				Total
12 Cells	x	4 Cells	x	2 Replications	=	96 Sections

Pavements with only one overlay will be included in the initial experiment. Future monitoring of the pavements for subsequent overlays will provide data on performance of multiple overlays.

Main Experimental Design Factors The following secondary-tier main factors are recommended:

- Asphalt concrete overlay thickness.
- Asphalt concrete overlay initial stiffness.
- Structural number of the existing pavement.

The initial stiffness of the AC overlay can be estimated from the asphalt content, density and the viscosity grade or penetration of the asphalt cement using Van der Poel's or MacLeod's nomograph. The factorial stiffness levels should be "low" and "high." The total existing pavement structural number should have "low" and "high" factorial levels.

Number of Sections AC overlays of flexible pavements are located throughout the United States. There are more miles of this type of rehabilitated pavement than any other type of rehabilitated pavement. Thus, it is recommended that full secondary-tier factorial designs be carried out in all of the 16 primary cells as shown in Figure 8. Total number of sections of flexible pavement with AC overlay = 16 primary cells x 8 secondary cells x 2 replications = 256.

GPS Experimental Design for AC Overlay of Jointed Concrete Pavement

Pavement Type Definition This type of pavement is specifically defined as a jointed concrete pavement (either plain or reinforced) overlaid only once with asphalt concrete. This type of rehabilitation is utilized throughout the United States for jointed concrete pavements.

Main Experimental Design Factors

The following secondary-tier main factors are recommended:

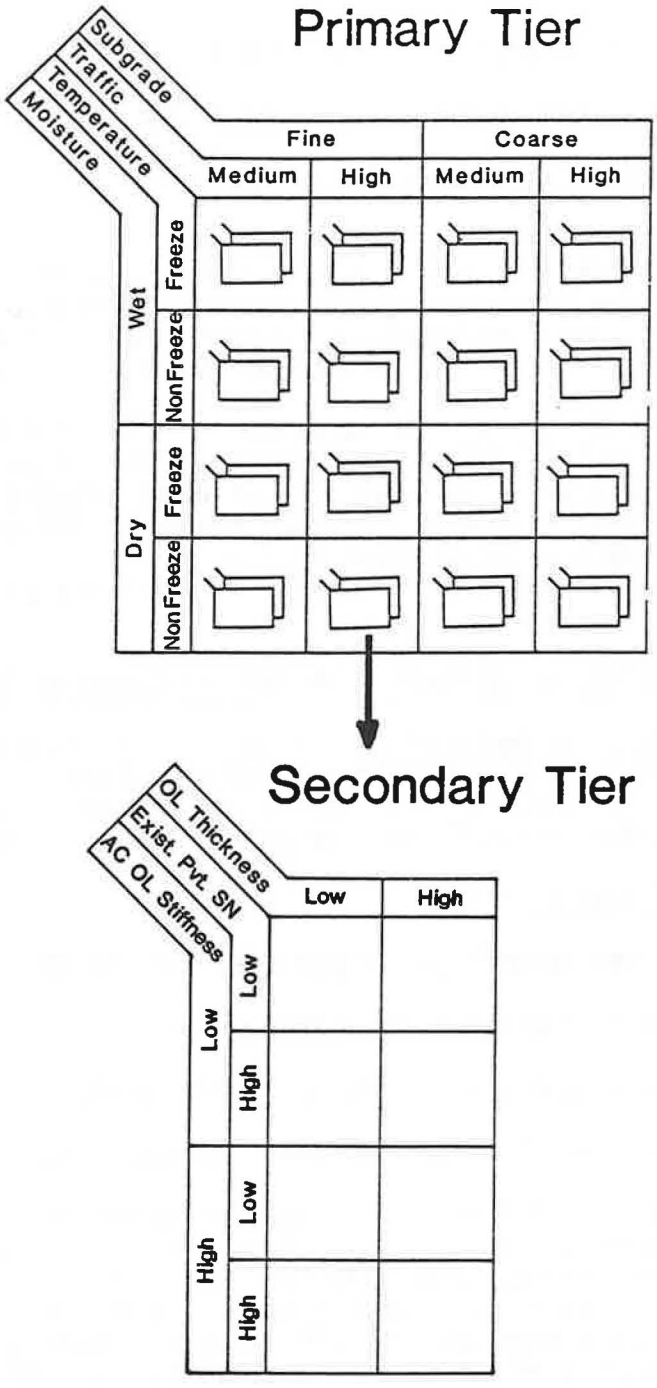
- Asphalt concrete overlay thickness.
- Asphalt concrete overlay initial stiffness.
- Type of existing jointed concrete pavement.

The initial stiffness of the AC overlay can be estimated from the asphalt content, density, and the viscosity grade or penetration of the asphalt cement using Van der Poel's or MacLeod's nomographs. The factorial stiffness levels should be "low" and "high." The existing jointed concrete pavement type can be either JPCP or JRCP. Because joint spacing varies between these two types of pavement, it is an implicit factor in the experimental design.

Number of Sections Jointed concrete pavements with AC overlays are located throughout the United States. This type of rehabilitated

FIGURE 8. TRA 2

GPS: AC WITH AC OVERLAY



16 Primary Cells x 8 Secondary Cells x 2 Replications = 256 Total Sections

pavement probably has the most mileage of any type of rehabilitation of jointed concrete pavements. Thus, it is recommended that full secondary-tier factorial designs be carried out in all 16 of the primary cells as shown in Figure 9. Total number of sections of jointed concrete pavement with AC overlay = 16 primary cells x 8 secondary cells x 2 replications - 32 not included = 224.

GPS Experimental Designs for PCC Overlays of Concrete Pavement

Pavement Type Definition This type of pavement is specifically defined as a bonded or unbonded concrete overlay placed over an existing concrete pavement (either plain jointed, reinforced jointed or continuously reinforced). This type of rehabilitation has been utilized in several locations in the United States. The experimental designs will be presented separately for bonded and unbonded overlays.

Main Experimental Design Factors for Bonded Concrete Overlays The following main secondary-tier factors are recommended:

- Bonded concrete overlay thickness.
- Type of existing concrete pavement.

All three types of conventional concrete pavements and two different thickness levels of bonded concrete overlay will be included.

Number of Sections for Bonded Concrete Overlays Bonded concrete overlays are located in several states. These overlays have generally been constructed using currently recommended techniques within the past 10 years. It is recommended that secondary- tier factorial designs be carried out in 8 of the primary cells as shown in Figure 10. A number of these sections exist on in-service highways, but several may need to be constructed. Total number of bonded concrete overlay sections = 8 primary cells x 6 secondary cells x 2 replications - 16 JRCP and CRCP sections not included in the dry nonfreeze zone = 80.

Main Experimental Design Factors for Unbonded Concrete Overlays The following secondary-tier main factors are recommended:

- Unbonded concrete overlay thickness.
- Type of existing concrete pavement.

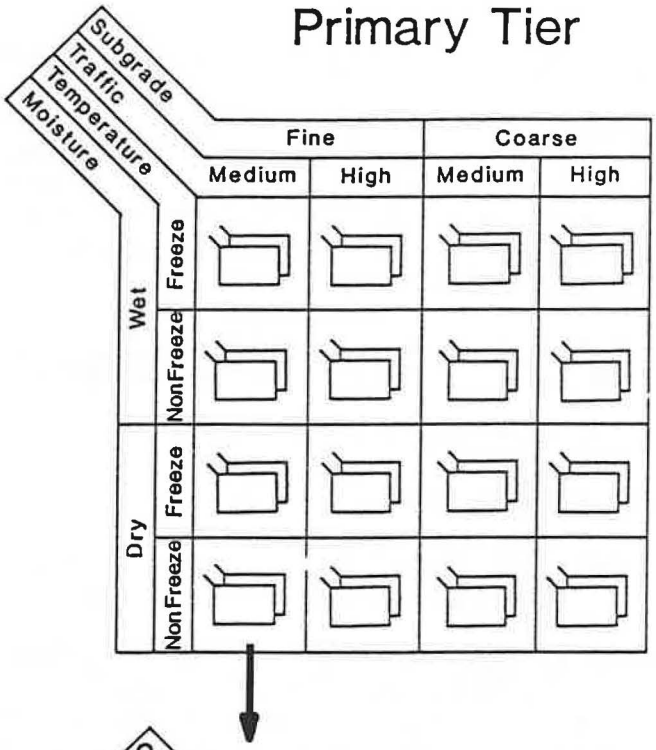
All three types of conventional concrete pavements are included. Two different thickness levels of unbonded overlay will be included.

Number of Sections for Unbonded Concrete Overlays Unbonded concrete overlays are located in several states. These existing overlays have been constructed for many years. Only fine-grained subgrade is included because the type of subgrade is not expected to significantly affect performance due to the thick pavement involved. It is recommended that secondary-tier factorial designs be carried out in 4 of the primary cells as shown in Figure 11. Some of these sections may need to be constructed.

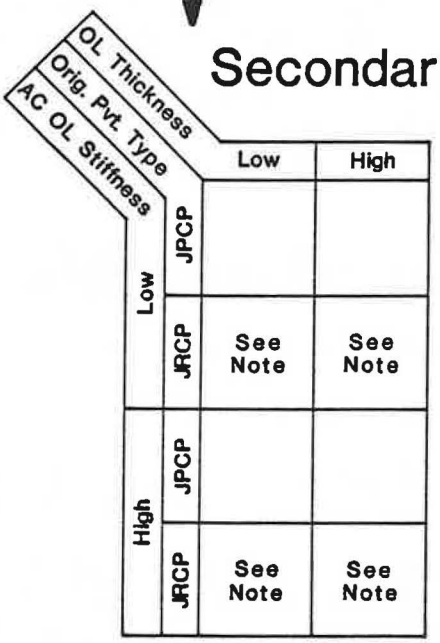
FIGURE 9. TRA 2

GPS: AC OVERLAY OF JCP

Primary Tier



Secondary Tier



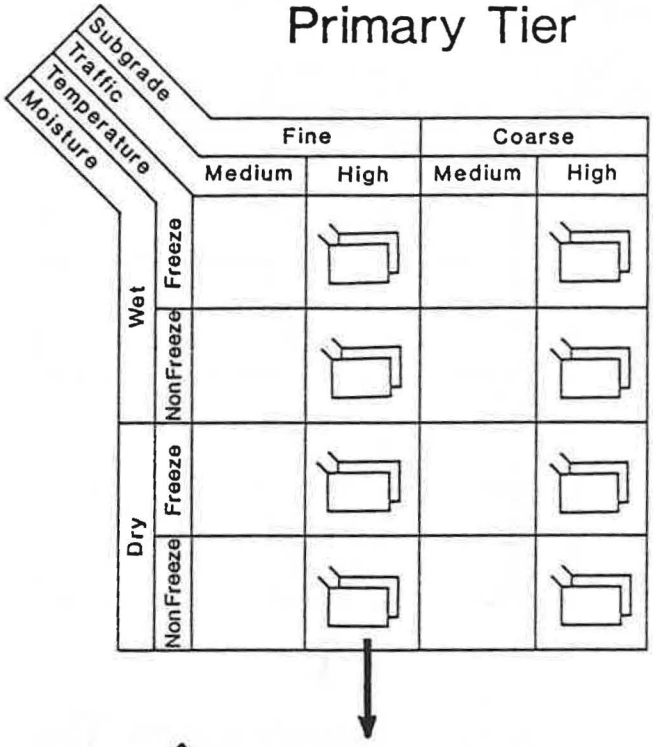
NOTE: JRCP not included in Dry–Nonfreeze Zone.

16 Primary Cells x 8 Secondary Cells x 2 Replications − 32 JRCP not Included = 224 Total Sections

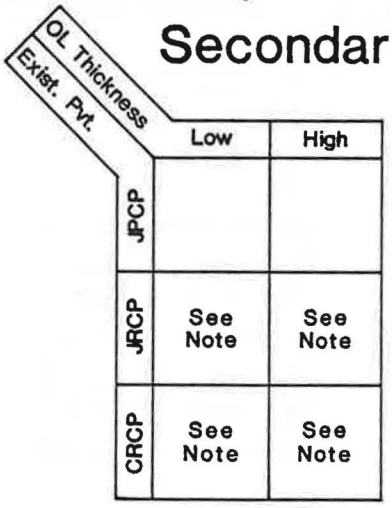
FIGURE 10. TRA 2

GPS: BONDED PCC OVERLAY OF JCP & CRCP

Primary Tier



Secondary Tier



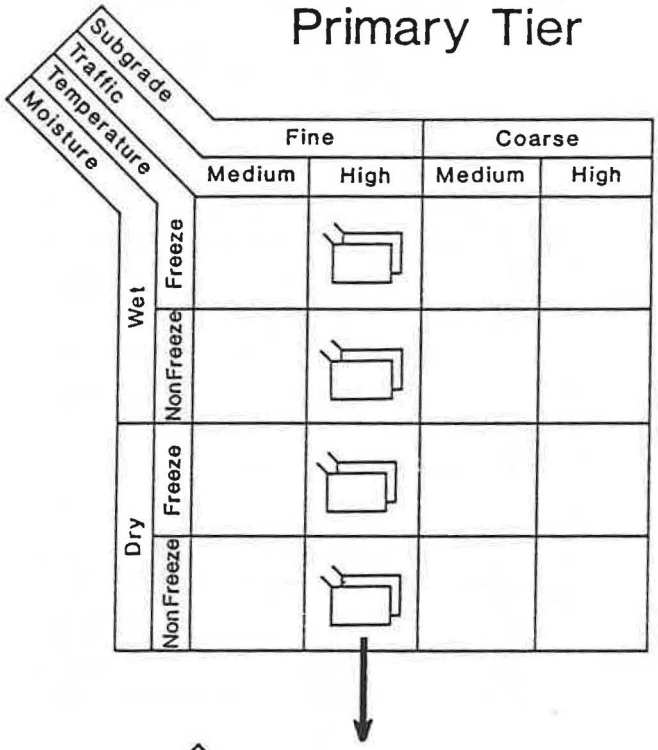
NOTE: JRCP and CRCP not included in Dry-Nonfreeze Zone.

8 Primary Cells x 6 Secondary Cells x 2 Replications − 16 JRCP and CRCP not Included = 80 Total Sections

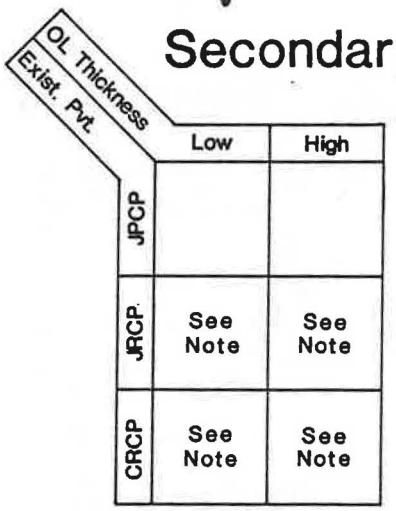
FIGURE 11. TRA 2

GPS: UNBONDED JCP OVERLAY OF JCP & CRCP

Primary Tier



Secondary Tier



NOTE: JRCP & CRCP not included in Dry-Nonfreeze Zone.

4 Primary Cells x 6 Secondary Cells x 2 Replications − 8 JRCP and CRCP not included = 40 Total Sections

Total number of unbonded concrete overlay sections = (4 primary cells x 6 secondary cells x 2 replications) - (8 JRCP and CRCP sections not included in dry nonfreeze zone) = 40.

EXPERIMENT DESIGN FOR SPECIFIC PAVEMENT STUDIES

Tables 11 and 12 identify the general topics selected for intensive experiments for rigid and flexible pavements, respectively. They also show the number of test sections and "locations" tentatively assigned to each experiment. Because of the multiplicity of test sections in SPS at one location, material testing requirements and traffic measurements are reduced compared to GPS, where each test section will generally represent a location.

It may be noted that many primary tier cells are not to be filled. This generally results from applied judgement after much committee discussion to arrive at appropriate compromises between numbers of topics to be studied versus scope of the individual experiments.

The emphasis was placed on selecting cells that were believed to be most critical for the effects to be studied (i.e., high traffic and fine-grained subgrade for "Restoration of JCP"). Some of the topics, such as "Environmental Distress for PCC Pavements", were considered to require only eight cells as the "traffic factor" did not apply. The same experiment for flexible pavements was considered to need eighteen primary cells to divide fine-grained subgrade soils into those that are expansive and those that are frost susceptible, and to add "freeze-thaw cycling" to the temperature zones. Consideration may be given later to including JRCP or CRCP in dry non-freeze areas if there is sufficient State interest to construct these pavement sections.

The totals at the bottom of Table 11 indicate tentative totals of 862 test sections at 116 locations for the eleven rigid pavement studies proposed. Table 12 indicates for flexible studies a tentative total of nine experiments, involving 770 test sections at 116 locations. The combined totals for SPS are twenty experiments, involving 1632 test sections at 232 locations.

Tentative factorial experiment designs and details appear subsequently for each of the general SPS topics identified in Tables 10 and 11. It is important to remember that these experiment designs are quite tentative. In some cases, they may represent good experiment designs that will be implemented as is after further study, but in many others changes should be expected after further study. In the case of "new concepts" for both pavement types, no experiment per se was developed, but 50 test sections for each were approved by the advisory committee as "place holders" for studying such concepts as they become apparent.

It should be remembered that the regional LTPP contractors will also be responsible for implementation and monitoring of SPS studies in support of other SHRP TRA's. Two maintenance studies have already been incorporated to support the field study objectives for TRA 3. TRA 4 has tentatively identified a need for "field trials" on: 1) up to six test sections for studies of concrete durability and 2) 28 test sections for

TABLE 11
TRA 2 NUMBERS OF RIGID PAVEMENT TEST SECTIONS SELECTED FOR SPS EXPERIMENT DESIGN.

Description of Study Project	Primary Tier Cells	Secondary Tier Cells	Replications Per Cells	Total Sections	Total Locations
Effects of Preventive Maint. on JPCP	8	12	2	192	24
Load Equivalence Factors	8	12	2	168*	8
Restoration of JCP	4	32	2	224*	28
Effects of Subsurface Drainage	6	8	2	96	12
Environmental Distress	8	2	2	28*	14
New Concepts for Rigid Pavements	?	?	2	50	4
High Strength PCC	2	4	2	16	4
CRCP Overlays	2	4	2	16	8
Effects of Using Non-Erodable, High Strength Subbases	2	6	2	24	4
Effects of Retrofit Shoulders on JCP	3	4	2	24	6
Effects of Shoulder Design on Concrete Pavement Performance	2	6	2	24	4
			Totals	862	116

* JRCP and CRCP sections not included in Dry Nonfreeze zone.

TABLE 12
TRA 2 NUMBERS OF FLEXIBLE PAVEMENT TEST SECTIONS SELECTED FOR SPS EXPERIMENT DESIGN.

Description of Study Project	Primary Tier Cells	Secondary Tier Cells	Replications Per Cells	Total * Sections	Total Locations
Pretreated JCP with AC Overlay	4	12	2	84	14
Subdrainage	4	4	2	32	8
Hot Recycling	4	5	2	40	4
Cold Recycling	2	8	2	32	2
Preventive Maintenance	8	15	2	240	24
New Concepts for Flexible Pavements	?	?	2	50	4
Low-Volume Roads	8	4	2	64	16
Load Equivalence Factors	8	12	2	192	8
Environmental Distress	18	1	2	36	36
			Totals	770	116

* JRCP and CRCP sections not included in Dry Nonfreeze zone.

studies of the mechanical behavior of concrete. While the needs for test sections for TRA 1 are not yet apparent and will depend on coordinated sharing of projects with LTPP, it is expected that their needs will be substantial in terms of numbers of sections and additional materials sampling and testing. Inability to clearly define these support needs for other TRA's is not critical to LTPP planning at this stage, as these needs will be funded by the TRA's needing support. Additional staff, equipment, instrumentation, etc. may be added as required.

SPS Experimental Design for Effects of Preventive Maintenance on Concrete Pavement Performance

Research Problem Statement The effects of preventive maintenance on pavement performance has long been a controversial topic. Very little valid field performance data are available to assist in determining the actual effects over a variety of conditions. Existing pavement design procedures do not include procedures that allow the designer to directly consider the effect of different levels of preventive maintenance on performance.

Several different preventive maintenance techniques are available that are expected to increase pavement life. The determination of the effects of these techniques on extending pavement life could be extremely valuable for improving the overall cost-effectiveness of pavement design. Therefore, knowledge of these effects, perhaps transformed to predictive models, is an urgent need.

This experiment has been developed in coordination with the contractor for TRA 3, Maintenance Cost-Effectiveness, to support their needs for field studies. These studies should identify general data needs for evaluating other maintenance treatments, and to formalize an approach for such future evaluations.

Main Experimental Design Factors

1. All climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze)
2. Traffic loading rate (medium, high)
3. Preventive maintenance treatments (resealing of all transverse and longitudinal joints, subsealing)
4. Condition of existing concrete pavement (poor, fair, good)

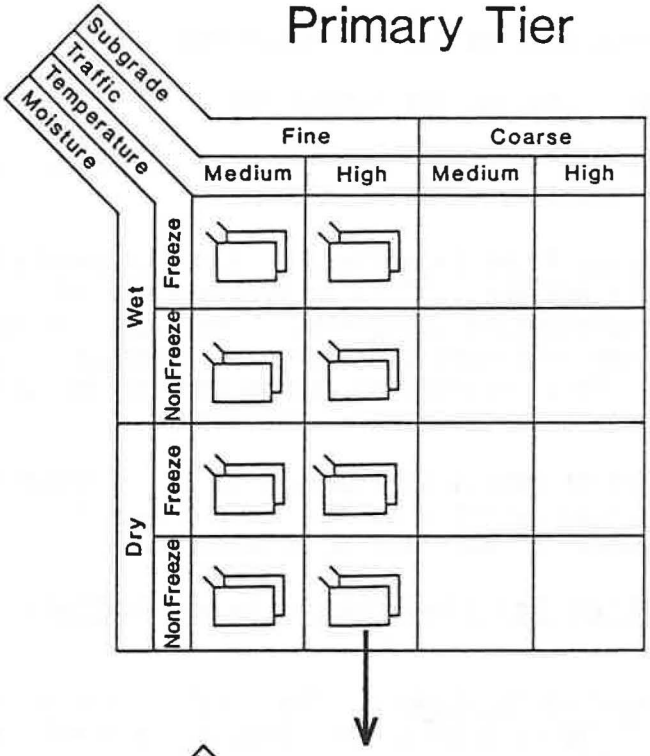
The experimental design is illustrated in Figure 12. Main factors to be held constant include subgrade soil type (fine grained), slab thickness and pavement type (JPCP).

Number of Sections All test sections will be selected along in-service highways that are in good to poor condition. For example, at one test site a series of preventive maintenance test sections could be constructed along an existing JPCP highway that has the desired traffic level,

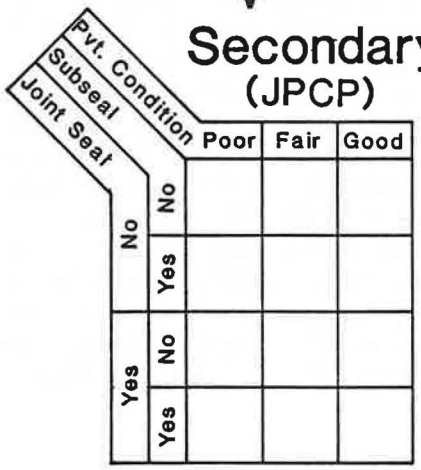
FIGURE 12. TRA 2

SPS: PCC PREVENTIVE MAINTENANCE

Primary Tier



Secondary Tier (JPCP)



8 Primary Cells x 12 Secondary Cells x 2 Replications = 192 Total Sections

subgrade soil and climate and the following characteristics specified in the first column of the secondary tier for a "poor" pavement condition:

Section 1: No joint sealing and no subsealing

Section 2: No joint sealing but subsealing

Section 3: Joint sealing but no subsealing

Section 4: Joint sealing and subsealing

The total number of experimental sections = 8 primary cells x 12 secondary cells x 2 replications = 196.

Major Products from Experiment A major product will be measured performance data and the ability to evaluate the effects of applying different preventive maintenance treatments. These performance data should show the benefits of the different preventive maintenance treatments on extending pavement life. This information can be used to implement more cost-effective maintenance and rehabilitation strategies.

Another important result is expected to be information and experience that may be utilized by TRA 3 to develop procedures for future use in evaluating the effectiveness of maintenance treatments.

SPS Experimental Design for Load Equivalence Factors for Concrete Pavements

Research Problem Statement The original and primary intention of the AASHO Road Test was to develop data that would permit the allocation of costs to different vehicular elements in a traffic stream. The objective was achieved by subjecting pavement sections to pure (i.e., unmixed) traffic, a feat which cannot be duplicated on in-service pavements. If, however, typical traffic streams can be split into three categories, (passenger vehicles, medium trucks, and heavy traffic) and each of them can be weighed at a weigh station, and if several strengths of pavement can be placed in sequence along the lanes travelled by the vehicles, an iterative analysis of the data collected may produce useful approximate load equivalence factors. Alternatively, mechanistic-empirical models could be calibrated from performance data and utilized to develop load equivalence factors. These new factors can show the effects of different climates and subgrade soils, and can contribute to evaluation of the AASHO Road Test load equivalence factors.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze)

2. Subgrade type (fine grained, coarse grained)

3. Type of pavement (JPCP, JRCP)

4. Slab thickness (low, high)

5. Type of traffic (At each site, traffic must be split into three streams: passenger cars, medium trucks, and heavy trucks)

The experimental design layout is shown in Figure 13.

Number of Sections All test sections will be constructed at sites where weigh-in-motion and automatic vehicle classification equipment are maintained. Each site will be along a highway with the desired traffic level, and identical sections are to be constructed in random order along three parallel roadways or lanes. The traffic stream will be sensed and split into three different types of traffic, each directed to one of the parallel roadways or lanes.

Total number of experimental sections = 8 primary tier cells x 12 secondary tier cells x 2 replications - 24 JRCP sections not included in dry nonfreeze zone = 168.

This study design is tentative and needs further investigation.

Major Products from Experiment The major products of this experiment will be data and calibrated mechanistic-empirical models of the performance (joint deterioration, faulting, cracking, pumping, roughness, present serviceability index) that show the relative difference in damage caused by the different vehicle types. This data set and predictive models can be used in cost allocation studies.

SPS Experimental Design for Restoration of Jointed Concrete Pavement

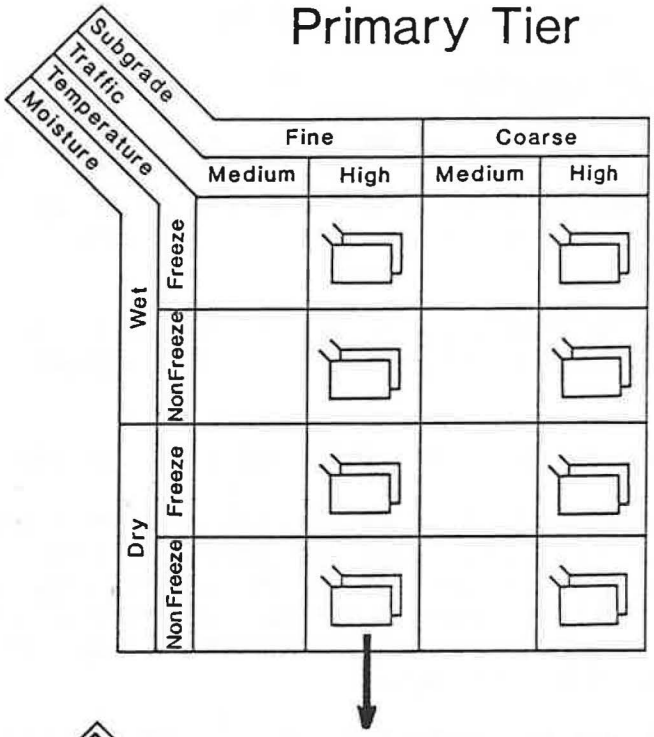
Research Problem Statement Various rehabilitation techniques (excluding overlays and recycling) have been applied to jointed concrete pavements to "restore" their condition and extend their service life for a number of years. These techniques normally include several of the following for any given project: diamond grinding, subsealing, full-depth repair, partial-depth spall repair, restoration of load transfer, resealing of transverse joints, resealing of longitudinal lane/shoulder joints, pressure relief joints, retrofit tied concrete shoulders and longitudinal subdrains. The performance of such "restored" pavements has not been formally monitored. Analytical design procedures are not available for most of the techniques. Many questions exist as to the timing of restoration and the appropriate designs of techniques for given traffic levels, pavement conditions and climates.

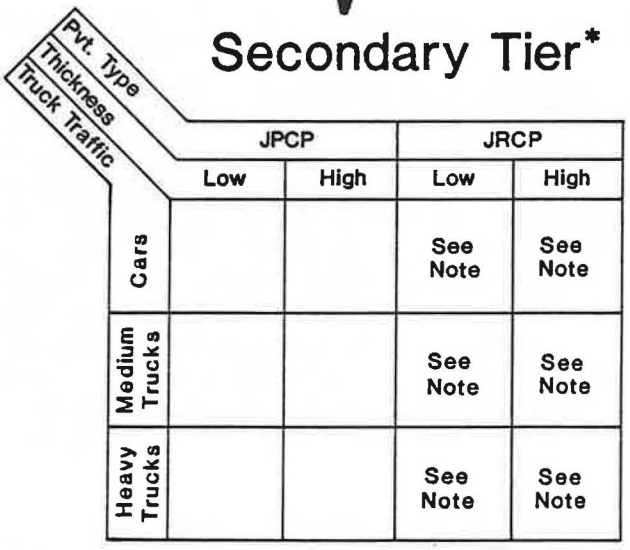
This type of rehabilitation has very definite economic advantages if it lasts for a substantial time period. Thus, a knowledge of the effects of different techniques on performance and the improvement of design procedures is an area of urgently needed research.

Main Experimental Design Factors Each pavement section included in this experiment will be rehabilitated as needed with full-depth repairs, partial-depth spall repairs, resealing of joints, diamond grinding, etc; but this study is primarily limited to the contributory effects of sub-

FIGURE 13. TRA 2

SPS: PCC LOAD EQUIVALENCE FACTORS





NOTE: JRCP not included in Dry–Nonfreeze Zone.

*per site
- 3 not adjacent lanes one direction
- 4 pvt. sections/lane

8 Primary Cells x 12 Secondary Cells x 2 Replications − 24 JRCP not Included = 168 Total Sections

draining and subsealing as indicated by the following experimental design plan:

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).

2. Type of existing pavement (JPCP, JRCP).

3. Thickness of existing slab (low, high).

4. Condition of existing pavement (fair, good).

5. Placement of subdrainage (no, yes).

6. Subsealing to restore full support (no, yes).

The experiment design is illustrated in Figure 14. Main factors to be held constant include traffic level (high), subgrade soil type (fine grained), and no "D" cracking/reactive aggregate problems.

Number of Sections All test sections will be constructed along in-service highways. For example, at one test site a series of test sections would be constructed (in random sequence) along an existing JRCP highway that has the desired slab thickness, condition, traffic level, subgrade soil and climate:

Section 1: No subsealing and no subdrainage.

Section 2: Subdrainage but no subsealing.

Section 3: Subsealing but no subdrainage.

Section 4: Subsealing and subdrainage.

Total number of experimental sections = 4 primary cells x 32 secondary tier cells x 2 replications - 32 JRCP sections not included in dry nonfreeze zone = 224.

Major Products from Experiment The major products will be information to improve restoration techniques and timing and the development of empirical-mechanistic predictive models of the performance (faulting, joint deterioration, cracking, pumping, roughness, present serviceability index) of jointed concrete restoration. The performance data and models can be used to improve design procedures.

SPS Experimental Design for Effects of Subsurface Drainage on Concrete Pavement Performance

Research Problem Statement Many research studies of rigid pavement performance have identified poor subsurface drainage as a major factor in premature failures. Current pavement design procedures all mention that the pavement design must consider the subdrainage of the pavement. Despite all of these findings and recommendations, there is still much controversy about how to design a well drained rigid pavement section. Subdrainage design procedures are available, but are not widely accepted and

FIGURE 14. TRA 2

SPS: PCC RESTORED JCP

Primary Tier

Subgrade Moisture	Traffic Temperature	Fine		Coarse	
		Medium	High	Medium	High
Wet	Freeze				
	NonFreeze				
Dry	Freeze				
	NonFreeze				

Secondary Tier

Pvt. Type / PCC Thickness / Condition / Subdrainage / Subsealing		JPCP				JRCP*			
		Low		High		Low		High	
		F	G	F	G	F	G	F	G
No	No								
	Yes								
Yes	No								
	Yes								

*NOTE: JRCP not included in Dry–Nonfreeze Zone.

4 Primary Cells x 32 Secondary Cells x 2 Replications − 32 JRCP not Included = 224 Total Sections

have not been verified from performance of in-service pavement sections. Many questions remain as to the best designs for given traffic levels, pavement conditions and climates. Since the improvement of subdrainage would have great potential for extending the life of rigid pavements, the improvement of subdrainage design procedures is an area of urgently needed research.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).

2. Subdrainage designs (typical "bathtub" design, meaning poor subdrainage, and three different free-draining subdrainage systems).

3. Subgrade type (fine grained and coarse grained).

4. Type of existing concrete pavement (JPCP, JRCP).

The experiment design is shown in Figure 15. The main factor to be held constant is traffic rate (high).

Number of Sections All test sections will be constructed along selected highways. For example, at one test site a series of test sections would be constructed (in random order) along a highway that has the desired traffic level, subgrade soil and climate:

JPCP:

Section 1: Typical "bathtub" type design with poor subdrainage.

Section 2: Alternate free subdrainage design No. 1.

Section 3: Alternate free subdrainage design No. 2.

Section 4: Alternate free subdrainage design No. 3.

JRCP:

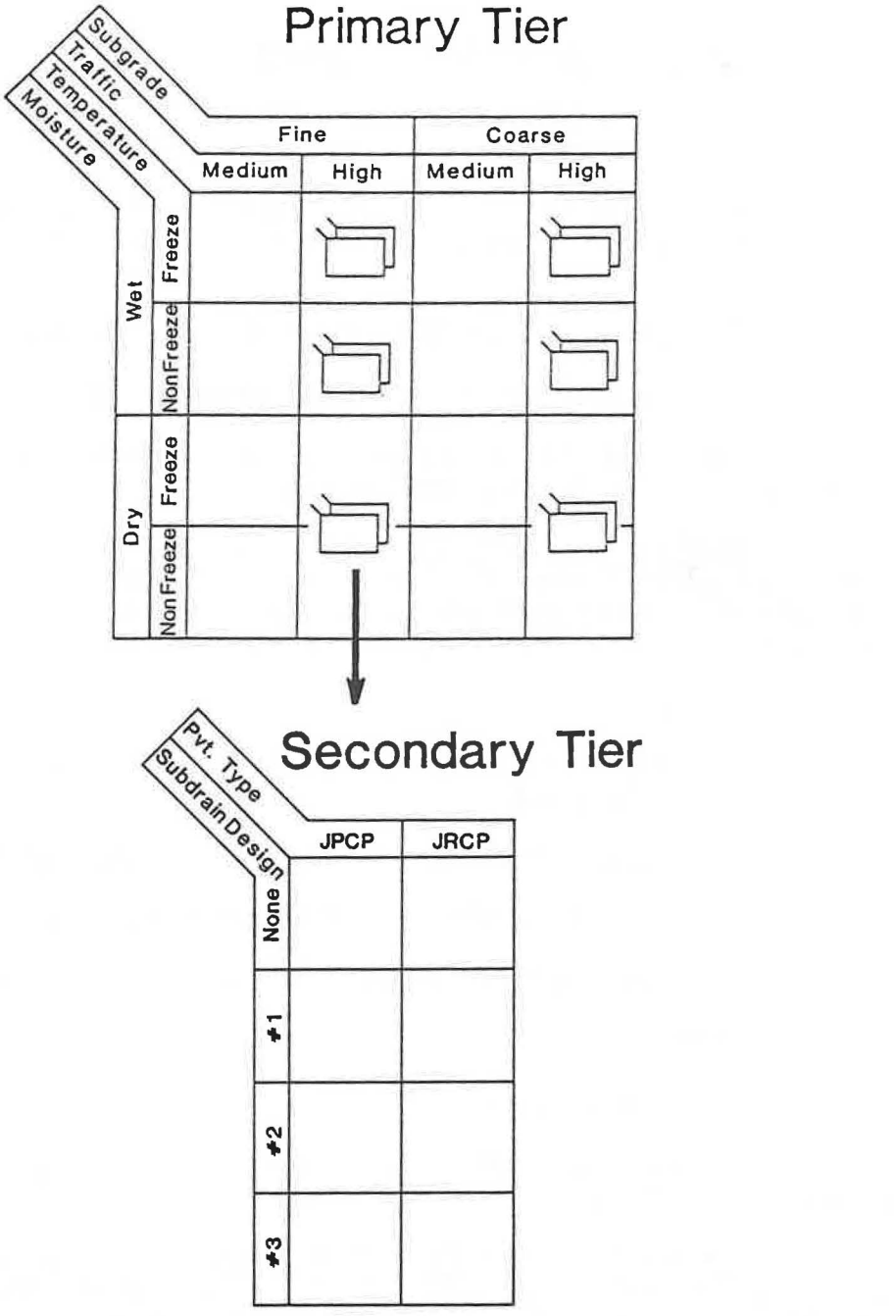
Repeat above sections.

Total number of experimental sections = 6 primary cells x 8 secondary cells x 2 replications = 96.

Major Products from Experiment The major product will be measured performance data and predictive models of the performance of jointed concrete pavements that are designed both with and without free-draining systems. These performance data and models will show the beneficial influence of subdrainage systems on delaying the development of distress and roughness. The performance data and models can be used to improve subdrainage design procedures.

FIGURE 15. TRA 2

SPS: PCC SUBSURFACE DRAINAGE



6 Primary Cells x 8 Secondary Cells x 2 Replications = 96 Total Sections

SPS Experimental Design for Concrete Pavement Environmental Distress

Research Problem Statement There is much controversy over the relative effects of environment and traffic loading on pavement deterioration. There exists very little actual pavement performance data from which to either develop or verify predictive models to aid in the analysis of this complex problem. This experiment will address the problem of determining the amount of deterioration that normally takes place for pavements that experience negligible accumulations of ESALs. (This occurs, for example, on parkways where trucks are banned but automobile traffic is allowed.) This study is comparable to the Loop 1 Experiment on the AASHO Road Test and is designed to complement the national General Pavement Studies and provide objective data on the effect of climatic and subgrade soil influences on flexible pavement performance in the absence of significant traffic. The climatic zones are defined by available moisture (wet and dry) and temperature (freeze, and no freeze).

One complicating consideration is that there may be a difference in performance when the pavement is entirely untrafficked and when it is trafficked by automobiles. This is particularly significant for asphalt-surfaced pavements, but is not believed to be significant for concrete-surfaced pavements. Thus, it may be possible to utilize sections for the rigid pavement experiment that do not have any traffic, as long as normal joint sealing maintenance is accomplished. However, it would be better if all sections had some automobile traffic to eliminate this consideration from the experiment.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).
2. Subgrade type (fine grained, coarse grained).
3. Type of pavement (JPCP, JRCP).

The experimental design layout is shown in Figure 16. Main factors to be held constant in each cell of the experiment include heavy truck traffic level (which must be negligible) and pavement design, which would be determined using standard sections and some average traffic conditions. (The pavement will not be extra thin just for automobiles.)

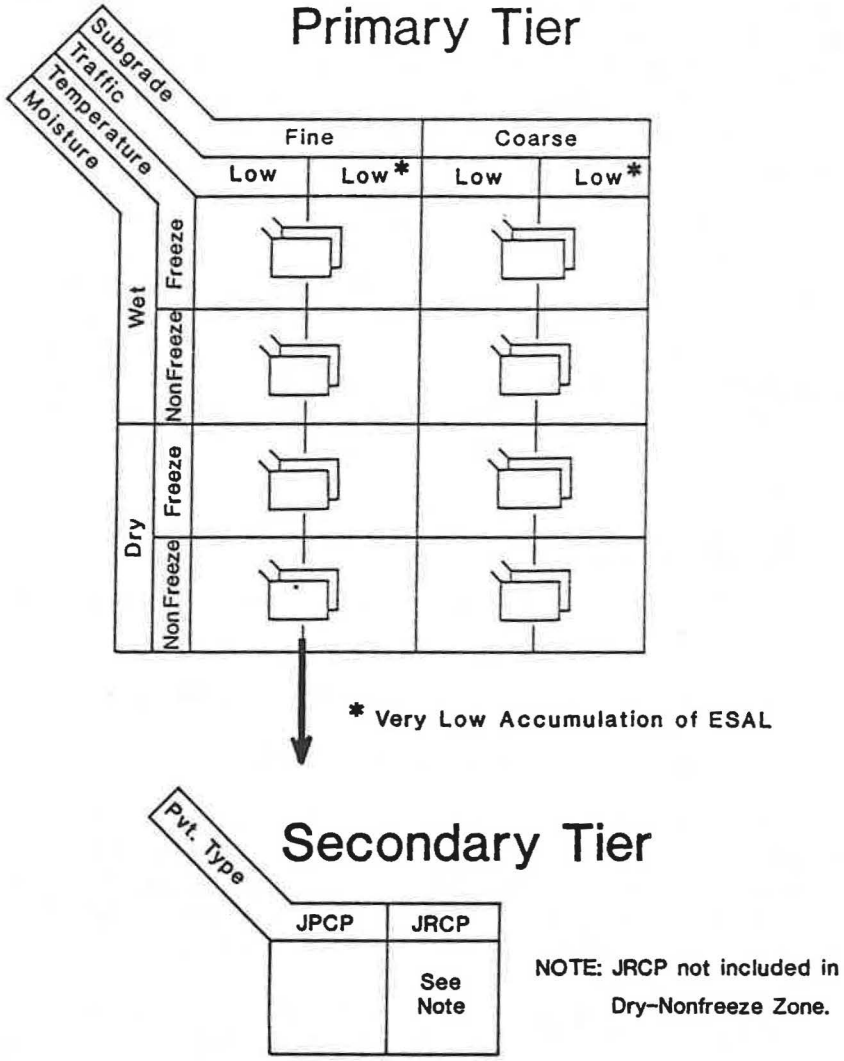
Number of Sections A few of the sections may be found in service; however, it is expected that a large number of the sections will need to be constructed specially to fit into the experiment design.

Total number of experimental sections = 8 primary tier cells x 2 secondary tier cells x 2 replications - 4 JRCP sections not included in dry nonfreeze zone = 28. This study design is tentative and needs further investigation.

Major Products from Experiment The major products will be predictive models of the performance (joint deterioration, faulting, cracking, pumping, roughness, present serviceability index). The environmental

FIGURE 16. TRA 2

SPS: PCC ENVIRONMENTAL DISTRESS



8 Primary Cells	x	2 Secondary Cells	x	2 Replications	-	4 JRCP not Included	=	28 Total Sections

performance data and models can be used along with other models where load is included (in the GPS experiments) and in various analyses where determining the relative effect of environment and traffic loadings is needed (e.g., cost allocation).

SPS Experimental Design for New Concepts for Rigid Pavements

Research Problem Statement There may be several recommendations for new concepts in rigid pavement design, rehabilitation, construction, or materials. There are no specific recommendations provided here as these will be sought out from the pavement community. It is considered an essential role of the Special Pavement Studies (SPS) to investigate new ideas by monitoring their performance and determining their life-cycle costs.

Main Experimental Design Factors

1. Climatic zones (at least two distinct zones).
2. Traffic rate (high).
3. Each innovative technique will have two replications.

The main factors to be held constant in all sections are the subgrade soil type (fine grained) and the traffic rate (high).

Number of Sections All test sections will be constructed along in-service highways. A series of test sections will be placed in random order along a highway with the desired levels of traffic and subgrade soil. A total of 50 experimental sections has been allocated to this experiment.

Major Products from Experiment The major products will be objective evaluations of new concepts for the design, rehabilitation, construction, and materials for rigid pavements, and sufficient data on each of the promising concepts to permit a preliminary calibration of mechanistic-empirical methods of analysis and design to be applied to each technique.

SPS Experimental Design for Effects of High-Strength PCC on Concrete Pavement Performance

Research Problem Statement The strength of the PCC slab is theoretically a very important factor in designing the thickness of the slab to resist fatigue cracking. All pavement design procedures show that an increased concrete strength will result in a decrease in required thickness for a given traffic level. Some field tests in Great Britain have also shown that increased pavement life was obtained with concrete slabs having higher strength concrete. Thus, it may be more economical to increase the concrete strength than it is to increase the slab thickness in certain design situations. There exists a need to determine the overall effects on pavement performance of an increase in concrete slab strength for use in different design options.

Main Experimental Design Factors

1. Climatic zones (wet and dry).

2. Concrete strength levels (normal, high).

3. Type of existing concrete pavement (JPCP, JRCP).

The experimental design layout is shown in Figure 17. Main factors to be held constant include subgrade soil type (fine grained), slab thickness and traffic rate (high).

Number of Sections All test sections will be constructed along selected highways. For example, at a given site a series of test sections would be constructed along a highway, randomly sequenced, that has the desired traffic level, subgrade soil and climate:

JPCP:
Section 1: Normal-strength concrete.
Section 2: High-strength concrete.

JRCP:
Repeat above sections.

Total number of experimental sections = 2 primary tier cells x 4 secondary tier cells x 2 replications = 16.

The major products will be measured performance data and predictive models of the performance of jointed concrete pavements that are designed with different levels of concrete slab strength. The performance data and predictive models will show the benefits of using increased concrete strength on the development of distress and roughness. The performance data and models can be used to improve pavement design.

SPS Experimental Design for Performance of CRCP Overlays

Research Problem Statement Several CRCP overlays have been placed over deteriorated rigid and flexible pavements in the United States. Their performance has been mixed due to a variety of problems related to construction deficiencies, poor joint load transfer in the existing pavement, etc. Those that have performed well have indicated the potential of CRCP overlays and that further research is definitely needed. Since an increase in structural capacity of existing pavements represents a vital need as traffic loadings continue to increase, the improved design of CRCP overlays is an area of urgently needed research.

Main Experimental Design Factors

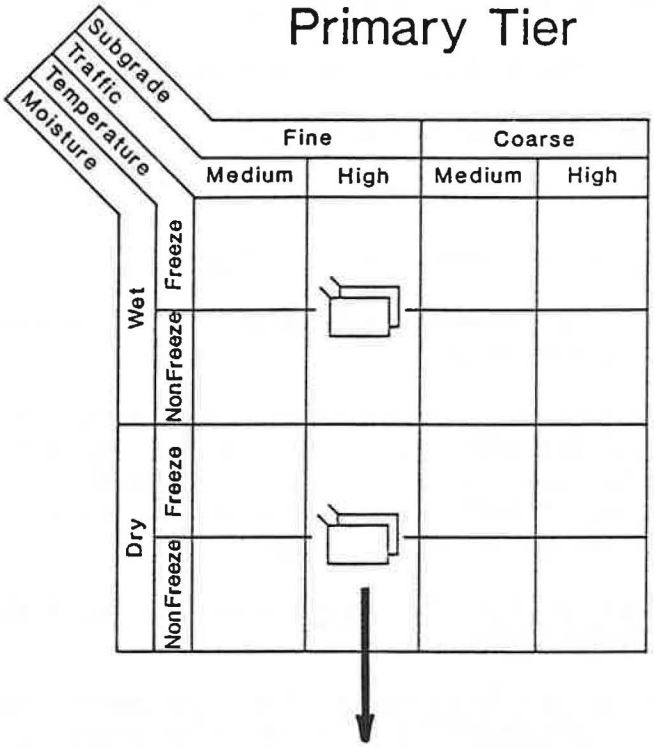
1. Climatic zones (wet, dry).

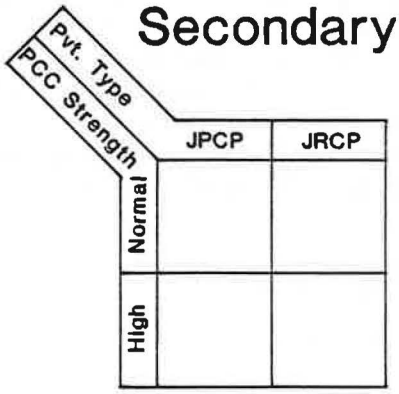
2. Thickness of CRCP overlay (low, high).

3. Type of existing concrete pavement (JCP, CRCP).

FIGURE 17. TRA 2

SPS: HIGH STRENGTH PCC





2 Primary Cells x 4 Secondary Cells x 2 Replications = 16 Total Sections

The experimental design layout is shown in Figure 18. Main factors to be held constant include subgrade soil type (fine grained) and traffic rate (high).

Number of Sections All test sections will be constructed along in-service highways. For example, at a given site a series of test sections would be constructed along a highway (randomly sequenced) that has the desired traffic level, subgrade soil and climate:

Section 1: Jointed concrete with thin CRCP overlay.

Section 2: Jointed concrete with thick CRCP overlay.

Section 3: CRCP with thin CRCP overlay.

Section 4: CRCP with thick CRCP overlay.

Total number of experimental sections = 2 primary cells x 4 secondary cells x 2 replications = 16.

Major Products from Experiment The major products will be measured performance data and predictive models of the performance of CRCP overlays. The performance data and prediction models will be used to compare the performance of CRCP to conventional hot mix AC overlays, and to improve procedures for design of CRCP overlays.

SPS Experimental Design for Effects of Non-Erodable, High-Strength Bases on Concrete Pavement Performance

Research Problem Statement Rigid pavements frequently exhibit a loss of support with subsequent faulting and slab cracking. The forces of water under pressure caused by heavy truck loads result in deterioration or erosion of practically all types of bases in common use. Some pavement design procedures show that to design for this loss of support requires either a much thicker slab or a reduced life, which results in much higher life-cycle costs. There exists a critical need to determine if there is a base type that will not result in a loss of support from erosion, and will also not cause any type of other serious deterioration. Since a reduction in loss of support has great potential for providing more cost-effective designs overall and for extending the lives of rigid pavements, this is an area of urgently needed research.

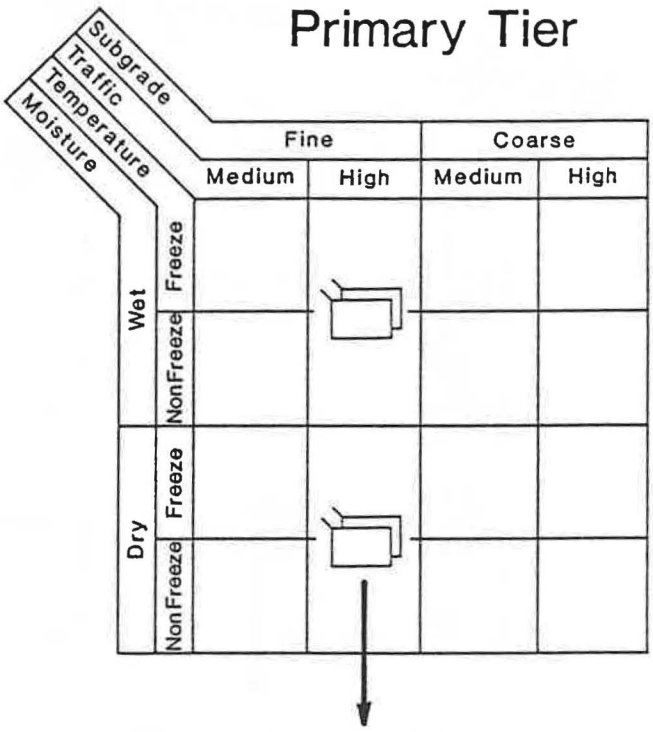
Main Experimental Design Factors

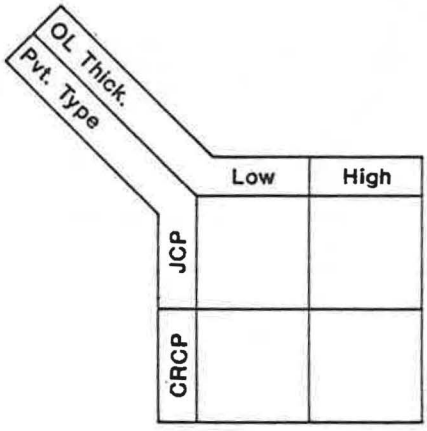
1. Climatic zones (wet, dry).
2. Base course designs (special AC hot mix design, lean PCC with two cement factors).
3. Type of existing concrete pavement (JPCP, CRCP).

The experimental design layout is shown in Figure 19. Main factors to be held constant include subgrade soil type (fine grained), slab thickness, and traffic rate (high).

FIGURE 18. TRA 2

SPS: CRCP OVERLAYS



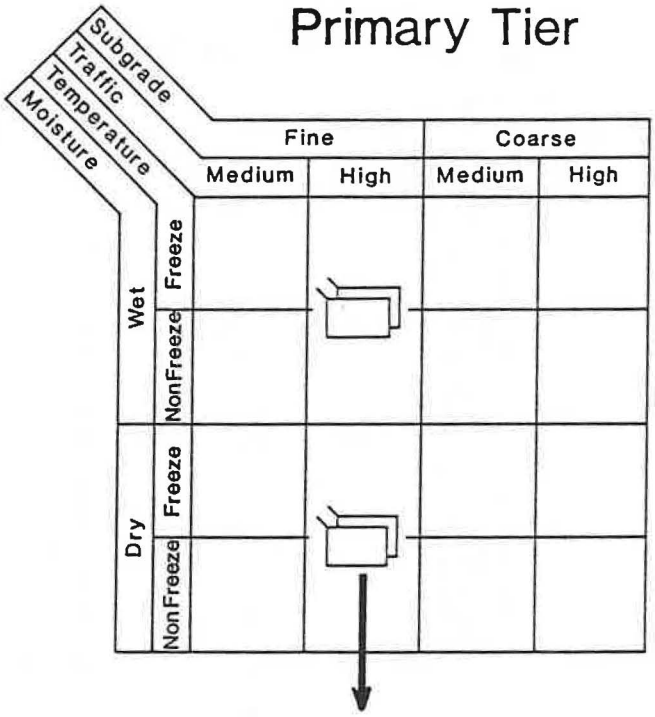


Primary Cells		Secondary Cells		Replications	=	Total Sections
2	x	4	x	2	=	16

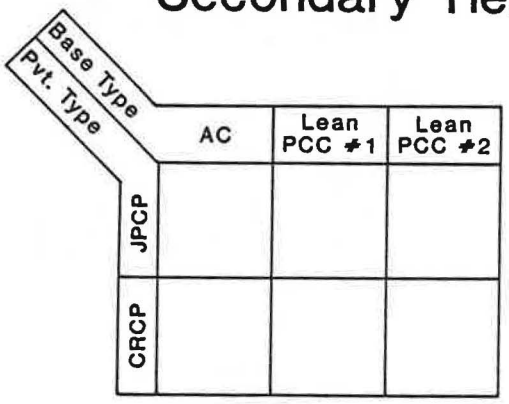
FIGURE 19. TRA 2

SPS: PCC WITH NON-ERODABLE HIGH-STRENGTH BASES

Primary Tier



Secondary Tier



Primary Cells		Secondary Cells		Replications		Total Sections
2	x	6	x	2	=	24

Number of Sections All test sections will be constructed along selected highways. For example, at a given site a series of test sections would be constructed along an existing highway under reconstruction (randomly sequenced) that has the desired traffic rate, subgrade soil, and climate:

JPCP:

Section 1: special AC hot mix design base.

Section 2: Lean PCC with lower cement factor.

Section 3: Lean PCC with higher cement factor.

JRCP:

Repeat above sections.

Total number of experimental sections = 2 primary cells x 6 secondary cells x 2 replications = 24.

Major Products from Experiment The major products from this experiment will be measured performance data and predictive models for the performance of JPCP and CRCP that are designed with "non-erodable" bases. The performance data and predictive models will show the benefits of different types of bases in reducing the occurrence of distress and roughness. The performance data and models can be used to improve base design.

SPS Experimental Design for Effects of Retrofit Tied Concrete Shoulders on Concrete Pavement Performance

Research Problem Statement The edge loading of slabs has long been recognized as a cause of substantial concrete pavement deterioration. This is particularly true for free edges along the lane shoulder joint. This is also the location where most of the moisture enters into the pavement structure. Current pavement design procedures do not include adequate techniques that allow the designer to directly consider the effect of different shoulder designs on the performance of the traffic lane. The cost effectiveness of the retrofit shoulder in extending the life of the mainline pavement is not well known. Many questions remain as to the cost-effectiveness of retrofit shoulders and how retrofit shoulders should be designed for different traffic levels and climates. Since the retrofit of a new tied shoulder on an existing concrete pavement is believed to have great potential for extending the life of the pavement by reducing edge stresses and deflections, the improvement of tied concrete shoulder retrofit design procedures is an area of urgently needed research.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry).
2. Retrofit shoulder designs (conventional AC, tied PCC).
3. Type of existing concrete pavement (JPCP or JRCP, CRCP).

The experimental design layout is shown in Figure 20. Main factors to be held constant include subgrade soil type (fine grained), slab thickness for each type of pavement and traffic rate (high).

Number of Sections All test sections will be constructed along selected highways. For example, at a given site a series of test sections would be constructed along an existing highway with deteriorated shoulders that has the desired type of pavement, traffic level, subgrade soil and climate:

JPCP or JRCP:

Section 1: Retrofit conventional AC shoulder.

Section 2: Retrofit tied PCC shoulder.

CRCP:

Repeat above sections.

Total number of experimental sections = 3 primary cells x 4 secondary cells x 2 replications = 24.

Major Products from Experiment The major products will be measured performance data and predictive models of the performance of jointed concrete pavements that are retrofitted with AC shoulders or tied concrete shoulders. The performance data and prediction models will show the life extension of the adjacent traffic lane due to different retrofit shoulder designs. The performance data and models can be used to improve rehabilitation strategies and design procedures.

SPS Experimental Design for Effects of Shoulder Design on Concrete Pavement Performance

Research Problem Statement The structural design of the shoulder has long been recognized as an influence on the performance of the adjacent traffic lane. Current pavement design procedures do not include techniques that allow the designer to directly consider the effect of different shoulder designs on the performance of the traffic lane. There is controversy about the cost effectiveness of shoulder design on extending the life of the mainline pavement. A few shoulder design procedures are available, but are not widely accepted and have not been verified from performance of in-service pavement sections. Many questions remain as to the best shoulder designs for given traffic levels and climates. Since the improvement of shoulder design has great potential for providing more cost-effective designs overall and for extending the life of rigid pavements, the improvement of shoulder design procedures is an area of urgently needed research.

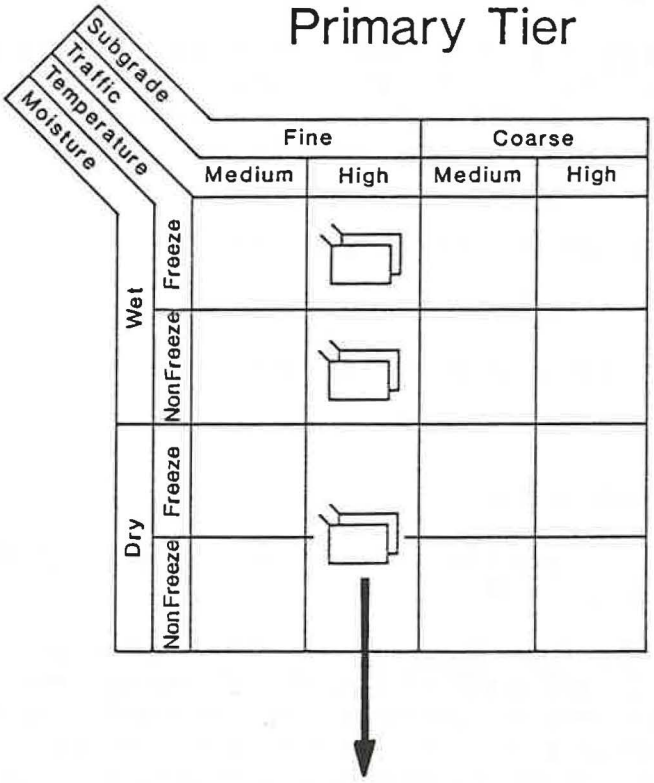
Main Experimental Design Factors

1. Climatic zones (wet and dry).
2. Shoulder designs (conventional AC, tied PCC, extra wide traffic lane).

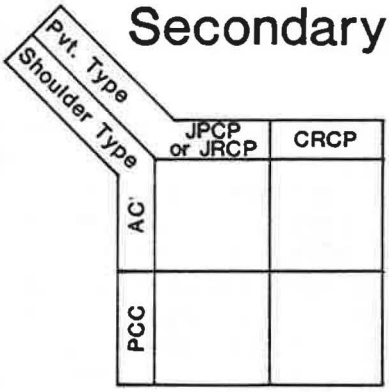
FIGURE 20. TRA 2

SPS: PCC RETROFIT SHOULDERS

Primary Tier



Secondary Tier



Primary Cells		Secondary Cells		Replications		Total Sections
3	x	4	x	2	=	24

3. Type of existing concrete pavement (JPCP, JRCP).

The experimental design layout is shown in Figure 21. Main factors to be held constant include subgrade soil type (fine grained), slab thickness and traffic rate (high).

Number of Sections All test sections will be constructed along selected highways. For example, at a given site a series of test sections would be constructed (and placed randomly) along a highway that has the desired traffic level, subgrade soil and climate:

JPCP:

Section 1: Conventional AC shoulder.

Section 2: Tied PCC shoulder.

Section 3: Extra wide traffic lane.

JRCP:

Repeat above sections.

Total number of experimental sections = 2 primary cells x 6 secondary cells x 2 replications = 24.

Major Products from Experiment The major products will be measured performance data and predictive models of the performance of jointed concrete pavements that are designed with different shoulder sections. The performance data and prediction models will show the benefits of different shoulder design systems on the development of distress and roughness in the adjacent traffic lane. The performance data and models can be used to improve shoulder design procedures.

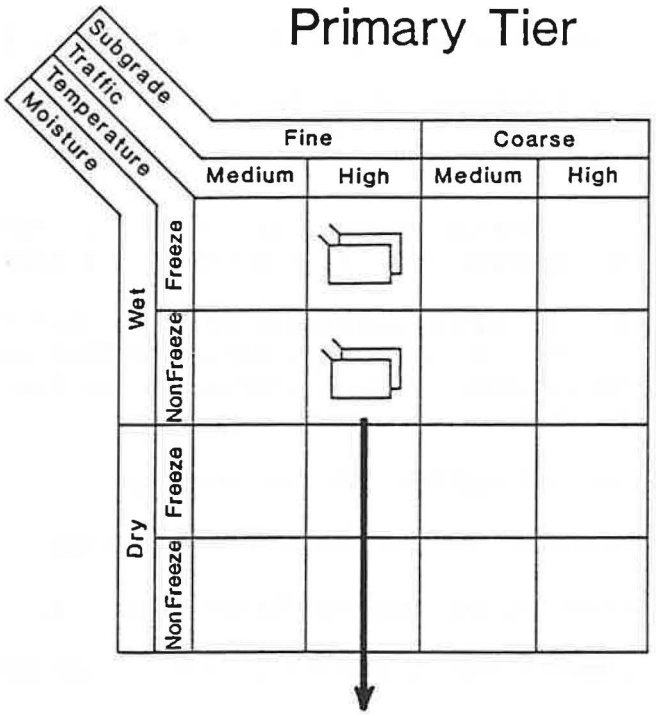
SPS Experimental Design for Asphalt Concrete Overlays Over Pre-Treated Jointed Concrete Pavement

Research Problem Statement Both cracking and seating and subsealing are being used to pre-treat jointed concrete pavements for asphalt concrete overlays. While they are both regarded as being desirable, and both techniques must be done carefully, neither has been systematically studied to determine its actual effect on overlay performance. Subsealing can be accomplished with heated bituminous or fluid cementitious materials, each of which have advantages and disadvantages. Both cracking and seating and subsealing can be used with jointed plain and jointed reinforced concrete pavement. There is also the unanswered question of what thickness of asphalt concrete overlay to use with each of these techniques. The study should be conducted in all four climatic zones because climate is expected to have a major influence on performance.

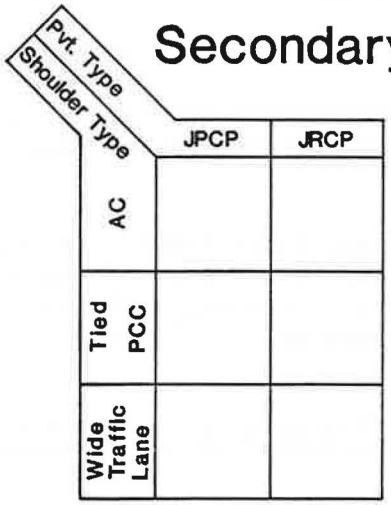
FIGURE 21. TRA 2

SPS: PCC SHOULDER DESIGN

Primary Tier



Secondary Tier



2 Primary Cells x 6 Secondary Cells x 2 Replications = 24 Total Sections

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).
2. Existing pavement type (JPCP, JRCP).
3. Preparation techniques (cracking and seating, subsealing).
4. AC overlay thickness (thin, thick).
5. Traffic rate (medium, high).

The experiment design is shown in Figure 22. Main factors to be held constant include subgrade type (fine grained) and high traffic level.

Number of Sections All test sections will be constructed along in-service highways. At a given site, a series of test sections would be constructed with random placement along a JPCP which has the desired traffic level, subgrade soil, and climate.

Section 1: Control section, thin AC overlay.

Section 2: Cracking and seating, thin AC overlay.

Section 3: Cracking and seating, thick AC overlay.

Section 4: Cementitious subsealing, thin AC overlay.

Section 5: Cementitious subsealing, thick AC overlay.

Section 6: Control section, thick AC overlay.

Total number of experimental sections = (4 primary cells x 12 secondary cells x 2 replications) - (12 JRCP sections not included in dry nonfreeze zone) = 84.

Major Products from Experiment The major products of this experiment will be data on the performance of asphalt-overlaid jointed concrete pavements treated by cracking and seating and subsealing. This information will help to develop or calibrate design procedures for these treatments.

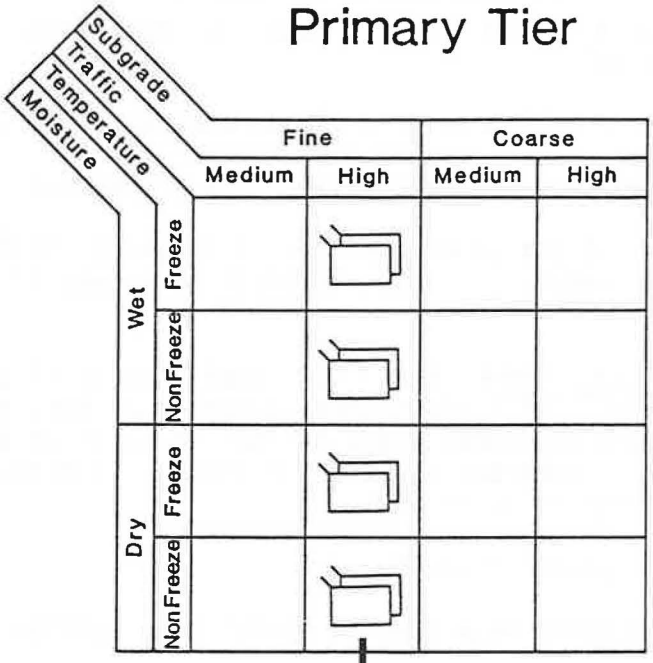
SPS Experimental Designs for Effects of Subdrainage On Asphalt Pavement Performance

Research Problem Statement Limited experience with pavement subdrainage to date has indicated the likelihood of significantly increased service lives of flexible pavements using well designed subdrainage. However, the performance of these pavements has not been studied systematically to determine which kinds of subdrainage work well and under what conditions. Both edge drains and pervious base layers need to be studied. The drainage layers should be monitored to determine if and when they become plugged with fines. Provisions should be made for flushing accumulated

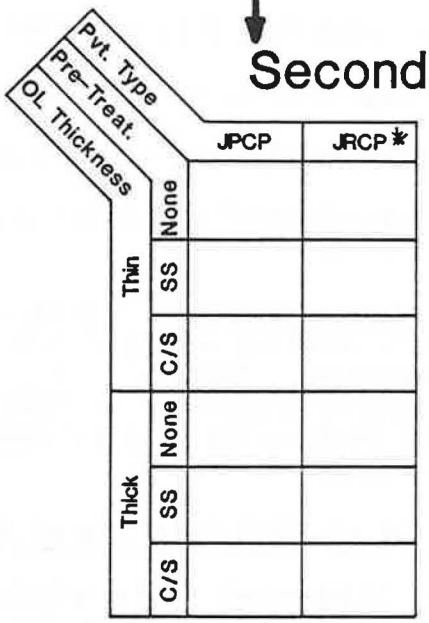
FIGURE 22. TRA 2

SPS: PRE-TREATED JCP WITH AC OVERLAY

Primary Tier



Secondary Tier



C/S = Crack & Seat
SS = Subseal

* NOTE: JRCP not included in Dry-Nonfreeze Zone.

4	Primary Cells	x 12	Secondary Cells	x 2	Replications	- 12	JRCP not Included	= 84 Total Sections

fines from edge drains. The study should be conducted in all four climatic zones.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).
2. Edge drains (fabric or drainage pipe on new pavements).
3. Pervious base drainage layers (new pavements).

The layout of the experiment design is given in Figure 23. Main factors to be held constant include subgrade soil type (fine grained) and traffic rate (high).

Number of Sections All test sections will be constructed along selected highways. At a given site, a series of test sections will be constructed in a random placement along a flexible pavement that has the desired traffic level, subgrade soil, and climate. An example of such sections along a new highway is as follows:

Section 1: Control section.

Section 2: Fabric edge drains, normal base course.

Section 3: Drainage pipe edge drains, normal base course.

Section 4: Fabric edge drains, pervious base course.

Section 5: Drainage pipe edge drains, pervious base course.

Total number of experimental sections = 4 primary cells x 4 secondary cells x 2 replications = 32.

Major Products from Experiment The major product will be measured performance data and predictive models of the performance of asphalt concrete pavements with subdrainage. These performance data and models will show the beneficial influence of subdrainage systems on the development of distress and roughness. The performance data and models can be used to improve subdrainage design procedures.

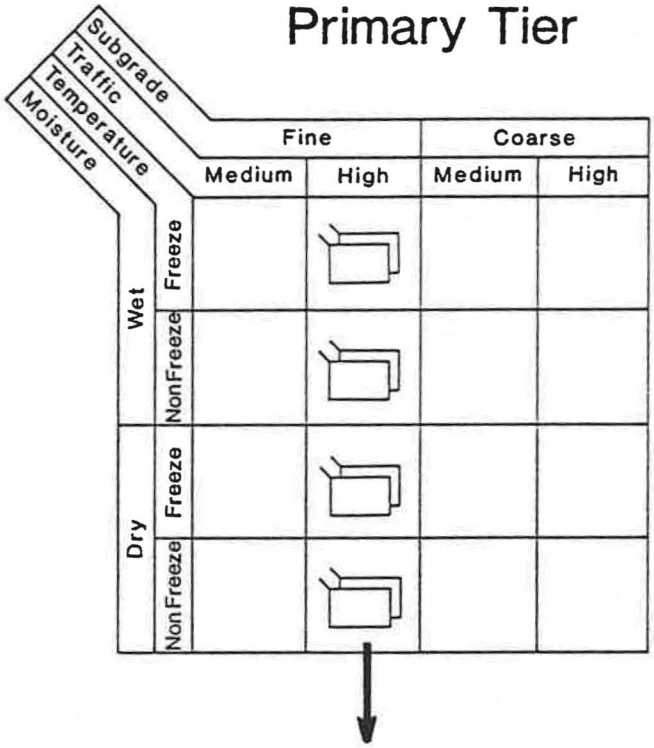
SPS Experimental Design for Hot and Cold Recycling of Asphalt Pavement

Research Problem Statement This study is divided into two parts: hot-recycled asphalt concrete pavement performance and cold-recycled asphalt concrete pavement performance. The objective in each case is to study particular factors of each treatment related to performance. For example, in hot recycling a systematic study can be made of recycling agents (or use of soft asphalt cement). In cold recycling, the thickness of the cold-recycled base and overlying riding surface can be studied systematically.

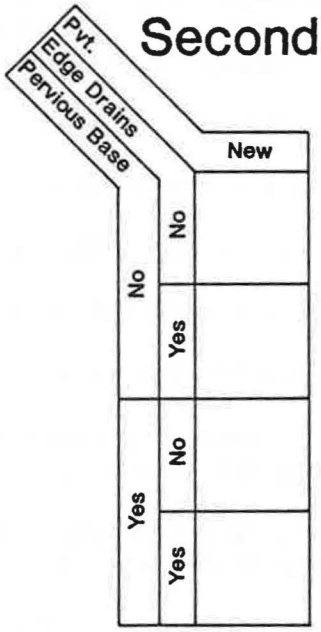
FIGURE 23. TRA 2

SPS: AC SUBDRAINAGE

Primary Tier



Secondary Tier



Primary Cells		Secondary Cells		Replications		Total Sections
4	x	4	x	2	=	32

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze for hot recycling; wet freeze and dry nonfreeze for cold recycling).
2. Hot recycling factors:
    a. Ratio of new aggregate to recycled aggregate (low and high).
    b. Recycling agents (two types).
3. Cold recycling factors:
    a. Percent new aggregate (low, high).
    b. Thickness of new base course (thin, thick).
    c. Thickness of surface course (thin, thick).

The layouts of the experimental designs are shown in Figures 24 and 25. Main factors to be held constant include subgrade soil type (fine grained) and traffic rate (high traffic for hot recycling and medium traffic for cold recycling).

Number of Sections All test sections will be constructed along in-service highways. At a given site, a series of test sections will be constructed in a random placement along a flexible pavement that has the desired traffic level, subgrade soil, and climate. An example for hot recycling of such sections along a highway is as follows:

Section 1: Control section.

Section 2: Low new-to-old aggregate ratio, recycling agent A.

Section 3: High new-to-old aggregate ratio, recycling agent A.

Section 4: Low new-to-old aggregate ratio, recycling agent B.

Section 5: High new-to-old aggregate ratio, recycling agent B.

Total number of hot recycling experimental sections = 4 primary cells x 5 secondary cells x 2 replications = 40.

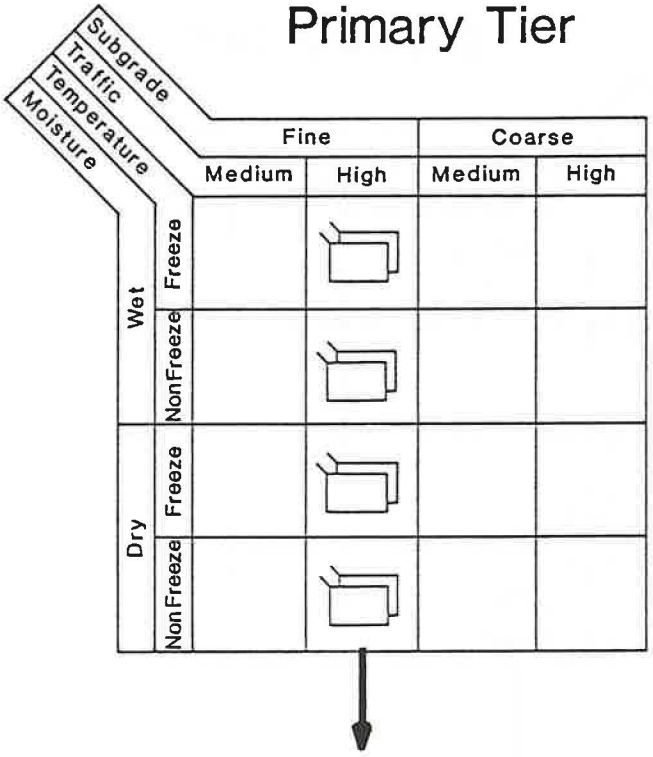
Total number of cold recycling experimental sections = 2 primary cells x 8 secondary cells x 2 replications = 32.

Major Products from Experiment The major products of this experiment will be objective measurements of the performance of hot- and cold-recycled pavements, with a quantitative assessment of the effectiveness of the most promising recycling agents and aggregate ratios and pavement structural design for cold recycling.

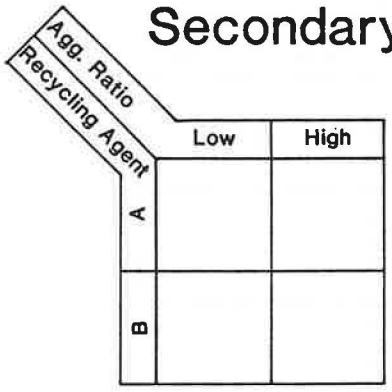
FIGURE 24. TRA 2

SPS: AC HOT RECYCLING

Primary Tier



Secondary Tier

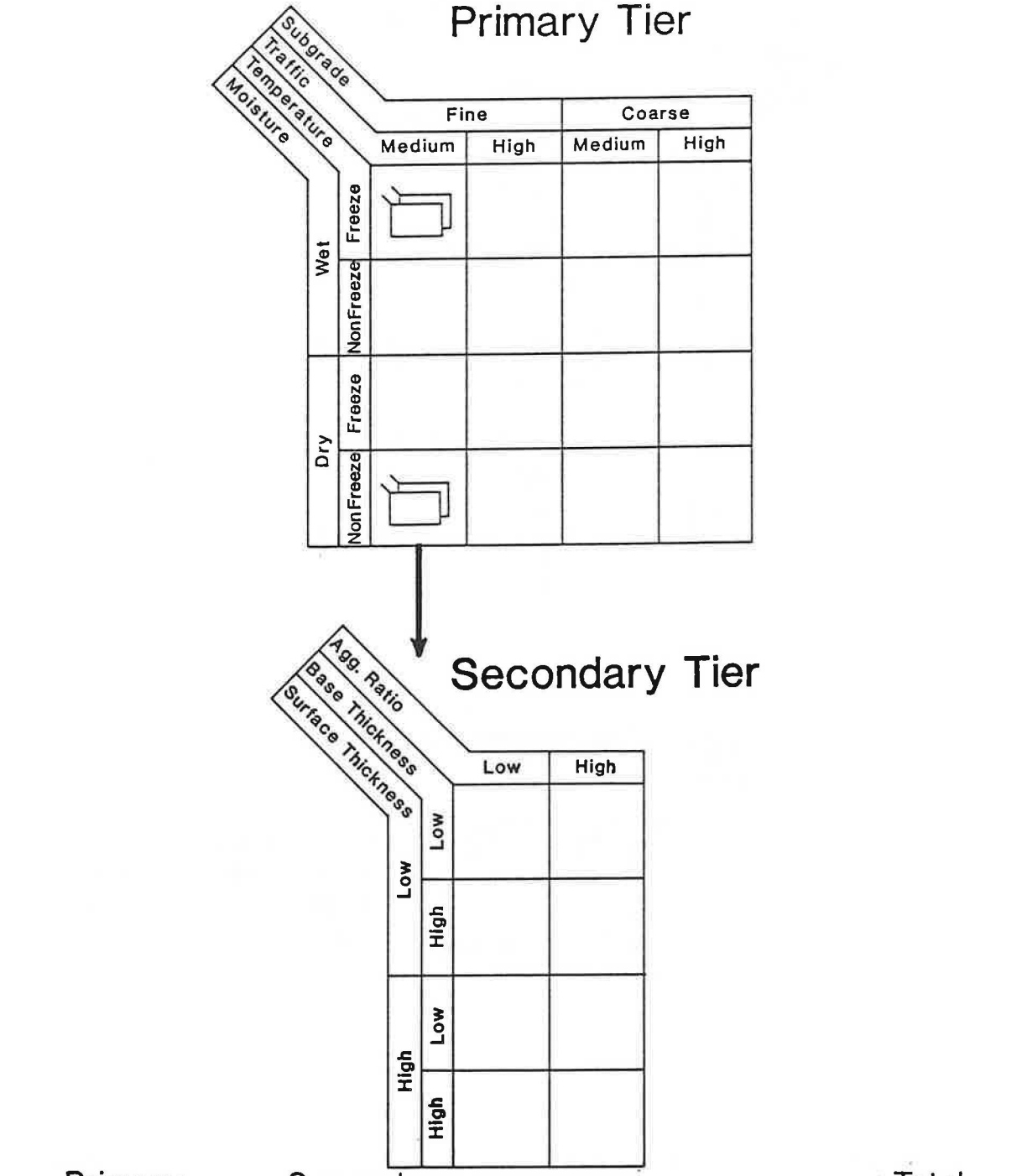


Note: One additional non-recycled section is needed per each secondary tier.

4 Primary Cells x 5 Secondary Cells x 2 Replications = 40 Total Sections

FIGURE 25. TRA 2

SPS: AC COLD RECYCLING



2 Primary Cells x 8 Secondary Cells x 2 Replications = 32 Total Sections

SPS Experimental Design for Effects of Preventive Maintenance on Asphalt Pavement Performance

Research Problem Statement A number of different types of surface treatments are used commonly by various agencies to retard fatigue cracking after it has started to appear. However, the relative effectiveness of these treatments is not well understood. Sufficient information is not available for rational selection of treatments in terms of severity of cracking, environmental factors, traffic levels, and other significant variables. The pavement test sections must be selected such that low, moderate, and high severities of fatigue cracking are treated by each type of surface treatment, with no treatment as one strategy. As high-type pavements with heavy traffic generally receive thicker overlays or more extensive rehabilitation, these experiments are to be conducted on pavements with low to medium traffic levels. It is expected that the results from these studies should produce a much better understanding of the effects of these surface treatments in terms of future performance, and a basis for selection of the best surface treatment for the conditions that exist.

This experiment has been developed in coordination with the contractor for TRA 3, Maintenance Cost-Effectiveness, to support their needs for field studies. These studies should identify general data needs for evaluating other maintenance treatments, and to formalize an approach for such future evaluations.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze)
2. Pavement condition (low-, medium-, and high-severity fatigue cracking)
3. Treatments (none, chip seal, slurry seal, thin overlay, crack sealing)
4. Traffic rate (low, medium)

The layout of the experimental design is shown in Figure 26.

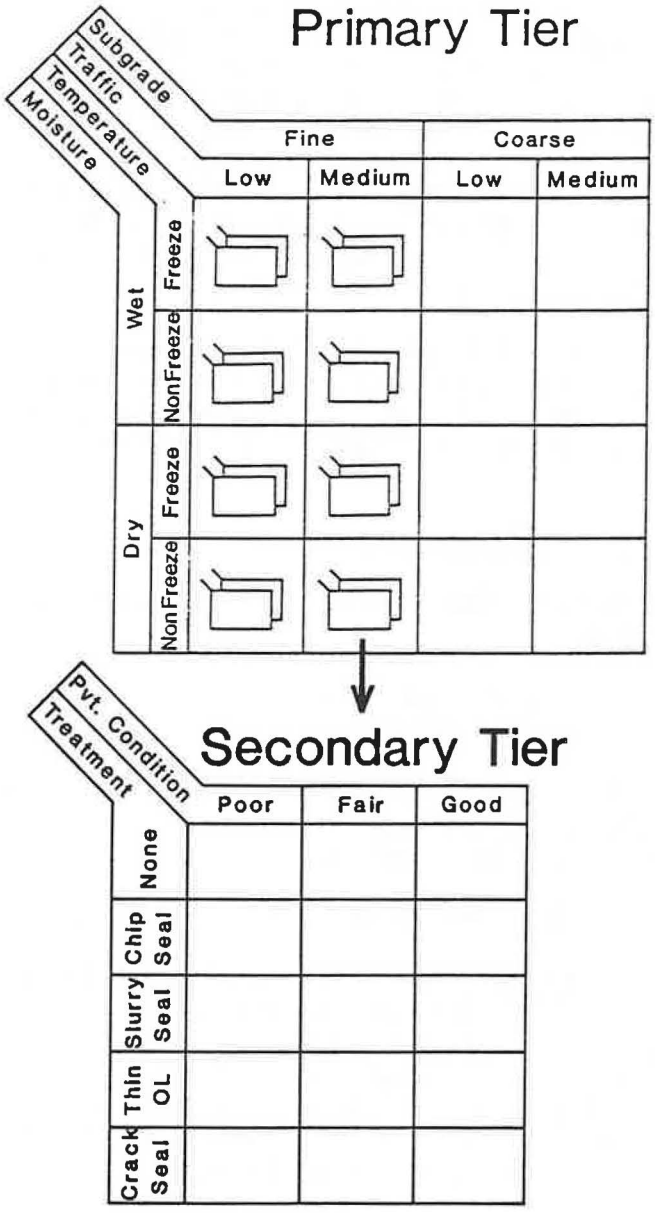
Number of Sections All test sections will be in-service highway sections. They must be selected in each of the four climatic zones and have the three levels of fatigue cracking severity. The pavement surface should be asphalt concrete over granular base, with designs consistent with traffic levels. It may be advantageous to select variable section lengths at the same locations for uniformity in most independent variables. Five treatments will be applied along each highway section.

Total number of experimental sections = 8 primary cells x 15 secondary cells x 2 replications = 240.

Major Products from Experiment A major product will be measured performance data and the ability to evaluate the effects of applying different preventive maintenance treatments to pavements exhibiting fatigue damage. These performance data and models will show the benefits of the

FIGURE 26. TRA 2

SPS: AC PREVENTIVE MAINTENANCE



8 Primary Cells x 15 Secondary Cells x 2 Replications = 240 Total Sections

different preventive maintenance treatments on extending pavement life. This information can be used to design more cost-effective maintenance and rehabilitation strategies.

Another important result is expected to be information and experience that may be utilized by TRA 3 to develop procedures for future use in evaluating the effectiveness of maintenance treatments.

SPS Experimental Design for New Concepts for Flexible Pavements

Research Problem Statement There may be several recommendations for new concepts in flexible pavement design, rehabilitation, construction, or materials. There are no specific recommendations provided here as these will be sought out from the pavement community. It is considered an essential role of the Special Pavement Studies (SPS) to investigate new ideas by monitoring their performance and determining their life-cycle costs.

Main Experimental Design Factors

1. Climatic zones (at least two distinct zones)
2. Traffic rate (high)
3. Each new concept will have two replications.

The main factors to be held constant in all sections are the subgrade soil type (fine grained) and the traffic rate (high).

Number of Sections All test sections will be constructed along in-service highways. A series of test sections will be placed in random order along a highway with the desired levels of traffic and subgrade soil. A total of 50 experimental sections has been allocated to this experiment.

Major Products from Experiment The major products will be objective evaluations of new concepts for the design, rehabilitation, construction, and materials for flexible pavements, and sufficient data on each of the promising concepts to permit a preliminary calibration of mechanistic-empirical methods of analysis and design to be applied to each technique.

SPS Experimental Design for Low-Volume Roads

Research Problem Statement Low-volume roads represent a large investment by state highway agencies in all parts of the nation. They are generally economical in construction and maintenance costs, but frequently are required to carry heavy, but economically important, loads for which they are not designed. This experiment is to evaluate the long-term performance of several types of commonly used low-volume roads, including those surfaced with a thin layer of asphalt concrete and with bituminous surface treatments. The crucial questions of load rating, load zoning, and maintenance costs occasioned by heavy loads can only be answered by this study.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).
2. Subgrade soil type (fine grained, coarse grained).
3. Structural number of base (low, high).
4. Surface types (thin asphalt concrete surface and bituminous surface treatment).

The tentative layout of the experimental design is shown in Figure 27. The main factor to be held constant is the total traffic which must be held low.

Number of Sections All test sections will be constructed or selected along in-service highways. In some cases it may be possible to place a series of test sections in random order along a highway with the desired level of traffic and subgrade soil. An example of this is as follows:

Section 1: Thin AC surface, low base course structural number.

Section 2: Thin AC surface, high base course structural number.

Section 3: Bituminous surface treatment, low base course structural number.

Section 4: Bituminous surface treatment, high base course structural number.

Total number of experimental sections = 8 primary cells x 4 secondary cells x 2 replications = 64.

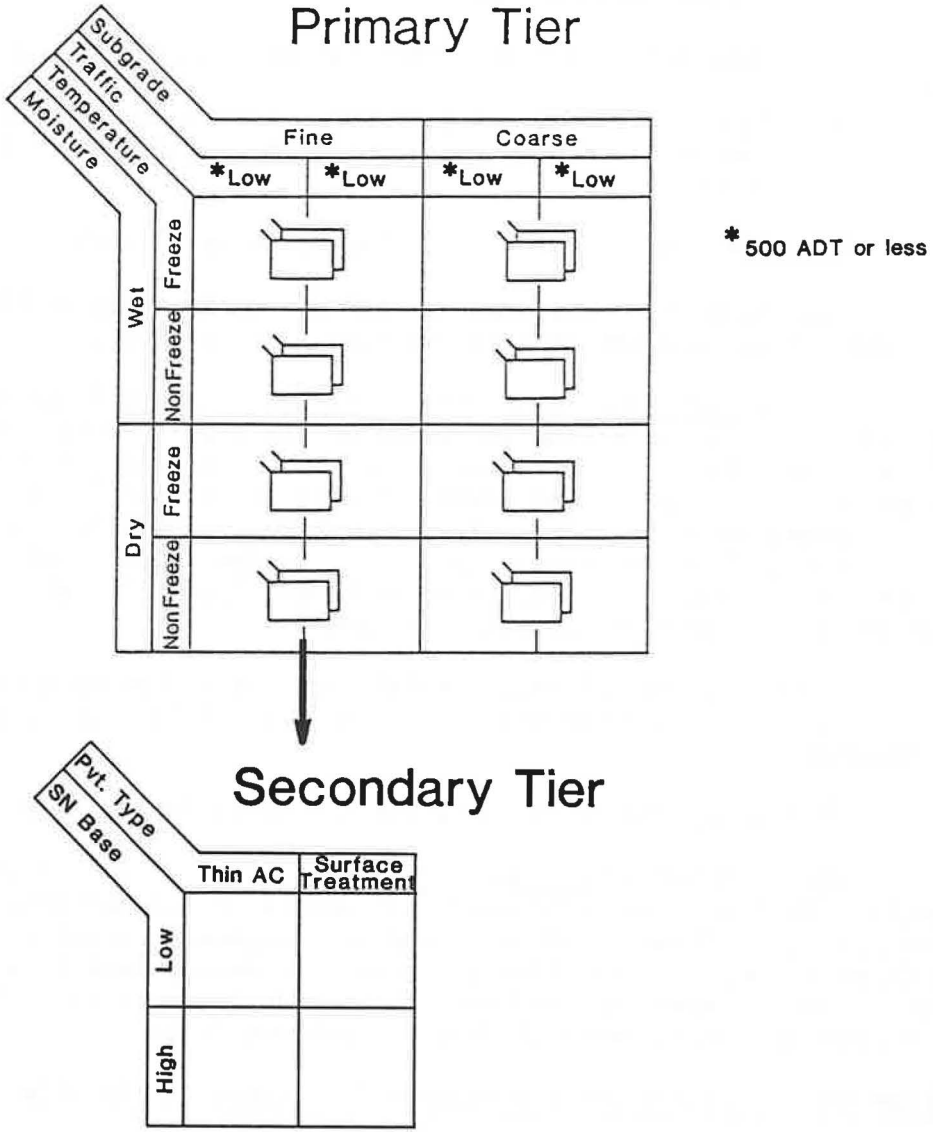
Major Products from Experiment The major products of this experiment will be evaluations of the long-term performance of several types of low-volume roads so that questions of load rating, load zoning, and maintenance costs can be fairly and adequately answered.

SPS Experimental Design for Load Equivalence Factors for Flexible Pavements

Research Problem Statement The original and primary intention of the AASHO Road Test was to develop data that would permit the allocation of costs to different vehicular elements in a traffic stream. The objective was achieved by subjecting pavement sections to pure (i.e., unmixed) traffic, a feat which cannot be duplicated on in-service pavements. If, however, typical traffic streams can be split into three categories, (passenger vehicles, medium trucks, and heavy traffic) and each of them can be weighed at a weigh station, and if several strengths of pavement can be placed in sequence along the lanes travelled by the vehicles, an iterative analysis of the data collected may produce useful approximate load equivalence factors. Alternatively, mechanistic-empirical models could be calibrated from performance data and utilized to develop load equivalence factors. These new factors can show the effects of different climates and

FIGURE 27. TRA 2

SPS: AC LOW-VOLUME ROADS



8 Primary Cells x **4** Secondary Cells x **2** Replications = **64** Total Sections

subgrade soils and can contribute to evaluation of the AASHO Road Test load equivalence factors.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet nonfreeze, dry freeze, dry nonfreeze).

2. Subgrade soil type (fine grained, coarse grained).

3. Type of traffic (At each site, traffic must be split into three streams: passenger vehicles, medium trucks, and heavy trucks.).

5. Structural number (four levels in each lane).

The layout of the experimental design is shown in Figure 28. The main factor to be held constant is the high traffic level.

Number of Sections All test sections will be constructed at sites where weigh-in-motion equipment and automatic vehicle classification equipment are maintained. Each site will be along a highway with the desired traffic level and identical sets of test sections are to be constructed along three parallel roadways or lanes. These sections having different structural number will be placed in random order. The traffic stream will be sensed and split into three different types of traffic, each directed to one of the parallel roadways or lanes.

Total number of experimental sections = 8 primary cells x 12 secondary cells x 2 replications = 192. A total of 16 sites are required for this experiment.

This study design is tentative and needs further investigation.

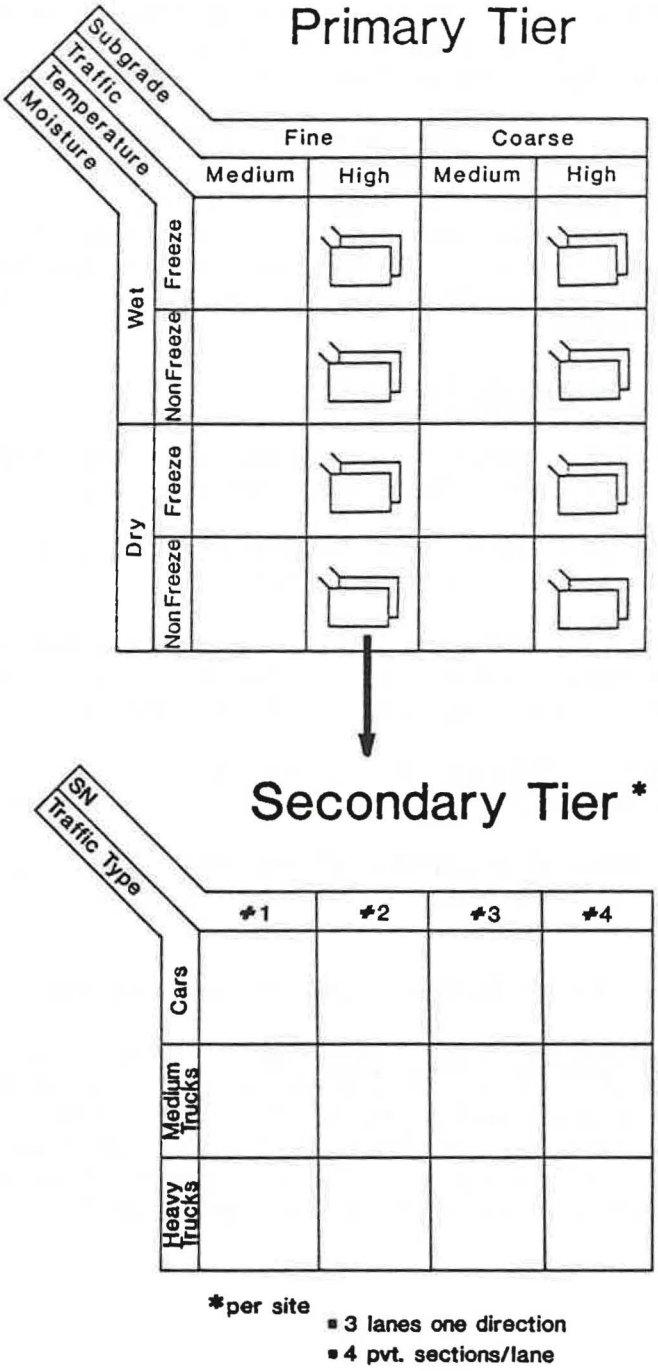
Major Products from Experiment The major products will be data and calibrated mechanistic-empirical models of the performance (joint deterioration, faulting, cracking, pumping, roughness, present serviceability index) that show the relative difference in damage caused by the different vehicle types. These data and predictive models can be used in cost allocation studies and improvement of load equivalence factors.

SPS Experimental Design for Environmental Distress in Flexible Pavements

Research Problem Statement There is much controversy over the relative effects of environment and traffic loading on pavement deterioration. There exists very little actual pavement performance data from which to either develop or verify predictive models to aid in the analysis of this complex problem. This experiment will address the problem of determining the amount of deterioration that normally takes place for pavements that experience negligible accumulations of ESALs. (This occurs, for example, on parkways where trucks are banned, but automobile traffic is allowed.) This study is comparable to the Loop 1 Experiment on the AASHO Road Test and is designed to complement the national General Pavement Studies and provide

FIGURE 28. TRA 2

SPS: AC LOAD EQUIVALENCE FACTORS



8 Primary Cells x 12 Secondary Cells x 2 Replications = 192 Total Sections

objective data on the effect of climatic and subgrade soil influences on flexible pavement performance in the absence of significant traffic.

The subgrade soils include expansive soils, frost-susceptible soils, and subgrade soils that are susceptible to neither expansion nor frost action. The climatic zones are defined by available moisture (wet and dry) and temperature (hard freeze, freeze-thaw cycling, and no freeze).

One complicating consideration is that there may be a difference in performance when the pavement is entirely untrafficked and when it is trafficked by automobiles. Although this is not particularly significant for concrete-surfaced pavements, it is significant for asphalt-surfaced pavements. Thus, all sections selected for the flexible pavement experiment must carry traffic (automobile only) in order to eliminate this consideration from the experiment.

Main Experimental Design Factors

1. Climatic zones (wet freeze, wet freeze-thaw, wet nonfreeze, dry freeze,dry freeze-thaw, dry nonfreeze).

2. Subgrade soil type (expansive soil, frost-susceptible soil, nonsusceptible granular soil).

The layout of the experimental design is shown in Figure 29. The main factors to be held constant include the thickness of each pavement layer and a low number of 18-kip equivalent single-axle loads.

Number of Sections All test sections will be selected along in-service highways and will constitute a national experiment.

Total number of experimental sections = 18 primary cells x 1 secondary cell x 2 replications = 36. A total of 36 sites are required for this experiment.

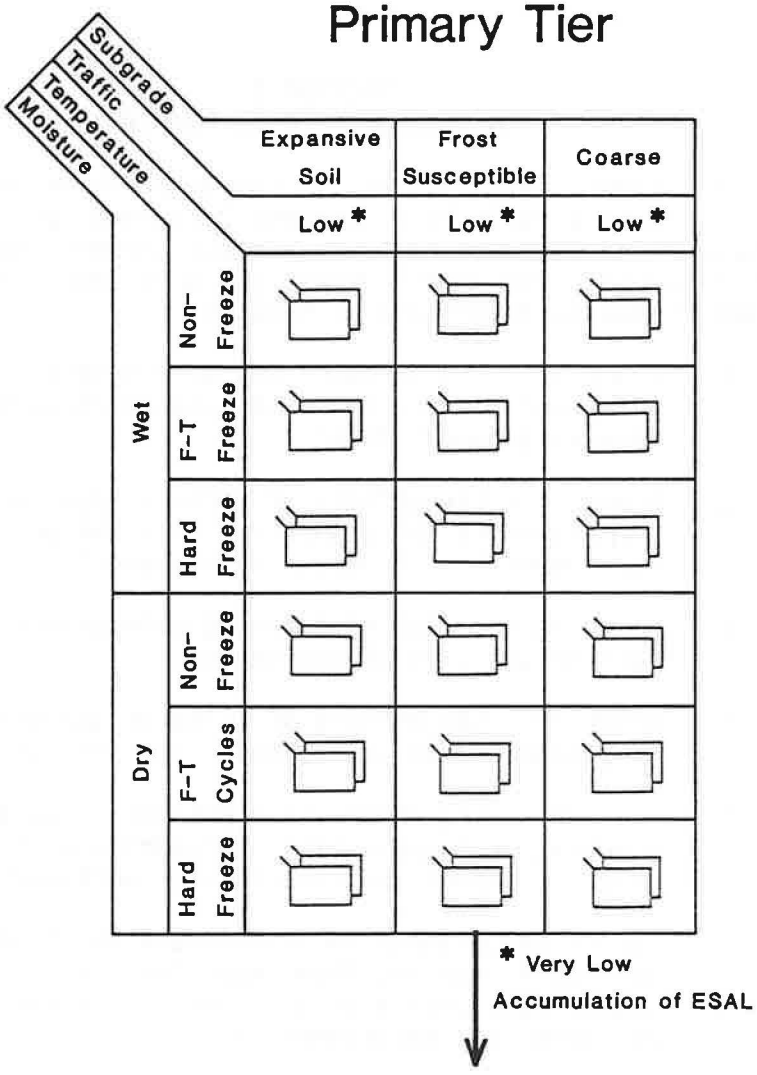
This study design is tentative and needs further investigation.

Major Products from Experiment The major products of this experiment will be objective data on the performance of flexible pavements controlled by the subgrade and climate. This experiment is a necessary complement to the national General Pavement Studies (GPS) experiments and will provide essential data for cost allocation studies which show the extent to which flexible pavements are damaged by influences other than traffic.

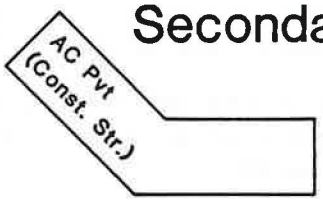
FIGURE 29. TRA 2

SPS: AC ENVIRONMENTAL DISTRESS

Primary Tier



Secondary Tier



18 Primary Cells x 1 Secondary Cells x 2 Replications = 36 Total Sections

SECTION 5
TRA 2 RESULTS TO BE ACHIEVED

The direct result to be achieved from the Long-Term Pavement Performance Studies will be a National Data Base, which can be used to answer a number of important questions about pavement management and design. The most important of these questions were identified in Transportation Research Board Special Report 202 as follows:

1. What are the proper design and construction procedures for pavement rehabilitation and overlays to provide economical renewed pavement life?

2. What are the effects of various types and levels of pavement maintenance on pavement life and performance? What is the cost benefit of pavement maintenance?

3. What is the cost of deferred maintenance and the ultimate effect on the life of the highway?

4. What are the effects of climatic and environmental variables on pavement life and pavement performance?

5. Are the long-term load effects (load magnitude, type, frequency, and summation of loads) now correctly evaluated for pavement design and construction methods?

6. Is it necessary to reevaluate the load equivalency factors developed from the AASHO Road Test in order to apply them over a wide variety of pavement strengths, material types, and environments?

7. What are the relative effects and interactions of load and environmental (climatic) variables on pavement deterioration, performance, and service life?

8. What are the effects of varying subgrade material types and strengths on pavement construction requirements and ultimate performance?

9. What is the load-carrying capacity of a pavement when the design life is reached?

10. What are the effects of alternative drainage designs on pavement performance and service life?

DATA ANALYSIS

The usual products or results gained from analysis of any data base are equations that describe the relationships among various data elements in the data base. In this case, dependent variables in the equation will generally be major distress or performance measures, and the independent variables will be the data elements whose variations have significant effects on the dependent variables. These independent variables will include material characteristics, environmental data, traffic data, pavement structure data, etc. Such equations may be used in pavement management systems to predict the deterioration of pavements and to select rehabilitation or repair strategies. They may be modified to design equations or transformed into nomographs for design of original pavements or overlays.

Other information of great importance may be obtained somewhat more directly to indicate such things as which rehabilitation techniques perform best, and cost efficiency in terms of performance and relative cost. Similar information may be gained relative to performance versus maintenance levels or versus quality control during construction.

The AASHO Road Test data is still used today for purposes not conceived at that time, and this data base will undoubtedly also serve other as yet unidentified purposes. Consequently, it is extremely important that the experiment structure provides maximum flexibility to serve the many modeling and analysis purposes that will be required of it. The two-tiered approach selected makes it possible to easily work with various segments of the total data base in developing local, regional, or national models. Other appropriate divisions in the data base for special interests may also be made effectively.

The overall expectation from the improved predictive equations, improved design procedures, and additional insight gained as to pavement performance is expected to be better pavement performance at a lesser cost. The potential savings may be expected to be enormous, especially if the somewhat elusive user costs are also considered.

EXPECTED MAJOR END PRODUCTS AND RESULTS

Major end products expected from LTPP Studies include:

1. More reliable new pavement design procedures and standards,
2. More reliable rehabilitation design procedures and standards,
3. Improved cost allocation analysis,
4. More accurate pavement needs estimates,
5. Improved pavement management systems,
6. Improved pavement maintenance policy.

It is expected that many useable results will have accrued within five years of initial funding. These should include:

1. Standardized data collection procedures - The LTPP data collection procedures for pavement condition, environment, traffic count and classification, and truck weighing (WIM) are expected to become the national standards since these procedures and the equipment used will represent the "state of the art." Highway agencies may profitably adopt these procedures (either through purchase of equipment or services) to greatly increase the amount of data available at reduced unit costs. This should impact very favorably on pavement management capabilities.

2. Improved pavement performance models - Analysis of the data in the National Pavement Data Base beginning around Year 4 may be expected to produce empirical models for a number of distresses for which they are badly needed. As there will be a distribution of pavement ages and the initial levels are generally known, such models may be quite good. Data will also be available for calibration of mechanistic-empirical models for use in research (computer road tests, etc.) and perhaps for design.

3. Improved design methods - The improved predictive models discussed above may be used to evaluate and modify existing design methods, or to develop new design methods using the improved predictive models as a basis. Better performance at reduced costs should be the very desirable result.

4. Improved evaluation methods/procedures - The methodology for evaluating pavement condition and structural capacity may be expected to improve greatly with the implementation of uniform techniques, state-of-the-art measurement equipment, and improved performance prediction models.

5. Greatly improved understanding of pavements in general - It is expected that the broad scale observation of pavement and the analysis of a statistically sufficient data base will greatly clarify the effects of various design features, construction techniques, materials, maintenance and rehabilitation strategies, loads, climate, etc. on pavement performance. This improved understanding of "how pavements perform", supplemented by better prediction models, should allow much more effective management of the nation's pavements.

However, we must "stay the course" for the full fifteen to twenty years to satisfactorily understand the long-term performance of pavements.

A much more extensive list of the General Results and Products of LTPP is presented in Table 13, which presents a time-staggered list of products, and their estimated stage of completion for early, intermediate, and long-term time periods.

TABLE 13
TRA 2 GENERAL RESULTS AND PRODUCTS OF LTPP

P = Partly Complete; U = Useable Result; R = Refined Product; C = Complete

GENERAL RESULT	RESULTS EARLY (5 yrs)	INTERMEDIATE (6-10 yrs)	LONG-TERM (10-20 yrs)
1. Standardized data collection procedures.	C	C	C
2. Demonstrate State-of-the-Art Equipment for data collection.	U	R	R
3. Impetus for development of improved data collection equipment.	U	U	R
4. National Pavement Data Base	P	U	C
5. Pavement Data Management System	U	R	C
6. Improved Pavement Performance Models	U	R	C
7. Improved Original Design Methods	U	R	C
8. Improved Rehabilitation Design Methods	P	U	C
9. Improved Evaluation Methods/Procedures	U	R	C
10. Improved Design/Rehabilitation Strategy Procedures	P	U	C

TABLE 13 (continued)
TRA 2 GENERAL RESULTS AND PRODUCTS OF LTPP

P = Partly Complete; U = Useable Result; R = Refined Product; C= Complete

GENERAL RESULT	RESULTS EARLY (5 yrs)	INTERMEDIATE (6-10 yrs)	LONG-TERM (10-20 yrs)
11. Effects of Subsurface Drainage	P	U	C
12. Effects of Subgrade	P	U	C
13. Effects of Load	P	U	C
14. Effects of Materials	P	U	C
15. Improved Life Cycle Cost Analysis	U	R	C
16. Effect of Pavement Condition Prior to Rehabilitation	U	R	C
17. Evaluation of New Materials	P	U	C
18. Evaluation of Innovative Design and Rehabilitation Technique	P	U	C

A need has also been identified by the Advisory Committee for establishment of a procedure for "forensic engineering" when early deterioration occurs in pavements included in the GPS and SPS experiments. Planning for such studies has not been developed, but should be completed and implemented during the first year of the LTPP activities. Intensive study of causes of early deterioration, and effective communication of these results to the "pavement community" at large, could result in major future cost savings.

SECTION 6
TRA 2 IMPLEMENTATION OF RESULTS

Planning for implementation of the expected results described in the previous section is preliminary, as the thrust of the work effort (as for the other SHRP TRA's) has been toward the design of the experiments. The primary objectives of the experiment design effort were to optimize the value of the data in the resulting national data base, develop an efficient organization plan for operating the massive data collection activity required, plan the details of the data collection, estimate the costs for various strategies for experiment design and operation, and iteratively revise the planning for consistency between the experimental designs and costs.

It is important to remember that these are long-term studies, intended to continue for some twenty or more years. This means that both the analysis of data and subsequent implementation of results will be continuous from around Year 4 past Year 20. It is expected that useful information, improved predictive equations, and other results may be expected by Year 5; but that our understanding of pavements and the accuracy of the predictive equations will increase as the numbers of observations in the data base increase with time.

IMPLEMENTABLE RESULTS AND EXPECTED BENEFITS

The implementable results will be primarily in the form of predictive equations, but will also in many cases be the results of objective comparisons of performance. The predictive equations should find implementation through their use in improving existing design procedures and through use as the basis for new design procedures. The predictive equations are badly needed for pavement management systems to enhance their capabilities for predicting pavement performance.

The predictive equations should and undoubtedly will be used for numerous sensitivity analyses, which may be expected to point the way toward better selections of materials, design features, quality control levels for construction, etc. Calibrated mechanistic-empirical models may be used to run extremely low-cost "computer road tests" to develop load equivalence factors in terms of all the significant distresses and performance measures that result in "failure" (conditions requiring repair, rehabilitation, or reconstruction).

The relative performance of pavements with varying attributes will provide insight as to the best choices and design features such as subdrainage types, shoulder types, shoulder designs, etc. Comparisons of the performance of pavements with varying maintenance techniques or strategies will

provide insight very valuable to maintenance engineers in selecting the techniques to be used and the points at which the techniques should be applied. Evaluation of the effects of variability in material properties may be expected to offer great assistance to construction engineers in establishing appropriate levels of quality control.

EXPECTED BENEFITS FOR SHA PAVEMENT MANAGEMENT SYSTEMS

One major use for the LTPP results will be incorporation into SHA Pavement Management Systems. The critical elements hindering the implementation of PMS at the State level have been the quantifications of pavement performance and life cycle costs. Current practices and procedures provide predictions of pavement performance and costs, but not nearly to the levels of accuracy required to maximize the effectiveness of these systems. It is expected that the improved predictive capabilities and better understanding of the impacts of various rehabilitation and maintenance strategies will greatly enhance the abilities of the State Highway Agencies to manage their pavement systems.

In addition to the long-term benefits discussed above, it is expected that the data collection and information management procedures implemented for LTPP will rapidly become a national standard. Also, equipment manufacturers are mobilizing to produce better equipment for more thorough and economical field measurements of traffic and axle weights, pavement distress, pavement profile, etc. It is expected that this "revolution" in data collection and management will benefit all SHA's directly in providing far more needed data at reduced unit costs. The adoption of uniform and consistent procedures for calibration of equipment, data collection, and data management will allow effective interchange of data between SHA's in a specific region or environment.

Each SHA will have ready access to the National Pavement Data Base, so they will be able to utilize data from their state (or others) for any research or management purpose desired. Some SHA's have already expressed an interest in greatly expanding their participation in LTPP, even at their own expense, if necessary, so that they may have a statistically sufficient data base for their own state.

Although not a specific result, the LTPP Information Management System may also serve as a model for similar State systems. Two initial elements required for the implementation of a State PMS are: 1) collection of high quality pavement condition data and 2) the ability to store, access and analyze the data in an efficient manner, both in headquarters and field office locations. Development of an integrated pavement information management system is a difficult and expensive process; one that a number of SHA's have been reluctant to undertake. The LTPP information management system is expected to provide a data base frame work that can be implemented by the SHA's to expedite the implementation of more effective pavement management systems. Appropriate revisions may be then made as required for specific PMS needs.

Implementation of LTPP data collection, storage and analysis techniques and results will yield the following overall benefits to the State's Pavement Management Systems:

1. Availability of factual data on pavement life/costs/design and policy effects and enhanced distress/performance prediction capability.

2. Improved understanding of pavement performance will have an important positive impact on the total cost of replacing and rehabilitating the highway infrastructure.

3. Increased pavement life overall due to improved design techniques.

4. Improved decision/policy making.

5. Improved credibility with legislature/public.

6. Reduced road user costs due to smoother pavements and less lane closure time.

7. Reduced future maintenance funding problems through better planning and analysis of past performance.

IMPLEMENTATION ISSUES FOR FUTURE CONSIDERATION

In order to design the experiments, it was first necessary to understand what primary analyses should be conducted on the national data base in order to satisfy the goal established by TRB Report 202 and the objectives established by the SHRP Advisory Committee on Pavement Performance. While there is rather general agreement on what analyses will be required, there has not to date been general agreement on who will conduct these analyses and what the responsibilities will be for insuring coherence in these results and their appropriate implementation.

It is generally recognized that the national data base will be used for many purposes that have not yet been identified. For this reason, more emphasis has been given to insuring that it is adequate than to limiting the data elements to be included. The consensus of the discussions appears to be that SHRP will have a role to play in the analysis of the data, but that the data will be available on a "read only" basis to the "highway community" at large. This means that it will likely be used for hundreds or thousands of graduate theses; numerous FHWA and NCHRP contracts; studies undertaken by State highway agencies through universities and in-house; studies by private sector consultants and industry; and by various foreign agencies who will be interested in it as they have been in the results from the AASHO Road Test. This raises the spectre of the national data base being used for a multiplicity of purposes and interests with little or no control over whether its use is consistent with its inference space, or if appropriate results are derived.

Some of us involved in the planning to date feel that SHRP should take the lead in the analysis so that the results from a data base collected with rigid standards do not become fragmented and variable in quality. Others feel that the analysis of the data and implementation of results

should properly be the responsibility of other agencies such as TRB, FHWA, the State highway agencies, and others.

There has certainly been a problem in the past with millions of dollars of research effort being spent through dozens of research agencies with results that enjoy limited implementation, usually on a very local basis. Many efforts have been undertaken, with considerable success, to integrate this massive program into a more cohesive whole, yet it is very doubtful that as much as one half of the research results produced in this nation are implemented in any meaningful way whatever. This would appear to indicate that much thought and organization needs to be given to the analysis of the national data base and implementation of the results. Time will be available for this while the data is collected and the data base formulated.

The implementation of the knowledge gained from statistical analyses to develop predictive models, calibration of mechanistic-empirical models, and comparative analyses of performance of pavements with various attributes may be expected to follow traditional channels. However, the undertaking of this monumental Long-Term Pavement Performance study represents recognition that past approaches have not been quite adequate and that a new concentrated approach is required to provide efficiency and appropriate direction for national pavement research. It would indeed be unfortunate if similar emphasis was not given to the development of implementation procedures that are equally concentrated and directed to insure that the implementation of the results of this massive effort are realized and are appropriate. This will require much study and cooperative effort within AASHTO and various national agencies, but fortunately there is time for this to occur while the data is being collected. It is recommended that appropriate implementation studies be initiated simultaneously with the implementation of the integrated plan for the data collection.

SECTION 7
TRA 2 SCHEDULE OF PROJECT TASKS AND SUBTASKS

The Long Term Pavement Performance Program has been divided into specific Tasks and Subtasks, which are identified in Table 14. The projected scheduling for the performance of these tasks and subtasks is shown as Figure 30. This schedule includes items currently being performed as part of the "transition contract", funded by the FHWA to provide a smooth transition from the preceding Long-Term Monitoring work effort into the SHRP Long-Term Pavement Performance Studies. Most of the transition work effort is shown during Year "-1" on the performance schedule. The formal start of LTPP is considered in this schedule to be October 1, 1986, as this has been the established goal for SHRP funding. If funding is delayed, revisions in this schedule will be necessary.

It is believed that the flow of events depicted in Table 14 and Figure 30 is generally self-evident. However, it may be worthwhile to include some additional explanation. Tasks 2-1, 2-2, and 2-3 are preparatory to the implementation activities, and are to be completed during 1986. Tasks 2-4 and 2-5 are to be completed as early in 1987 as possible so that data collection for GPS (Task 2-6) can begin. The intent is to implement a total of 1200 GPS sites the first year, and 360 GPS the second year.

Preparations for implementation of the SPS are to begin in 1987 with general SPS data collection getting underway in 1988. The tentative planning for implementing SPS sections is for 88 sites the second year and 144 the third year. Limited analysis of data may begin in 1989 and analysis will continue then through 2007.

TABLE 14
TRA 2 IDENTIFICATION OF SPECIFIC TASKS AND SUBTASKS FOR LONG-TERM PAVEMENT PERFORMANCE STUDIES

Task	Subtask
2-1 DEVELOP LTPP IMPLEMENTATION PLAN	
	2-1.1 Develop Detailed GPS Experiment Plan
	2-1.2 Develop GPS Site Selection Procedures
	2-1.3 Develop Detailed SPS Experiment Plan
	2-1.4 Develop Instrumentation Criteria for SPS
	2-1.5 Evaluate Equipment for Measuring Distress and Performance
	2-1.6 Recommend Equipment and Develop Procurement Documentation
	2-1.7 Develop Information Management System
	2-1.8 Develop Integrated Implementation Plan
2-2 IMPLEMENT STATE PARTICIPATION AND SELECT TEST SECTIONS	
	2-2.1 Initial State Contacts
	2-2.2 Regional Meetings
	2-2.3 Initial SHA Identification of Candidate GPS Test Sections
	2-2.4 Screening Candidate GPS Test Sections
	2-2.5 State Visits to Review Proposed GPS Test Sections
	2-2.6 Selection of GPS Test Sections
	2-2.7 Initiate Procedures to Develop SHA Participation in Specific SPS Projects
2-3 PROCUREMENT OF SHRP CONTRACTS	
	2-3.1 Establish Final Contract Organizational Requirements (Central and Four Regions - Select Regional Office Locations)
	2-3.2 Develop RFP's for LTPP Contract Procurement
	2-3.3 Preparation of Proposals by Contractors
	2-3.4 Review of Proposals and Contractor Selections
	2-3.5 Contract Awards
2-4 MOBILIZING CONTRACTOR ORGANIZATIONS	
	2-4.1 Locating, Procuring, and Furnishing Office Space
	2-4.2 Hiring and/or Relocating Personnel
2-5 EQUIPMENT PROCUREMENT, INSTALLATION, AND CHECKOUT	
	2-5.1 Procurement of Automatic Vehicle Classification (AVC) Systems
	2-5.1.1 First Year GPS Sites
	2-5.1.2 Second Year GPS and SPS Sites
	2-5-1.3 Third Year SPS Sites

TABLE 14 (continued)
TRA 2 IDENTIFICATION OF SPECIFIC TASKS AND SUBTASKS
FOR LONG-TERM PAVEMENT PERFORMANCE STUDIES

Task Subtask

2-5.2 Installation and checkout of AVC Systems by SHA's

2-5.2.1 First Year GPS Sites
2-5.2.2 Second Year GPS and SPS Sites
2-5.2.3 Third Year SPS Sites

2-5.3 Procurement of Low-Cost Weigh-In-Motion (WIM) Systems

2-5.3.1 First and Second Year GPS and SPS Sites
2-5.3.2 Third Year SPS Sites

2-5.4 Installation and Checkout of WIM Systems

2-5.4.1 Sites Implemented First and Second Years
2-5.4.2 Sites Implemented Third Year

2-5.5 Procurement of Distress, Deflection, and Performance Measurement Equipment
2-5.6 Checkout Equipment and Establish Data Collection Procedures

2-6 GPS DATA COLLECTION

2-6.1 Implement IMS Plan for Handling Data (GPS and SPS)
2-6.2 Inventory Data Collection for All GPS Test Sections and Transfer of Data to Local and National Data Bases
2-6.3 Coring and Boring/Material Testing
2-6.4 Review of Inventory Data for Final Adjustments to Test Section Selections
2-6.5 Initiate Distress and Performance Monitoring and Transfer of Data to Local and National Data Bases

2-7 IMPLEMENTATION OF SPS PROGRAM

2-7.1 Development of Final Detailed Needs of Other TRA's for Field Test Sections
2-7.2 Coordination with SHA's to Develop Participation in Specific Studies (Special Design and Construction)
2-7.3 SHRP/SHA Coordination on Design
2-7.4 Develop Instrumentation Needs and Plan Installation
2-7.5 Construction of Special SPS Sections (Including Installation of Instrumentation)

2-8 SPS DATA COLLECTION

2-8.1 Inventory Data Collection for SPS Test Sections and Transfer to local and national data bases

TABLE 14 (continued)
TRA 2 IDENTIFICATION OF SPECIFIC TASKS AND SUBTASKS
FOR LONG-TERM PAVEMENT PERFORMANCE STUDIES

Task	Subtask
	2-8.2 Coring and Boring/Materials Testing
	2-8.3 Distress and Performance Monitoring and Transfer of Data to Local and National Data Bases
2-9 CONSIDERATION OF ACCELERATED PAVEMENT TESTING (APT)	
	2-9.1 ALF Shakedown Test, Trial Deployment, and Evaluation
	2-9.2 Evaluate Potential of APT
2-10 ANALYSIS OF LTPP DATA	
2-11 IMPLEMENTATION OF LTPP RESULTS	

FIGURE 30
TRA 2 SCHEDULE FOR SPECIFIC TASKS AND SUBTASKS
FOR LONG TERM PAVEMENT PERFORMANCE STUDIES
(SEE TABLE 9 FOR TASK AND SUBTASK IDENTIFICATION)

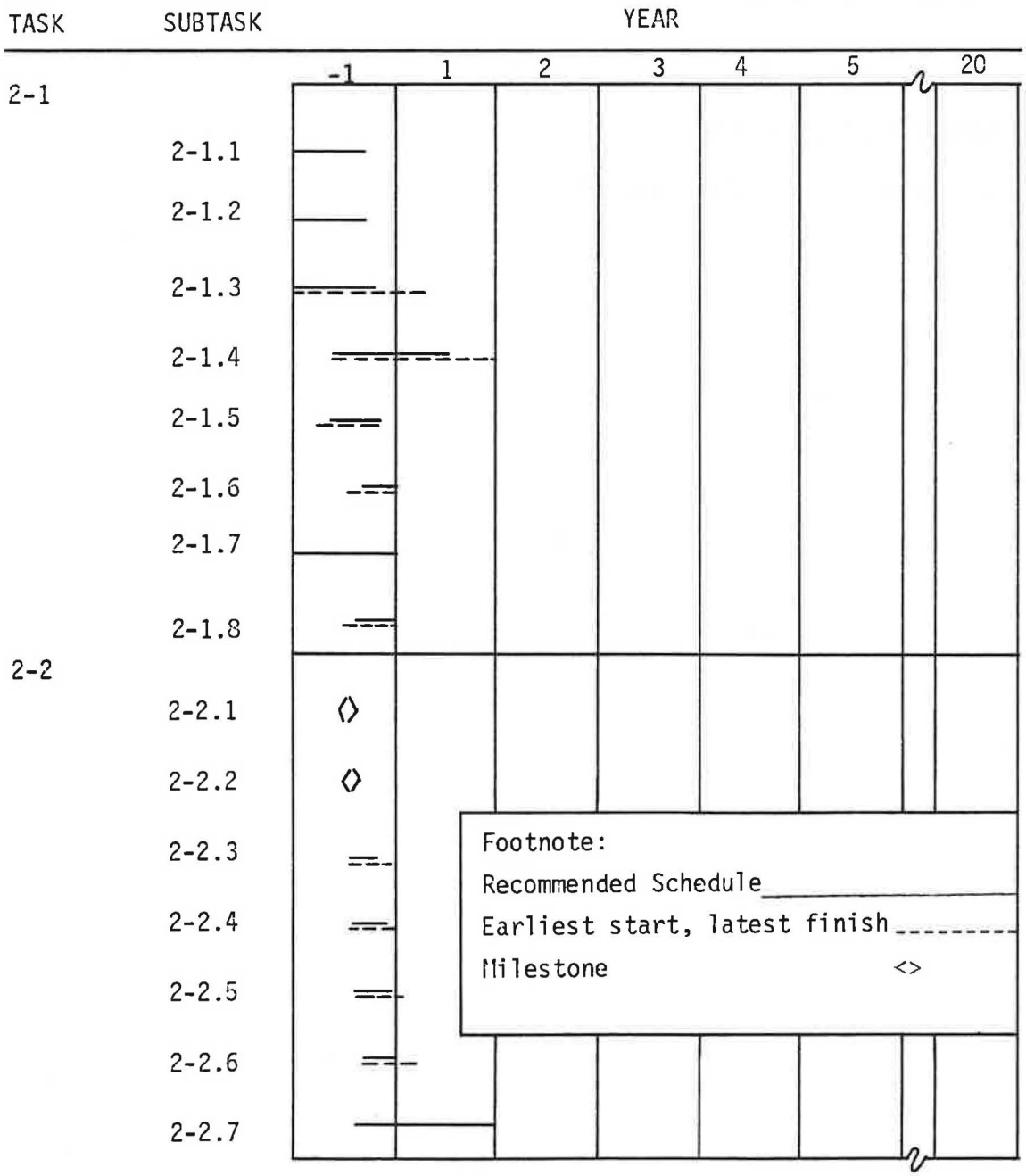


FIGURE 30
TRA 2 SCHEDULE FOR SPECIFIC TASKS AND SUBTASKS
FOR LONG TERM PAVEMENT PERFORMANCE STUDIES
(SEE TABLE 9 FOR TASK AND SUBTASK IDENTIFICATION)
(continued)

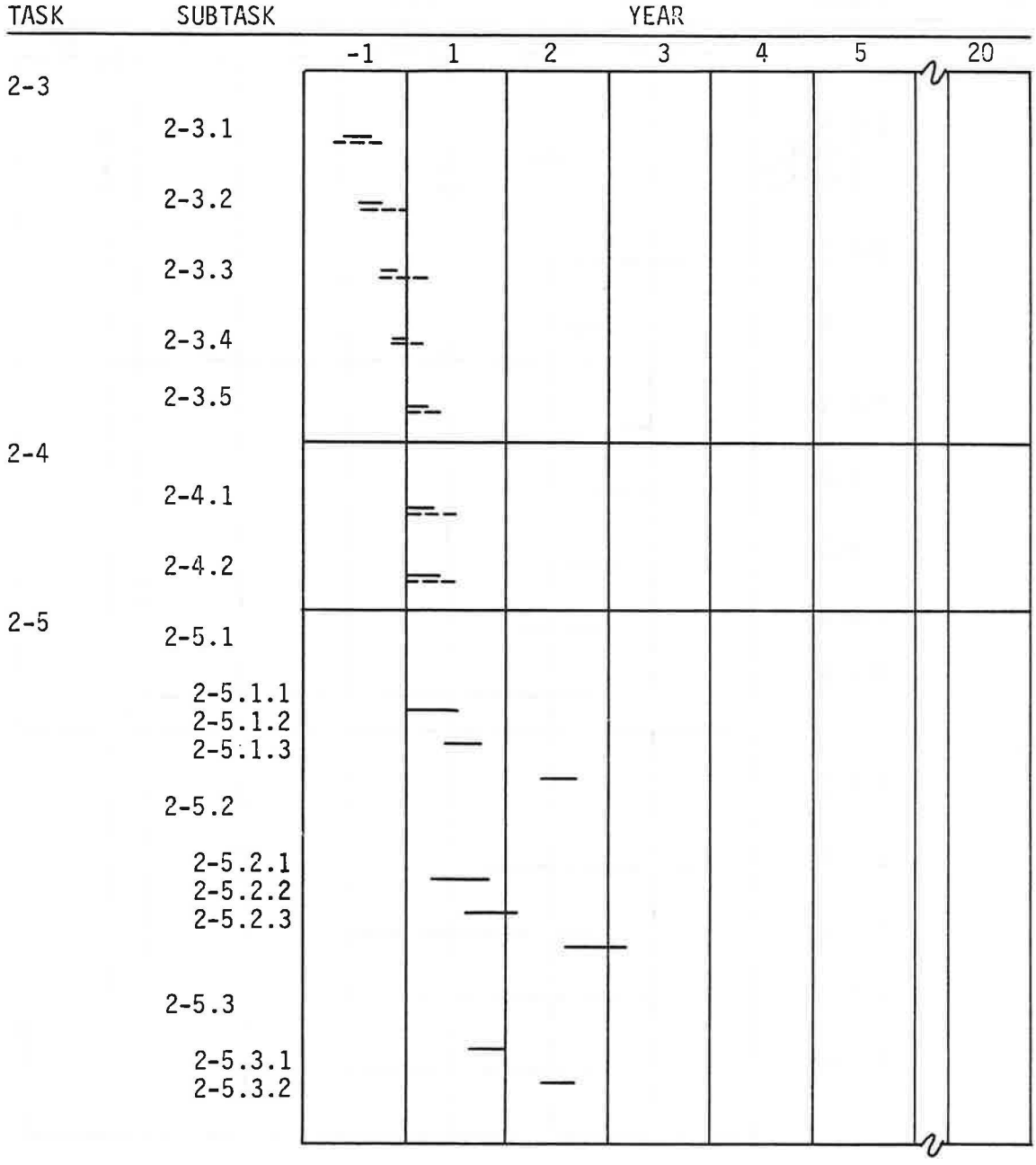


FIGURE 30
TRA 2 SCHEDULE FOR SPECIFIC TASKS AND SUBTASKS
FOR LONG TERM PAVEMENT PERFORMANCE STUDIES
(SEE TABLE 9 FOR TASK AND SUBTASK IDENTIFICATION)
(continued)

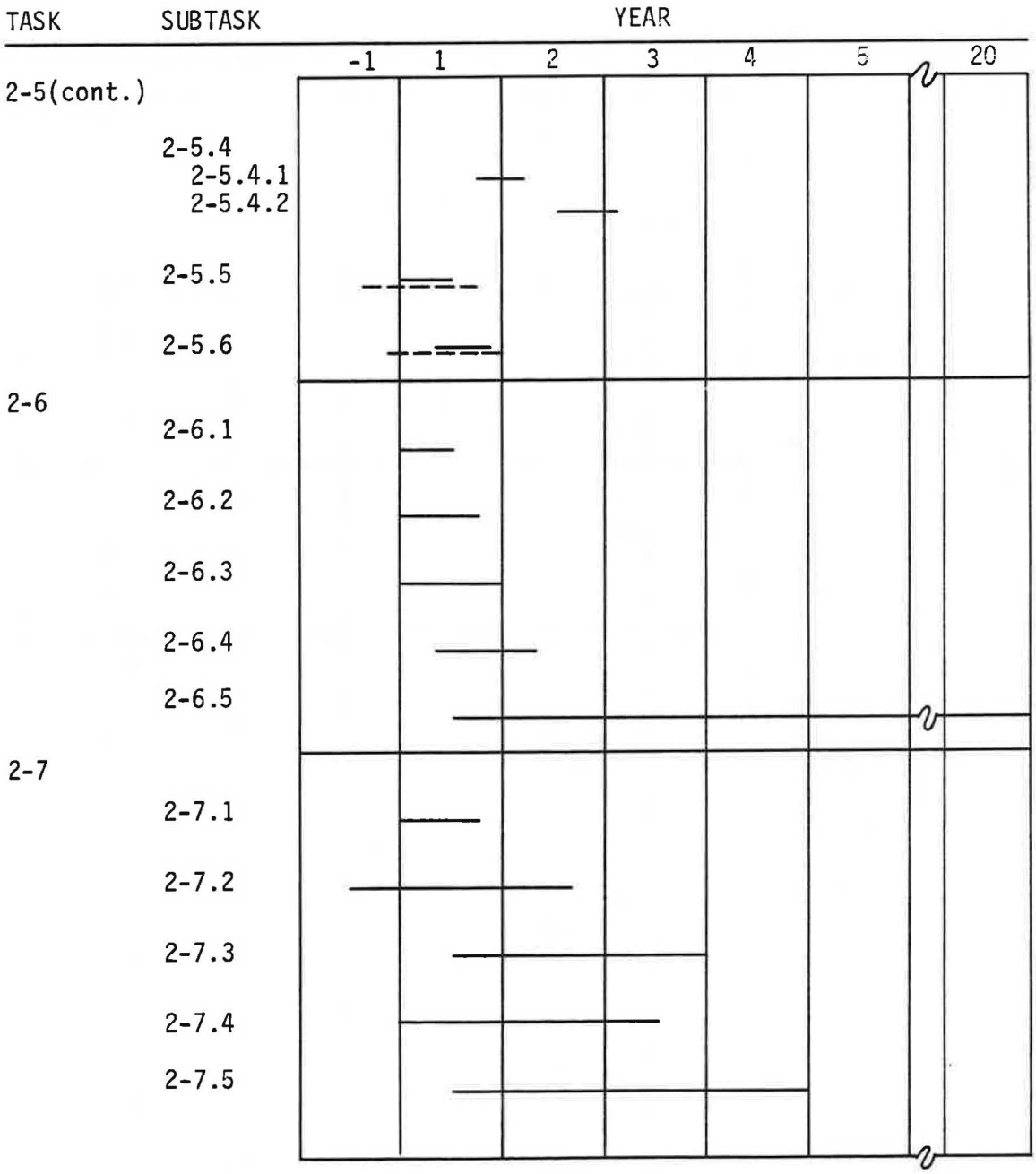
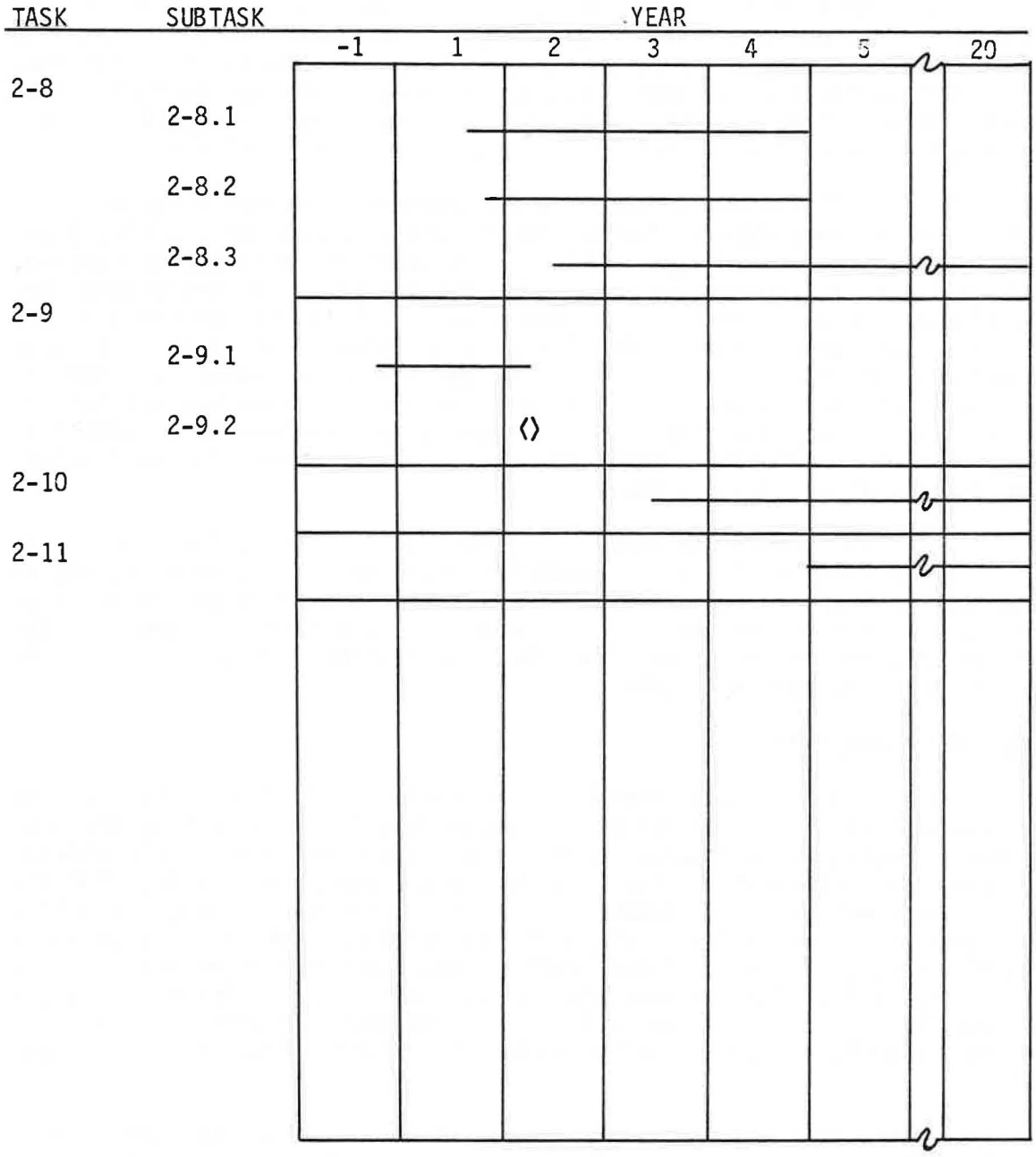


FIGURE 30
TRA 2 SCHEDULE FOR SPECIFIC TASKS AND SUBTASKS
FOR LONG TERM PAVEMENT PERFORMANCE STUDIES
(SEE TABLE 9 FOR TASK AND SUBTASK IDENTIFICATION)
(continued)



SECTION 8
TRA 2 BUDGET

As stated in Section 3, there has been an ongoing interaction during formulation of the research plan between estimated costs for managing and conducting the program, purchasing equipment, and material testing; numbers of GPS sections to be monitored; and numbers of SPS topics that can be studied. The primary constraint is, of course, the anticipated budget, which is estimated as ten million dollars per year in 1985 dollars.

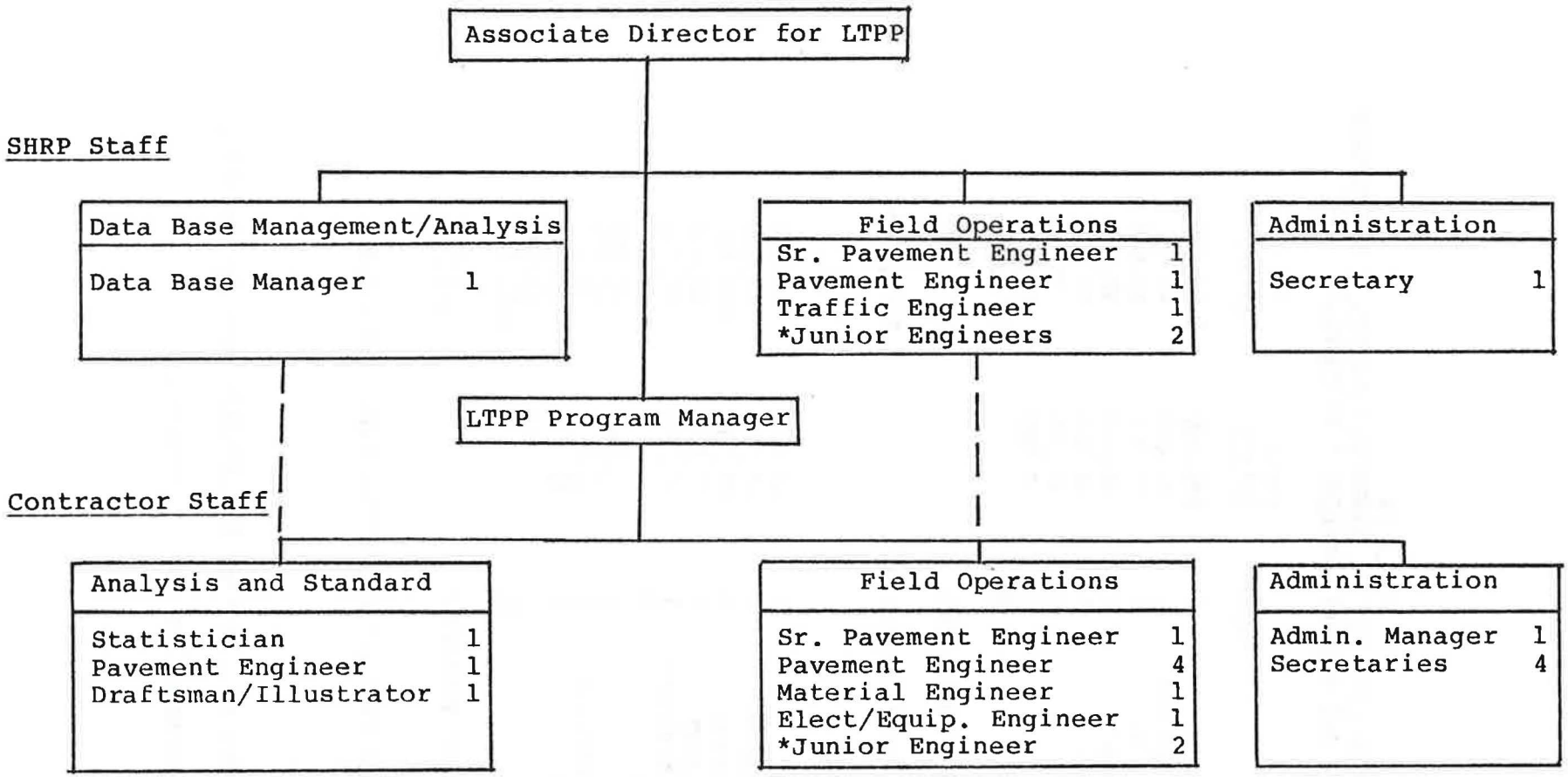
The SHRP Advisory Committee on Pavement Performance has provided guidance and recommendations during the iterative process of experiment design and preparation of cost estimates to match the anticipated funding. Some significant recommendations regarding the management of the program include the division of central management responsibilities between SHRP and contractor personnel, data collection on a regional basis by four regional contractors, and the use of SHRP funds to purchase most needed equipment to insure uniformity. A logical division of responsibilities between participating State Highway Agencies and SHRP regional contractors as presented in Table 9 (Section 3 of this report) was critically important to the development of the budget presented herein.

This section of the report provides cost estimates for budget purposes. In addition to the anticipated SHRP funding requirements, estimates of the SHA work effort requirements are also included based on the division of responsibilities presented in Table 9. These estimates are included herein as they are an additional fundamental requirement of the program, although not directly funded by SHRP.

CENTRAL LTPP MANAGEMENT

The Central Management Organization of the Long Term Pavement Performance Studies will be primarily responsible for implementing the program and managing these studies so that the established goals are achieved. The tentative organization chart adopted by the Advisory Committee for the central management group is shown on Figure 31. This chart indicates primary management by contractor staff, with limited SHRP staff to provide guidance and direction. The estimated staffing expense for this organization is shown on Table 15, with the resulting annual contractor staffing cost given as $1,355,000. This figure does not include the staffing costs for the central SHRP staff, which is not expected to be funded from the LTPP annual budget.

A breakout of the estimated equipment costs for the central management office is shown in Table 16. The total estimated cost of equipment



* FHWA or SHA personnel on loan to project.

FIGURE 31 · TRA 2 Organization Chart for Central LTPP Management, Limited SHRP Staff and Primary Management by Contract

TABLE 15
TRA 2 BREAKOUT OF LTPP CENTRAL STAFFING EXPENSES, LIMITED SHRP STAFF AND PRIMARY MANAGEMENT BY CONTRACT

Staff	Number	Annual Salary	Total Salary
Assoc. Director	1	$60,000	$ 60,000
Sr. Pavement Engineer	1	40,000	40,000
Sr. Data Base Adm.	1	40,000	40,000
Pavement Engineer	1	40,000	40,000
Traffic Engineer	1	40,000	40,000
Junior Engineer	2	30,000	**
Secretary	1	18,000	18,000
	8		$238,000
Overhead (150% of $238,000)			$357,000
Total Central SHRP			$595,000*
Contractor Staff			
Program Manager	1	60,000	60,000
Sr. Pavement Engineer	1	40,000	40,000
Pavement Engineers	5	40,000	200,000
Materials Engineer	1	40,000	40,000
Elect./Equip. Engineer	1	40,000	40,000
Junior Engineer	2		**
Statistician	1	40,000	40,000
Draftsman/Illustrator	1	20,000	20,000
Admin. Manager	1	30,000	30,000
Secretaries	4	18,000	72,000
	18		$542,000
Overhead (150% of $542,000)			813,000
Annual Contractor Staffing Cost			$1,355,000

*Not to be funded by LTPP from $10,000,000 expected annually.

**FHWA or SHA personnel on loan to project.

TABLE 16
TRA 2 BREAKOUT OF ESTIMATED EQUIPMENT COSTS FOR CENTRAL OFFICE, LIMITED SHRP STAFF AND PRIMARY MANAGEMENT BY CONTRACT

Items of Equipment	Estimated Costs
1. Vehicles, 3 @ $12,000	$ 36,000
2. Word Processing Equipment and Software	25,000
3. Micro Computers, Terminals and Ancillary Equipment	20,000
4. Misc. Equipment Not Identified	20,000
Total Estimated Cost	$101,000
Note: Amortizing over four years so assume annual cost of 25% of total purchase cost.	$ 25,250/yr.

for this office is given as $101,000, which includes a contingency of $20,000 for miscellaneous equipment not yet identified.

TYPICAL REGIONAL ORGANIZATION

Current planning provides for four regions to be established for the SHRP LTPP program, and the program will be conducted in each of these regions by a Regional Contractor. The Organization Chart for a typical regional office is shown in Figure 32. These contractors will report directly to the central management organization. They will also work closely with the participating State Highway Agencies in their region.

The regional contractors will be directly responsible for all activities necessary for implementation and operation of the program. Much of the initial work such as initiating the cooperative efforts with State Highway Agencies and the selection of test sections will have been completed during the "transition period", but some adjustment during implementation will undoubtedly be required. Policy matters will generally be coordinated through SHRP/AASHTO channels.

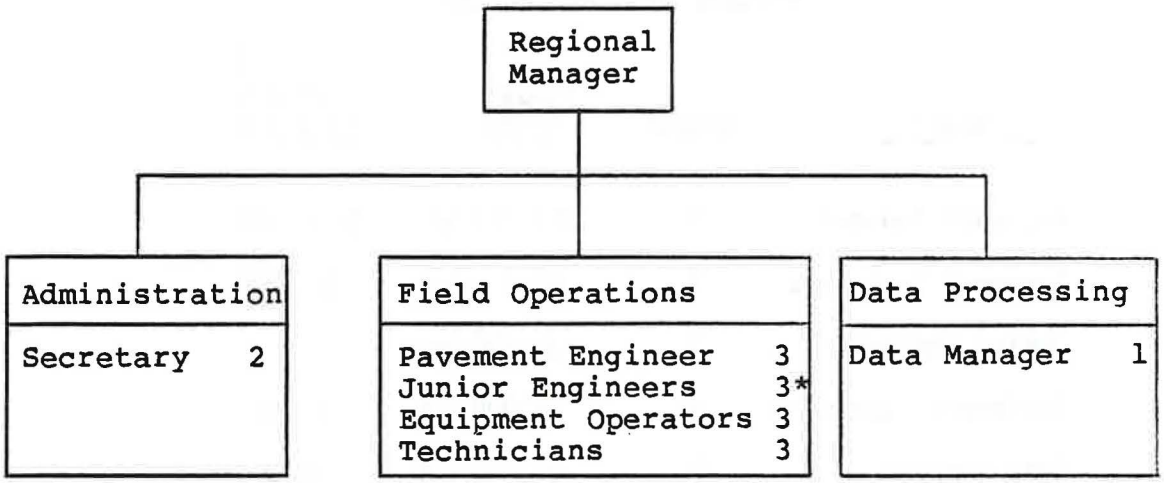
The estimated costs for staffing, operating expenses not included in overhead, and equipment costs appear in Tables 17, 18, and 19, respectively. The breakout of estimated costs for material testing for rigid pavements appears in Table 20 and for flexible pavements in Table 21. It is considered for purposes of this estimate that the primary material testing effort will occur during the first 3 years as new test sections are entered into the study, but $15,000 per year has been included for subsequent years as there will undoubtedly be other test sections added or other needs for material testing.

Although substantial costs for material testing will be required to support other TRA activities (especially studies for asphalt, concrete, and maintenance cost effectiveness), only the requirements for TRA 3, Maintenance Cost Effectiveness, are sufficiently defined to have been included in these cost estimates. This does not represent a problem for LTPP cost estimating as the other TRA's will be expected to fund their requirements to the extent that they are excess to LTPP study needs. In fact, the planning for TRA 3 included the expectation of funding all or a portion of the two maintenance studies presently included in the SPS experiment design. One example of a known requirement for asphalt studies will be periodic coring and material testing for asphalt concrete materials on selected SPS projects. This data will be needed to study the aging process in asphalt concrete mixtures. TRA 2 will also need expanded sampling programs for their projects to support much broader testing requirements in terms of additional tests and the development of new test procedures.

Finally, Table 22 provides an estimated cost for a typical regional operation for the 5-year funding period. This table includes staffing, material testing, operating costs, and equipment costs to derive the annual funding requirements for the LTPP studies.

TOTAL ESTIMATED COST TO SHRP FOR A FIVE YEAR PROGRAM

The costs for the central organization and regional organizations have been combined to develop a total five year cost for the Pavement



* SHA personnel on loan to project.

FIGURE 32.TRA 2 Organizational Chart for Typical SHRP Regional Organization

TABLE 17
TRA 2 BREAKOUT OF REGIONAL STAFFING EXPENSES, FOR A TYPICAL REGIONAL OFFICE

Staff	Number	Annual Salary	Total Annual Salaries
Regional Manager	1	$50,000/yr	$ 50,000
Pavement Engineers	3	40,000/yr	120,000
Junior Engineers	3	30,000/yr.	*
Equipment Operators	3	20,000/yr.	60,000
Data Manager	1	30,000/yr.	30,000
Secretary	2	18,000/yr.	36,000
Technician	3	20,000/yr.	60,000
Payroll			$356,000
Overhead @ 150% (Contractor Personnel)			534,000
Overhead for SHA Personnel @ 100% of $90,000			90,000
		Total	$980,000/yr.

* SHA personnel on loan to project

TABLE 18
TRA 2 BREAKOUT OF OPERATING EXPENSES FOR A TYPICAL REGIONAL OFFICE

	ITEM OF EXPENSES	ESTIMATED ANNUAL COSTS
1.	Telephone Calls, $700/mo. x 12	*
2.	Auto Operating Expenses, 6 vehicles @ 30,000 miles each @ $0.21/mile	37,800
3.	Parts and Outside Repairs for Equipment, (other than AVC and WIM estimated @ 5% of acquisition Costs)	41,800
4.	Air Transportation, 12 trips per month x 12 @ $300	*
5.	Per Diem, 144 trips @ 3 days x $60	*
6.	Ground Transportation for Trips, 144 trips @ $40 Average	*
7.	Express Mail, 30 per month x 12 x $20 Average	*
8.	Per Diem, 6 persons with average of 120 days/yr. x $60	43,200
9.	Misc. Other Expenses	25,000
	Est. Annual Cost	$147,800**

* Included in Overhead
**Material testing costs not included.

TABLE 19
TRA 2 BREAKOUT OF ESTIMATED EQUIPMENT COSTS FOR TYPICAL REGION

Items of Equipment	Assuming 25 Percent of AVC and WIM Funded by SHRP
1. Device Combining a) profilometer, b) rut measurement, and c) photographic recording of distress	$ 500,000
2. Falling Weight Deflectometer with Van, 2 @ $100,000	200,000
3. Electronics and Cabinet for AVC, WIM, and Telemetry plus modem, 448 units at $2500	280,000
4. Central AVC/WIM Data Collection Centers, 12 units at $20,000	60,000
5. Piezoelectric cable sensors for WIM, 448 units at $600 per 2-lane instl.	67,200
6. Additional site equipment, such as temperature control, and cost for utility connections to site; 448 sites at $1500	168,000
7. Micro Computers and Ancillary Equipment	30,000
8. Shop Equipment for Maintenance	20,000
9. Project Vehicles, 3 @ $12,000	36,000
10. Instrumentation, 49 Test Sections @ $2500	123,000
11. Miscellaneous Equipment	50,000
Total Estimated Cost	$1,532,000
Note: Amortize over four years, so assume annual cost of 25% of total purchase cost.	$ 383,500

TABLE 20
TRA 2 BREAKOUT OF ESTIMATED COSTS, MATERIAL TESTING FOR RIGID PAVEMENTS (IN 1985 DOLLARS)

Test	Unit Cost	Average Number	Estimated Costs
Concrete Testing			
Compressive Strength	$ 25	3	$ 75
Indirect Tensile Strength	25	3	75
Elastic Modulus	40	3	120
Soil Testing			
Sieve Analysis on Subbase Material	$ 40	4	160
Atterberg Limits on Subbase Material	25	4	100
Sieve Analysis on Subgrade Soil	25	3	75
Atterberg Limits on Subgrade Material	25	3	75
Coring and Boring			800
Total for a Rigid Pavement Section			$1480

GPS:

*568 Sections x $1480 =	$840,640
1/4 Per Region (142 sections) =	$210,160 /region
GPS Materials Testing to be performed during the First Year of the Project	

SPS:

**170 Sections x $1480 =	$251,600
1/4 Per Region (42.5 Sections) =	$ 62,900 /region
First Year (None)	0
Second Year (10 Sections) =	$ 14,800 /region
Third Year (16.5 Sections) =	$ 24,420 /region
Fourth Year (16 Sections) =	$ 23,680 /region

* AC overlay over jointed PCC not included here.

** This number was developed by considering the nature of the testing requirements for individual SPS studies. It generally involves more than one, but less than the total of sections at a location.

TABLE 21
TRA 2 BREAKOUT OF ESTIMATED COSTS, MATERIAL TESTING
FOR FLEXIBLE PAVEMENTS (IN 1985 DOLLARS)

Test	Unit Cost	Average Number	Estimated Costs
Asphalt Concrete			
Extraction of Asphalt	$ 95	2	$ 190
Viscosities of Asphalt at 140 and 275F (ASTM D2171)	140	2	280
Ductility of Asphalt (ASTM D113)	120	2	240
Penetration at 77F (ASTM D5)	120	2	240
Softening Point (ASTM D36)	100	2	200
Density	25	3	75
Dynamic Modulus of Asphalt Concrete at Three Temperatures (ASTM D4123-82 or ASTM D3497-79)	225	2	450
Soil Testing			
Atterberg Limits on Base Material	25	4	100
Sieve Analysis on Base or Subbase	40	4	160
Moisture-Density Compaction Tests on Base, Subbase, or Subgrade Materials	100	2	200
Resilient Modulus for Base, Subbase, or Subgrade Materials	80	4	320
Sieve Analysis on Subgrade Soil	40	3	120

TABLE 21
TRA 2 BREAKOUT OF ESTIMATED COSTS, MATERIAL TESTING
FOR FLEXIBLE PAVEMENTS (continued)

Test	Unit Cost	Average Number	Estimated Costs
Atterberg Limits on Subgrade Soil	25	3	75
Hydrometer Analysis	75	2	150
In situ Dry Density for Base or Subbase	Assumed to be measured by Drill Crew		
In situ Moisture Content	Assumed to be measured by Drill Crew		
Coring and Boring			800
Total for a Flexible Pavement Section			$3600

GPS:

992 Sections x $3600 = $3,571,200

1/4 per region (248 Sections) = $892,800/region

GPS Materials Testing to be performed during the First Year of the Project.

SPS:

*216 Sections x $3600 = $777,600

1/4 Per Region (54 Sections) = $194,400/region

First Year (None) = 0

Second Year (13.5 Sections) = $ 48,600/region

Third Year (20 Sections) = $ 72,000/region

Fourth Year (20.5 Sections) = $ 73,800/region

*This number was developed by considering the nature of the testing requirements for individual SPS studies. It generally involves more than one, but less than the total of sections at a location.

TABLE 22
TRA 2 ESTIMATED COST FOR A TYPICAL REGIONAL OPERATION
BY YEAR (IN THOUSANDS OF 1985 DOLLARS)

(Estimated 25 Percent of AVC and WIM Equipment Funded by SHRP)

Year	Staff	Material Testing	Operating Costs	Equipment	Total Cost
1	980	1,103	148	299	2,530
2	980	63	148	460*	1,651
3	980	96	148	588*	1,812
4	980	97	148	505*	1,730
5	980	15	148	119*	1,262
		Totals for 5 Years			$ 8,985
		Totals for 4 Regions			$35,940

*Includes interest @11% of unpaid balance and $50,000 additional equipment purchased.

Performance studies, as shown in Table 23. As may be seen, the proposed organization plan requires funding of $42,816,000, with approximately $7,200,000 remaining of the anticipated $50,000,000 budget. While every effort has been made to insure the accuracy of these estimates, it is believed that a substantial contingency fund must be included for unanticipated costs.

ESTIMATE OF STATE HIGHWAY AGENCY WORK EFFORT

In determining a reasonable estimate of the average State Highway Agency work effort required for participation in the LTPP program, consideration was given to those items listed in Table 9. These items were considered in the order shown, with reasonable estimates of the work effort (man-hours) involved for each based on information gained from the LTM Pilot Studies, discussions with SHA personnel, and our own experience. The estimates are given on the basis of one evaluation cycle for one section.

It has been assumed that all 50 states will be participants. Given the total number of GPS sites considered, this results in approximately 31 GPS sections per state. In addition, considering the total number of SPS experiments, and with the assumption that there shall be 7 SPS sections per location, then SPS will require an additional 5 locations per state. Therefore, for estimating purposes, the number of study locations per state was taken as 36.

During the selection of candidate sites, it is expected that the state will review more site locations for submittal than will actually be selected. For estimating purposes, it is expected that roughly twice the number of sections per state may be reviewed as candidate sections. This implies that the average participating SHA will collect the minimum inventory data items for submittal of at least 72 site locations.

Identification of Candidate GPS Sites

Identification of candidate GPS sites is expected to require collection of a subset of the inventory data items identified in the LTM Data Collection Guide, to be established as the "minimum data set for site selection". Based on information provided by those SHA's that are participating in the LTM Pilot Study program, an approximate work effort for collecting the limited set of inventory data items per site was evaluated. It is estimated that development of the required data for an average candidate LTPP site should require approximately 20 man-hours, which will include collection of the minimum data set and one visual site review. It is expected that the site review will be accomplished by local or district personnel to minimize travel time, and will include taking a few photographs of the site for review during the site selection process.

Once the sites have been tentatively selected, current planning requires a visit to the SHA by a team of two persons, including a representative of SHRP and one person from the contractor staff. This state visit should occur over a period of approximately one week, and should require about 80 man-hours of SHA work effort.

TABLE 23
TRA 2 ESTIMATED LTPP COST (IN THOUSANDS OF 1985 DOLLARS)
FOR FIVE YEAR PROGRAM
(ESTIMATED 25 PERCENT AVC AND WIM EQUIPMENT FUNDED BY SHRP)

Cost Items	Estimated Costs
Central Organization:	
Staff	2,710
Overhead	4,065
Equipment Costs	101
Subtotals	6,876
Regional Organizations:	
(from Table 17)	35,940
Total Estimated LTPP Costs	42,816
Remaining Funds	7,184

Inventory Data Collection for GPS Test Sections

Following final selection of the LTPP GPS sites, it will be necessary for the SHA to collect the remaining inventory data items for the sites selected, except for data to be derived from coring, boring, and material testing. It is estimated that this should require approximately 15 man-hours per site.

Assign a SHRP Coordinator

One of the requirements of a participating SHA will be to assign a specific person to act as a liaison between the SHRP staff and the participating SHA. Guidelines for the selection of the SHRP coordinator will be developed by SHRP. While the early stages of the LTPP effort may require a large percentage of the SHRP coordinator's time it is anticipated that on the average approximately 25 percent of the coordinator's time should be devoted to the LTPP effort.

Maintenance Data

The nature of the maintenance data to be collected has not as yet been established. It may be assumed, however, that it will be in terms of physical descriptions as well as fiscal data, so it will most usually not be in a form consistent with current SHA maintenance reporting procedures. Also, it will be for the specific test section, not the segments of a highway normally included as one unit for reporting.

Rehabilitation/Reconstruction Data

This data is reported only initially if the test section has been previously rehabilitated, or subsequently when rehabilitated or reconstructed during the monitoring period. It is expected that this will require 10 man-hours or less when such an event occurs.

Traffic Count, AVC, WIM

It is expected that the primary work effort required from the SHA with regard to the traffic count, AVC, and WIM equipment will be during the installation of the systems. Based on discussions with SHA personnel with experience in installation of this type of equipment, it is estimated that each installation will require about 48 man-hours. Once the automated capability with remote query is established, data collection effort is minimized. Some periodic maintenance and repair may also be required, but it is expected that these sites will usually become part of the SHA traffic study activity.

While traffic control will also be required during the installation period, this is discussed in a subsequent section.

Skid Resistance Data

Based on information provided by various SHA's currently collecting skid resistance data, it is estimated that each site will require approximately 6 man-hours for measurement of ten points within each of three,

one-tenth mile long subsections, located at the beginning, middle, and end of the LTPP site. This estimate includes travel between sites.

Traffic Control

It is anticipated that traffic control will be provided by the SHA through a district or local office during installation of the AVC and WIM equipment, and during the nondestructive pavement testing. Installation of the AVC and WIM equipment will generally occur once at each site location, and should require approximately 16 man-hours for traffic control. However only AVC equipment will be installed for those GPS test sections implemented the first year and WIM equipment will be delayed a year, so traffic control will be required twice for the first-year GPS sites. Current planning includes nondestructive testing of the pavements every two years, with each evaluation requiring approximately 8 man-hours for traffic control personnel.

Construction of Special Sections

It is not possible to estimate with much confidence the SHA work effort required for the construction of special sections, but it is possible to identify what will generally be involved. There will surely be a considerable work effort in coordinating the specific study requirements with SHRP representatives and identifying the specific design and construction details to be included. Designs and bid documents must be developed for each of the test sections.

There will undoubtedly be additional coordination required with construction contractors because of the multiplicity of pavement sections, plus closer construction inspection requirements than usual. For many studies, instrumentation will be required and must be installed during construction.

The amount of time involved will also depend on the scope of the specific experiments and their specific needs.

TECHNICAL RESEARCH AREA 3
DETAILED PLANNING FOR RESEARCH ON MAINTENANCE EFFECTIVENESS

Prepared for:
NCHRP Project Number 20-20(5)
Pre-Implementation Activities for the
Strategic Highway Research Program (SHRP)

January 1986

Prepared by:

Texas Research and Development Foundation
2602 Dellana Lane
Austin, Texas 78746

TABLE OF CONTENTS

		Page
	LIST OF FIGURES	TRA 3-ii
	LIST OF TABLES.	TRA 3-iii
	ABSTRACT.	TRA 3-iv
	SUMMARY OF FINDINGS	TRA 3-v
	ACKNOWLEDGEMENT	TRA 3-viii
SECTION 1	STATEMENT OF THE PROBLEM.	TRA 3-1
SECTION 2	GOALS AND OBJECTIVES OF THE PLAN.	TRA 3-3
SECTION 3	FORMULATION OF THE PLAN	TRA 3-4
SECTION 4	RECOMMENDED RESEARCH PLAN	TRA 3-14
SECTION 5	RESULTS TO BE ACHIEVED.	TRA 3-47
SECTION 6	IMPLEMENTATION OF RESULTS	TRA 3-53
SECTION 7	SCHEDULE OF PROJECTS, TASKS AND SUBTASKS.	TRA 3-54
SECTION 8	BUDGET.	TRA 3-57
APPENDIX A	TRA-3 POTENTIAL PROJECTS CONSIDERED BUT NOT INCLUDED IN RECOMMENDED RESEARCH PROGRAM.	TRA 3-A-1
APPENDIX B	BIBLIOGRAPHY.	TRA 3-B-1

LIST OF FIGURES

		Page
1.	HIGHWAY MAINTENANCE EXPENDITURES EXTRAPOLATED TO 1990 USING 8.75 PERCENT INCREASE PER YEAR. . . .	TRA 3-2
2.	MATRIX OF PROBLEMS AND PROCESSES TO SOLVE PROBLEMS.	TRA 3-11
3.	DESIGN FACTORIAL FOR MAINTENANCE COST-EFFECTIVENESS STUDIES	TRA 3-20
4.	PROJECT SCHEDULE FOR RESEARCH STUDY ON MAINTENANCE COST-EFFECTIVENESS.	TRA 3-55

LIST OF TABLES

		Page
1.	PROPOSED RESEARCH PLAN ON MAINTENANCE COST-EFFECTIVENESS	TRA 3-vi
2.	PROJECT STATEMENT EVALUATION FORM	TRA 3-7
3.	RESEARCH DESIGN PRESENTED AT THE NATIONAL WORKSHOP IN DALLAS.	TRA 3-10
4.	TRA 3 BUDGET.	TRA 3-58

ABSTRACT

A research plan is presented for investing 20 million dollars over five years to improve maintenance cost-effectiveness. The plan addresses the need for better maintenance management information by proposing projects to evaluate pavement maintenance effectiveness, and to develop automative procedures to collect and reduce pavement condition data following pavement treatments.

A project on improved materials, methods and equipment focuses on improving pavement surface repair and crack/joint sealing activities. Motorist and worker safety are considered in a project on improved traffic control devices and procedures for short-duration maintenance activities. Achieving the actual implementation of the maintenance research results is approached by proposing research to identify contemporary marketing technology in getting research used.

SUMMARY OF FINDINGS

This research plan addresses highway maintenance cost-effectiveness improvements by developing better information with which to manage resources, and by applying technological innovation to maintenance materials, equipment, and methods to increase productivity.

The plan consists of the five projects shown in Table 1. Project 3-1 concerns the need to understand maintenance treatment effectiveness in terms of pavement condition improvement and extended life. The study will parallel and be coordinated with the long-term pavement performance study over five years. This scientifically designed study will create a data base to evaluate the effectiveness of four flexible pavement maintenance treatments and two rigid pavement treatments. The project will generate a data base that includes environmental, traffic, extensive pavement characterization information, and performance data. The end product will be an understanding of the maintenance effectiveness of six specific pavement treatments, plus a study guide to be used by highway agencies in evaluating other maintenance treatments.

Project 3-2 was created to help highway agencies evaluate pavement maintenance effectiveness. Maintenance practices vary widely from one agency to another. The six specific treatments being studied in Project 3-1 cover only a few of the many variations in treatments, conditions, and environments. There remains a need to understand the effectiveness of pavement treatments not studied.

Project 3-1 will provide a procedural guide and outline extensive data collection needs. However, highway agencies are unlikely to fund and duplicate the data acquisition processes used in the research. Faster, more accurate, automated, and cost-effective data acquisition procedures are needed. Project 3-2 focuses on this problem by outlining a study program to develop measuring methods and instrumentation to quantify pavement conditions and the factors that influence pavement conditions. The study will define measurement needs and identify existing equipment, instrumentation, or methods that can be used in the measurement process. When existing technology is deficient, new instruments and processes will be developed. The study will produce specifications for measurement processes plus standard measurement and data reduction procedures.

The maintenance process can be made more cost-effective through the use of better materials, equipment and methods. This applies to both the maintenance activity and the traffic control procedures used to protect the motorist and worker during maintenance work.

TABLE 1
PROPOSED RESEARCH PLAN ON MAINTENANCE COST-EFFECTIVENESS

Improved Management Processes	Technological Improvements
Project 3-1 Quantifying Pavement Maintenance Effectiveness Task 3-1.1- Detailed experimental plan 3-1.2- Implementation plan 3-1.3- Implementation 3-1.4- Pavement treatment effectiveness evaluation 3-1.5- Training package **Project 3-2 Measuring Systems and Instrumentation for Evaluating Pavement Maintenance Effectiveness** Task 3-2.1- Existing measuring systems evaluation 3-2.2- New systems terms of reference 3-2.3- Prototype equipment fabrication and testing 3-2.4- Training package	**Project 3-3 Improved Materials and Equipment for Pavement Repairs and Crack Filling** Task 3-3.1- Available materials survey 3-3.2- Available equipment survey 3-3.3- Laboratory and field testing of materials 3-3.4- Develop equipment 3-3.5- Long-term material field testing 3-3.6- Training package **Project 3-4 Pavement Maintenance Work Zone Systems to Improve Worker and Motorist Safety** Task 3-4.1- Evaluate devices and procedures 3-4.2- Guides for new traffic controls 3-4.3- New traffic control development and testing 3-4.4- Training package
Implementing Research Results	
Project 3-5 Media Evaluation and Implementation Research in Highway Maintenance	

Project 3-3 will study the materials, equipment and procedures used in two prevalent pavement treatments: localized pavement surface repairs (essentially patching), and pavement joint and crack sealing. These activities will be studied for flexible and rigid pavements, urban and rural situations, both low and high traffic volumes, and all climatic conditions. The study is expected to identify a number of new and innovative applications for existing materials and material combinations. Also sought will be existing and new equipment to handle materials more efficiently, and finally, more productive procedures for executing the two pavement maintenance activities.

Project 3-4, on workzone systems, recognizes that major improvements in pavement activity productivity must be complemented with faster and more efficient procedures to install and remove traffic controls. This project will create objective procedures to evaluate both existing and newly developed devices and equipment. Emphasis is placed on developing better barriers, attenuators, and warning systems to improve motorist and worker safety. The end products will include specifications on the new materials and devices, plus training guides on improved traffic control installation and removal procedures.

Project 3-5 comes to grip with a fundamental concern of the maintenance community, i.e., getting research results used. New and innovative ways to implement research results are wanted. Contemporary marketing technology will be examined in depth, and specialists in this technology will interact with the maintenance research consultants for Projects 3-1 through 3-4. Together, they will produce a series of implementation units which will have been tested, evaluated, and modified to ensure their effectiveness in reaching the target constituencies.

ACKNOWLEDGEMENT

The research reported herein was performed under NCHRP Project 20-20(5) by the Texas Research and Development Foundation (TRDF). Bertell C. Butler Jr., President of TRDF, was the principal investigator. The other authors of this report are: Matthew J. Betz, Professor of Civil Engineering at Arizona State University and Kenneth A. Brewer, Professor of Civil Engineering at Iowa State University.

SECTION 1
STATEMENT OF THE PROBLEM

Nationwide alarm is being expressed concerning the condition of the country's streets and highways. Maintenance requirements are increasing as the roads increase in complexity, age and deteriorate following exposure to the environment and greater traffic loadings. State and local highway maintenance expenditures have grown nationwide at 8.75 percent per year over the past 15 years, as shown in Figure 1. They are expected to reach an annual level of 18 billion dollars by the end of 1985. Despite these ever-increasing expenditures, highway agencies are unable to cope with worsening conditions since inflation erodes the purchasing power of their resources. Ways must be found to improve the cost-effectiveness of future road maintenance expenditures.

Highway maintenance organizations are still budgeting based on historical experience. This perpetuates inequities and can result in widely diverse maintenance levels being practiced within the same organization. Increasing maintenance funds have not kept pace with inflation so each year's budget produces less labor, equipment and material. Opportunities to enhance maintenance efficiency lie in developing technological improvements in the equipment, materials, and processes used for maintenance. Also, better methods are needed to budget, program, schedule, and control maintenance resources. These objectives will require changes that can be guided by research.

Less than one percent of the Federally Coordinated Program of Highway Research and Development (FCP) is allocated for maintenance research. This reflects the lack of a constituency within the maintenance community who can lobby for research funds to address an area that is responsible for almost one-third of all highway expenditures. Consequently, very little research has been conducted to improve maintenance administrative practices and operational processes. At the state level, maintenance research is neglected because available funds are inadequate to handle the necessary maintenance workload caused by the increasing complexity of the physical plant. Centerline miles have increased only slightly over the past 20 years, averaging less than one-half percent increase per year. However, paved lane miles have increased substantially and the number of appurtenances such as signs, signals, lighting, reflectors, guardrails and so on have grown to enhance motorist safety. This increased inventory of maintainable highway components together with motorist expectations for even greater maintenance service levels will require every cent of available maintenance resources. As a result, limited funds are left over to invest in the research that can improve the cost-effectiveness of the resources actually invested.

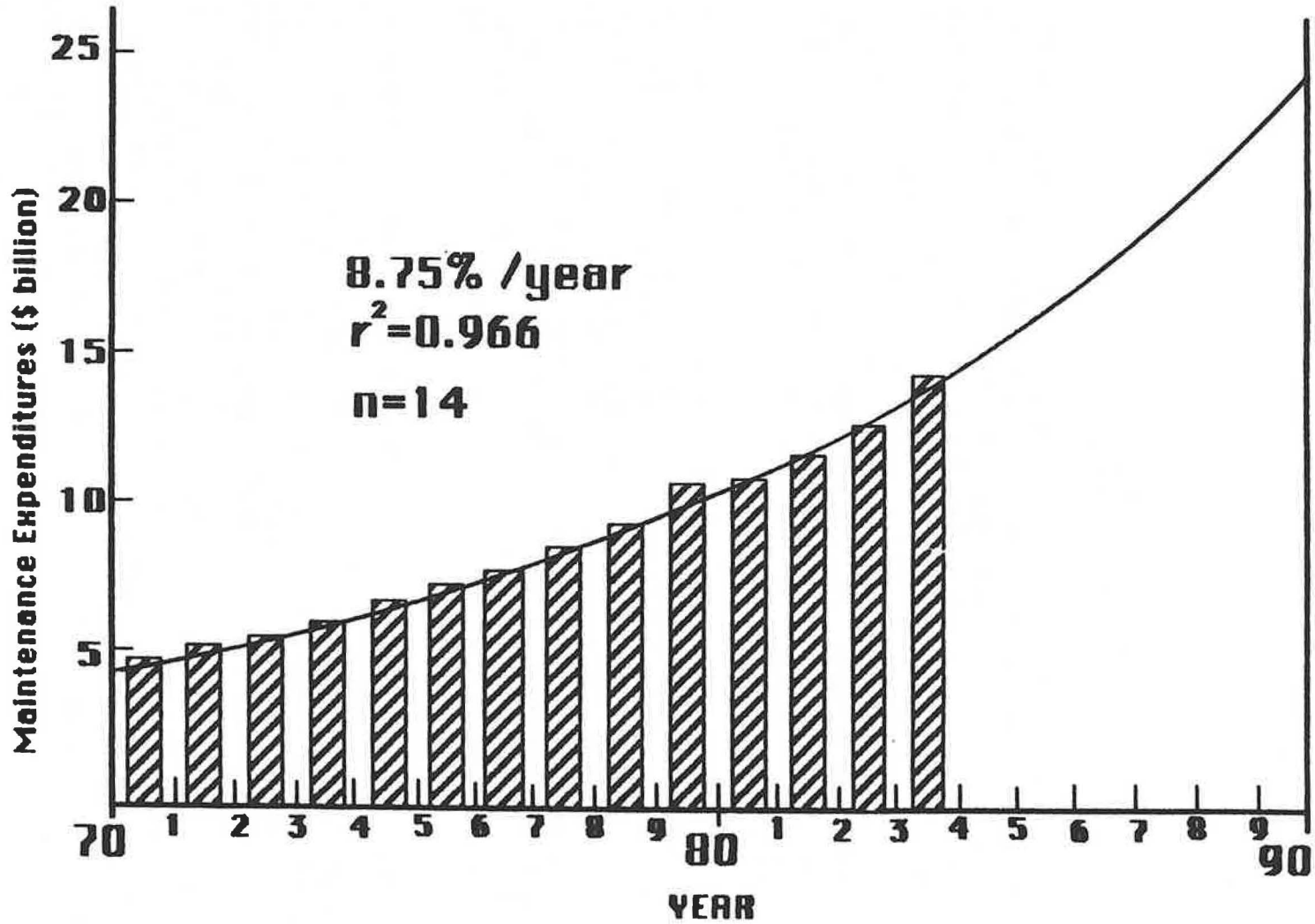


FIGURE 1. HIGHWAY MAINTENANCE EXPENDITURES EXTRAPOLATED TO 1990 USING 8.75 PERCENT INCREASE PER YEAR

SECTION 2
GOALS AND OBJECTIVES OF THE PLAN

Maintenance cost-effectiveness can be improved if maintenance managers are provided with better ways to budget, program and allocate resources. Further improvement can be achieved if the resources of labor, equipment and materials are used more efficiently. Therefore, the objective of this maintenance cost-effectiveness study is to conduct research that will lead to:

- Management information systems that will provide better capabilities of developing budgets, administering programs and allocating resources.
- Technological improvements in equipment, materials and processes that will increase productivity.

SECTION 3
FORMULATION OF THE PLAN

BACKGROUND REVIEW

A literature review of past identified research needs and ongoing research was conducted to provide insight to various areas of opportunity and to avoid redundancy in the program formulation. The materials reviewed are included in the study bibliography as Appendix B. Of considerable value in identifying past areas of highway maintenance research needs were the reports from maintenance research needs studies in 1975 at Lost Valley, Colorado and 1980 in Minneapolis, Minnesota. Although some of the study areas had generated successful research, the majority had not, and were therefore still fruitful areas for maintenance research. Also of considerable value was the chapter on maintenance cost-effectiveness in the report entitled "Strategic Transportation Research Study Technical Design" from the AASHTO Select Committee on Research to the AASHTO Executive Committee. Other maintenance-related literature was searched for research recommendations based on study results and to determine the present state-of-the-art in candidate research project areas.

Direct personal contacts were made with numerous highway personnel from federal, state and local agencies not included in the Advisory Committee. These contacts also helped to develop information on research needs and to evaluate the progress of ongoing studies. Discussions with maintenance personnel in the United Kingdom from the Ministry of Transport revealed that they had initiated studies to determine the effectiveness of various pavement maintenance activities, particularly, crack sealing, surface dressing, structural patching, and resurfacing. In-service sites were identified at 1155 locations and of these, 642 had satisfactory information with which to initiate an analysis of the performance of different treatments. The Transportation and Road Research Laboratory of the Ministry of Transport analyzed 1984 data and concluded that general deterioration relationships could be derived for surface dressings and overlays. However, they felt that there were insufficient sites to distinguish between the pattern and role of deterioration of these treatments on different road classes. They proposed refining their studies to develop more specific information on pavement conditions, including deflections, varying treatment materials (binder and chips), characterizing pavements by taking cores and obtaining accurate traffic information on each monitored site. They proposed to observe pavement condition deterioration at select sites for three or four more years and then evaluate the effectiveness of different treatments. They also proposed using expert opinion to get a rough idea of expected performance of each treatment before detailing a specific research study.

MAINTENANCE ADVISORY COMMITTEE MEETINGS

Since the study objective was to identify research to improve highway maintenance productivity and management processes, the operational and administrative personnel responsible for highway maintenance were the people who could best identify these needs. Therefore, a major thrust of the study effort was to interact with people involved with highway maintenance. An advisory committee was formed consisting of representatives of the highway maintenance organizations, industry, maintenance consultants and university researchers. This Maintenance Advisory Committee met four times. At an initial meeting in Washington, D.C., research study topics were sought for maintenance elements having a major impact on safety, serviceability, service life, and agency expenditures. Using this approach, successful projects were expected to have a major impact on maintenance cost-effectiveness. Identified as primary candidates in order of importance were pavements, shoulders, drainage and bridges. A key research topic was to design controlled experimental studies to quantify the effectiveness of different maintenance practices on element service life and element condition impact on road users. Results from these studies would permit maintenance workload predictions, maintenance service level evaluations, life cycle costs analyses, selection of optimum maintenance strategies, and the definition of highway agency data requirements. Another topic identified included designing, constructing or retrofitting elements to require no maintenance, minimum maintenance or at least to be maintainable. This would reduce both maintenance expenditures and traffic interference consequences.

Developing better methods, equipment and materials to perform maintenance addressed the need to improve maintenance productivity and unit costs. Further improvements thought possible were through preventive maintenance responses to anticipated failures detected using portable, rapid nondestructive sensing equipment. Finally, training guides were identified as a major need for equipment maintenance, safety procedures, productivity improvements, research implementation, motivation enhancements, and communication. The Committee felt that new and innovative ways needed to be found to get existing knowledge and research results actually used.

Seven projects were drafted to address the research needs identified through the search of literature and the areas of concern defined during the first Advisory Committee meeting. These projects follow:

I. "Develop Portable Nondestructive Sensing Equipment to Evaluate Maintenance-Conditions." Preventive maintenance was thought to be more cost-effective than corrective maintenance. Anticipating distress through condition measurements would permit timely preventive maintenance to be performed and make maintenance expenditure more cost-effective.

II. "Pavement Maintenance Effectiveness." Maintenance managers cannot quantify the effectiveness of different pavement maintenance treatments. This ability is needed to objectively define maintenance service levels, estimate annual maintenance workload and to select strategies that minimize life cycle pavement maintenance and rehabilitation costs.

III. "Develop Improved Equipment." Better equipment for use in maintenance activities can increase productivity, reduce labor requirements and minimize roadway occupancy time. Improved equipment management practices and equipment maintainability can reduce equipment needs by increasing its availability and utilization.

IV. "Improved Maintenance Materials." Small quantities of a wide range of materials that perform in substantially different environments are needed for maintenance activities. Improved materials need to be considered for any of the maintenance activities performed by highway organizations with the most promising materials being selected for in-depth evaluation and in-service testing.

V. "Maintenance Management Automated Interactive Graphic." First-line maintenance supervisors use manual procedures to plan, schedule and report work activity. Microcomputer interactive programming can be developed to allow supervisors to enter and to extract management information in real time.

VI. "Maintenance Information and Training Program." Successfully completed research that is not implemented is ineffectual. Traditional information transmission processes are not adequate. Innovative uses of contemporary marketing technology are needed to get the results the SHRP maintenance research implemented.

VII. "Simulation and Experts Systems for Management." Maintenance managers make decisions using intuition and experience because they do not have time to weigh all the facts. A methodology based on expert opinions and simulations can help managers make better informed decisions.

At the second convening of the Advisory Committee, each of the project statements was reviewed and critiqued by the committee. In the process an eighth project statement was developed.

VIII. "Quantify the Public Consequences of Pavement Conditions." The actual influence of pavement conditions on the motorist are not well quantified. The ability to relate pavement roughness, holes, obstacles or shoulder drop-offs to accidents and motorist behavior will allow user costs to be considered when selecting cost-effective pavement maintenance strategies.

Table 2 shows the results of the critique on each project statement. The table shows average ratings based on a critique at the end of the Advisory Committee meeting, from critiques later received in the mail from members not present, and those wanting more time to reflect on the project statements. The projects were also prioritized from one to eight (with eight being high). The average prioritized rating was scaled from zero to one hundred and produced the following numbers:

I.	Sensing Equipment	(52)
II.	Maintenance Effectiveness	(78)
III.	Improved Equipment	(52)

TABLE 2
PROJECT STATEMENT EVALUATION FORM

RATING	ASSESSMENT
1	None/ Worthless/ No
2	Slight/ Nill/ A Little/ Conceivable
3	Some/ Possible/ Maybe
4	Average/ Partial/ Moderate
5	Substantial/ High/ Probable
6	Most/ A Lot/ Highly Likely
7	Maximum/ Complete/ Highest/ No Doubt

	AVERAGES FOR PROJECT NUMBER							
EVALUATION ITEM	I	II	III	IV	V	VI	VII	VIII
Payoff to the Maintenance Community	4.80	6.35	4.95	4.95	3.60	5.12	4.62	4.19
Can be achieved in smaller research effort	2.73	2.05	3.03	3.20	4.53	3.55	3.00	2.97
Useful to maintenance organizations	5.14	6.28	5.26	5.40	4.00	5.47	4.49	4.23
Improve Highway Safety	4.63	5.21	3.93	4.64	2.72	4.17	3.66	3.77
Extend Service Life	4.76	6.23	3.64	5.49	3.05	5.26	3.83	3.31
Suitable for FHWA, TRB, or state research program	3.50	3.64	3.50	4.42	4.37	3.41	3.25	4.07
Improve Serviceability	5.00	5.93	4.17	5.26	2.92	4.19	4.02	3.67
Improve Management Processes	4.76	5.33	4.34	3.90	4.97	5.22	5.29	4.39
Will be used by Maintenance Organization	5.12	5.81	4.88	5.14	3.95	5.12	4.17	3.59
What level of funding should be assigned to each project (1=1 million dollars)	3.16	5.70	2.86	2.95	.58	2.19	2.75	1.96

IV.	Improved Materials	(49)
V.	Interactive Graphics	(22)
VI.	Training	(56)
VII.	Expert Systems	(44)
VIII.	Public Consequences	(22)

Based on the critiques by the Committee on the individual project statements, the Committee suggested the following:

Project I: Expand to address devices and procedures for more than just pavements. Consider worker safety and exposure to traffic in evaluating measuring processes, and involve private industry where appropriate. Operator skills need not be minimal as long as equipment can gather lots of data fast: the key factor is cost-effectiveness. The committee suggested making the verbiage more generic to broaden project scope.

Project II: Provide adequate funding since this project could represent the highest payoff in the entire SHRP program. Search out and use existing state DOT data where possible. Preventive maintenance should not be used in any restrictive sense because treatments unknown today may be preventive maintenance at some future time.

Project III: Include a life cycle cost analysis for equipment, define the market for any needed equipment, consider other equipment suggested in committee discussions, make verbiage more generic to broaden scope.

Project IV: Do not limit to finding improved substitutes for existing materials, suggest using an advisory panel to define problem areas, consider new applications when weaknesses are identified through early detection (Project I), liaison with asphalt, concrete and bridge deck TRAs. The evaluation and testing of any newly developed or identified maintenance materials must be tied closely to the L-TPP project.

Project V: Not a major research area, states currently have capability, combine with Project VII.

Project VI: High priority project, considerable applicability to other SHRP TRAs. Develop training/implementation approaches that embrace private sector sales and marketing concepts to get research end products used.

Project VII: High priority and should be global if not universal in scope. Include all variables and interactions. Include both data and strategic processes, use optimization, uncertainty models and expert systems. Start with top management-oriented simulation model using regionally based default data base.

Project VIII: Very mixed responses, either extremely high or low priority. Consensus, not a project suitable to undertake in SHRP.

In addition to the specific comments on each problem statement, the Maintenance Advisory Committee observed a need to identify specific informational requirements of the highway maintenance community. They suggested that warrants be established for each data item that is recommended. The warrants were to be in terms of usefulness, probability of being used and cost-effectiveness. The cost-effectiveness would depend on the extent, frequency, reliability, speed and costs of acquisition. They also said that the research final products should be defined in a form that is readily implementable such as in standards, practices, usable equipment and materials. The Committee further said that a high cost to implement a project is not detrimental to its value if long-term benefits and costs are put into proper prospective.

Based on the critique and comments provided by the Advisory Committee at the San Antonio Meeting, Project VIII was dropped and Project V was combined with Project VII. The remaining project statements were modified to reflect the Committee's comments. A research plan embracing the six remaining projects was presented to the participants of the National Workshop in Dallas and is shown in Table 3.

At Dallas, the maintenance cost-effectiveness research plan was judged to be too general and broad in scope and not sufficiently problem-oriented. In the breakout sessions, the workshop participants concentrated on narrowing the scope of each project and identifying specific maintenance problems. The project statements as configured were considered processes to solve problems that lacked specificity.

At the conclusion of the Dallas workshop, the research design was presented as the matrix shown in Figure 2. Each problem is listed on the vertical axis and solving each problem involves the components shown on the horizontal axis. The process involves:

- Quantifying the characteristics of the problem using measures of the severity and extent of the problem and identifying any contributing causes. This needs to be done quickly, inexpensively, and accurately.
- Understanding the effectiveness of alternative maintenance responses in eliminating or minimizing the problem, following the characterization of the problem and the identification of factors that influence its evolution.
- Recognizing that for a select response, alternate materials can be used. Therefore guidelines are needed for selecting the best material for conditions, the influencing factors and the traffic situation.
- Considering that prevailing conditions and factors should guide the selection of an efficient process for a particular material and that this process may require special equipment.
- Defining or developing the equipment that needs to be available to implement any process selected.

The research required to improve the process and, therefore, provide more cost-effective solutions to problems involves:

TABLE 3
RESEARCH DESIGN PRESENTED AT
THE NATIONAL WORKSHOP IN DALLAS

Management Processes	Operational Procedures
I. Sensing Equipment to Measure and Evaluate Maintenance Conditions - Data needs - Available devices - Modification options - New equipment development - Training	IV. Improved Maintenance Equipment - Identify needs - Evaluate existing units - Establish new unit requirements - Develop & test phototypes - Management guide - Training
II. Strategic Model to Guide Management Decisions - Data Base - Methodologies - Software - Training	V. Improved Maintenance Materials - Required characteristics - Available material candidates - Acceptability testing - Long-term performance testing - Training
III. Pavement Maintenance Effectiveness Quantification - Experimental plan - Information management system - Implementation plan - Data collection - Modeling - Decision methodology - Training	
VI. Maintenance Training Guidelines - Evaluate existing materials - Training state of the art - SHRP maintenance project interaction - Establish constituency - Formulate delivery mechanisms	

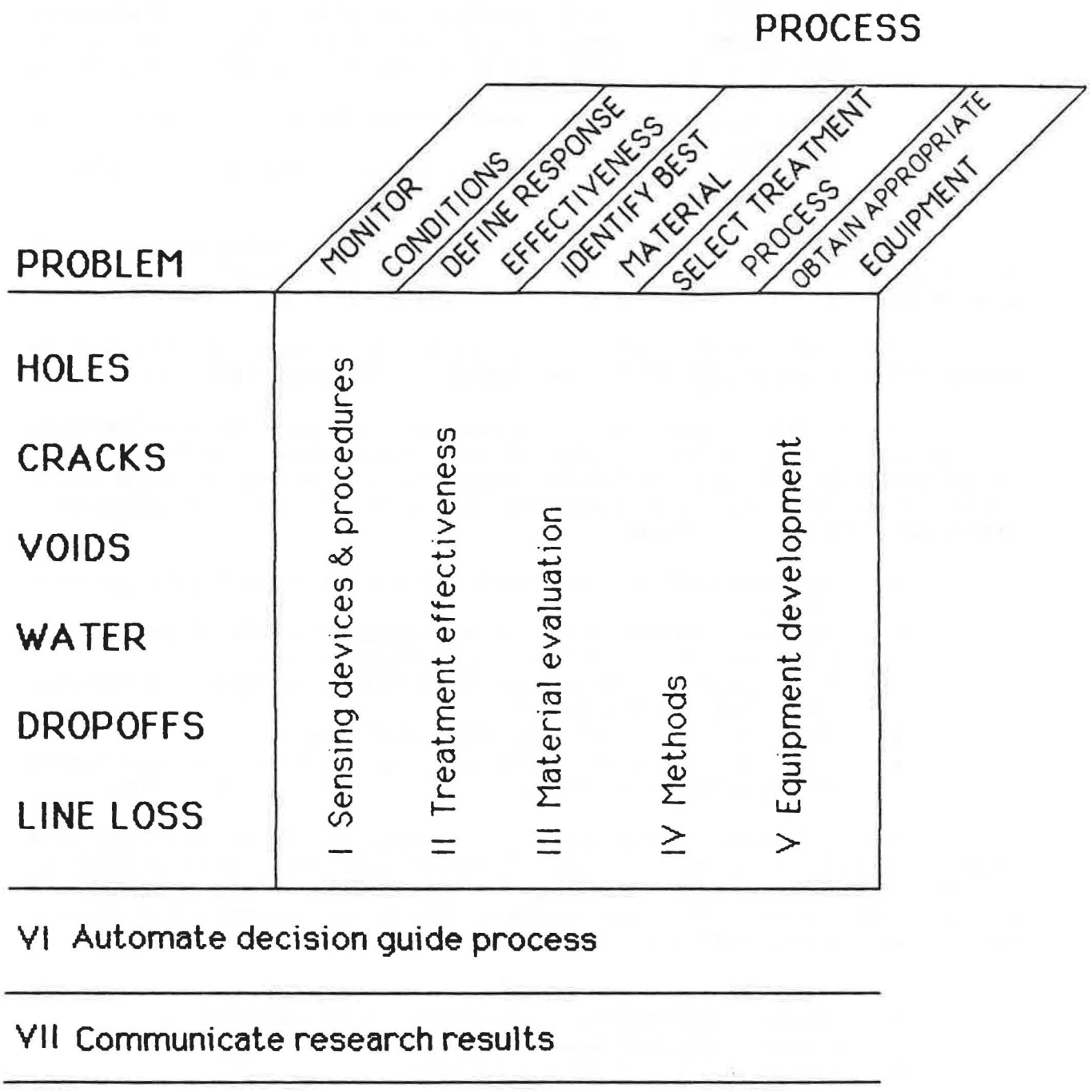


FIGURE 2. MATRIX OF PROBLEMS AND PROCESSES TO SOLVE PROBLEMS

- Developing fast, inexpensive, and accurate monitoring (sensing) procedures.
- Quantifying the effectiveness of alternative maintenance treatments in response to a variety of problems and conditions.
- Establishing the capabilities of optional materials that can be used in a select treatment.
- Defining efficient treatment procedures to use in eliminating problems.
- Developing or modifying equipment to maximize treatment efficiency.

Management processes can be improved by incorporating the results of the research into an automated process to guide the selection of the most appropriate response to each pavement and shoulder problem.

The training project lies outside the research matrix but is directed toward enhancing the implementation of the matrix study results.

The Advisory Committee met in Las Vegas to redefine a maintenance cost-effectiveness research plan based on the guidelines developed at the Dallas Workshop. The problem "pavement holes" was examined at length and a series of research topics that address various facets of the problem were discussed. The topics included:

- Improved methods, equipment and materials to repair pavement holes.
- Studies to determine the effectiveness of different maintenance treatments in correcting or preventing holes.
- Procedures and measures to detect problems and monitor conditions leading to holes.
- The influence of holes on motorists' behavior.
- Automated management processes to guide first-line supervisors select maintenance treatments to prevent or repair holes.

Also discussed at the Las Vegas meeting was the development of a project statement that addressed overall maintenance administrative needs in a study entitled "A Structured Decision Analysis System." This project would embrace simulations, empirical analyses and expert systems and provide managers with a methodology to interrelate:

- technical research findings,
- consensus judgements of professionals in maintenance,
- economic resource opportunities and constraints,
- operational rules and regulations,
- operational data bases, and
- performance criteria and method effectiveness.

The concept of developing a decision analysis system was discussed at length. The Committee was very divided on the suitability or value of such a project. Many believed that some facets were futuristic. Others felt that adequate systems existed and what was needed was better information to improve various components of those systems. The Committee recommended that the maintenance cost-effectiveness research plan concentrate on developing an improved understanding of the effectiveness of maintenance and better

measures with which to monitor maintenance effectiveness. The information could then be used to improve existing decision processes.

Another research project discussed was a slightly modified version of the project statement related to the use of research results. This project had the unanimous support of the Advisory Committee in Dallas and was now being titled "Media Evaluation and Implementation Research in Highway Maintenance." This project still had the Committee's unanimous support. A final project suggested addressed the need to improve motorist and worker safety when pavements are occupied to perform maintenance.

The Advisory Committee was presented with ten project statements and rated the series of research titles as high, medium, or low priority. The projects rated high form the basis for the maintenance cost-effectiveness research plan.

SECTION 4
RECOMMENDED RESEARCH PLAN

IMPROVED MANAGEMENT PROCESSES

Effective maintenance administration involves planning work based on need, budgeting the work within resource constraints, selecting and executing work to meet environmental and traffic constraints, and monitoring expenditures and achievements. Present maintenance management system needs are based on historical records. These records document the average level of expenditures annually by activity and highway class but reflect practice rather than need. These practices are based on policies developed partly in response to the public's comments, partly in response to extending the historical pattern of highway maintenance methods, partly in response to the intuitive judgment of maintenance engineers, partly in response to the motivation of the maintenance supervisor who gives priority to performing those activities that the maintenance crews are capable of doing effectively and efficiently, partly in response to court instigated pressures through tort litigation, and partly to data bases indicating a practice (or practices) that will extend the life of highway elements. Consequently, maintenance programs reflect established practices. The effectiveness of these practices has never been adequately evaluated because present systems are not able to objectively define how well different maintenance treatments improve conditions or slow the deterioration of maintainable highway elements.

The maintenance level being achieved on highways is reflected by maintenance element conditions. The National Bridge Inspection Program and pavement management systems are developing condition information, but it is largely subjective. This condition information, collected over time, permits gross assessments to be made of the relationship between maintenance expenditures and maintenance service levels. However, this data base is not precise enough to investigate the relationship between a specific maintenance treatment and its timing on subsequent maintenance element performance. Therefore, the relationship between a maintenance treatment and the subsequent performance of a maintenance element cannot be quantitatively defined.

Uniform and accurate measures of maintenance element condition over time are needed. These measures, together with corresponding information that will characterize the maintenance element, quantify exposure to climate and traffic influences, and document the type, extent, and timing of all maintenance or rehabilitation treatments, will allow the creation of data bases that can be analyzed to establish maintenance element performance models to quantify maintenance effectiveness.

Establishing such a data base requires a coordinated effort on the part of highway agencies. This can only be achieved through a structured program of research that is managed by some central organization with a long-term commitment of funds. SHRP is such a program so this need for a data base to evaluate the effectiveness of maintenance treatments is a problem well-suited to the SHRP program.

Currently, maintenance expenditures are the greatest for pavements. An evaluation of fiscal year 1984 expenditures for 42 state highway agencies showed that 37 percent of their direct highway maintenance expenditures went for pavement maintenance. Therefore, an improved understanding of the effectiveness of different pavement maintenance activities offers opportunities to affect major improvements in maintenance cost-effectiveness.

Pavement maintenance effectiveness is defined as the degree to which a treatment prevents or retards the pavement deterioration process (which means improving pavement performance). Damage models are used to quantify pavement performance. A damage model is a mathematical equation that predicts the extent of pavement distresses such as cracking, ruts, roughness, skid or other conditions. Damage models include variables to explain the effect of traffic, the environment, and the character of the pavement on the evolution of damage. Pavement maintenance effectiveness can be evaluated by determining a maintenance treatment's influence on a pavement damage model prediction.

Creating a data base on pavement maintenance effectiveness will allow pavement damage models to be modified to explain the influence of different maintenance treatments on pavement performance. Such models provide an objective basis for setting maintenance service levels and establishing maintenance programs to optimize the use of available resources. In the process, objective maintenance service levels can be established since pavement condition thresholds will be defined to guide maintenance response times. The result will be better (and more timely) maintenance, and extended service life for the highway pavement. The models also will define data requirements to refine models or calibrate them for various agencies. Finally, the data base and models will permit maintenance workload models to be developed for use in the maintenance budgeting process.

To determine the effectiveness of a given maintenance treatment, factors affecting pavement performance must be addressed first. These factors include the pavement structure, material properties, traffic and load distribution, and the environment. Then maintenance factors are included. These include (1) pavement condition at the time of treatment, (2) weather conditions at time of treatment, and (3) the amount of time that completed treatment is closed to traffic.

The data base needed to evaluate the effectiveness of pavement maintenance can be created in two ways. The first is through a controlled study where objective measurements are made of all the factors that might influence the effectiveness of a specific maintenance treatment. A second approach is to define for a highway organization the factors that must be measured over time to permit the effectiveness of different maintenance treatments to be evaluated, and then have the maintenance organization record these measures.

This research plan addresses both approaches. Two research projects are proposed. The first is entitled "Quantification of Pavement Maintenance Effectiveness." This scientifically designed study will create a data base to evaluate the effectiveness of six specific pavement maintenance treatments. An analysis of this data base should identify the factors that need to be monitored to evaluate pavement maintenance effectiveness. Also, pavement damage models can be modified to reflect the influence of the six treatments studied on pavement performance. The models will then define the effectiveness of each maintenance treatment in terms of pavement, traffic, and environmental factors.

Maintenance practices vary widely from state to state and between jurisdiction units within states. One cannot simply specify the application of a chip seal. The specifications for this activity vary widely since a range of asphaltic and aggregate materials are used. Also varied are the gradation of aggregates, the use of polymers or other additives, and the extent of surface preparation prior to surface treatment. In addition to these variations, there is a range of pavement designs and conditions being treated and different environments (climate, traffic, subgrades) where the pavement must perform.

The proposed study on maintenance effectiveness represents a major first step. It will produce objective assessments of the effectiveness of six specific treatments for a range of conditions. However, it will not answer the needs of many maintenance organizations. There will still be a need to understand the effectiveness of pavement treatments not studied and variations in the treatments studied.

Maintenance organizations will need to conduct their own evaluation of maintenance effectiveness. The proposed study will serve as a guide since it will define the factors to measure. It also will define measurement units, analysis processes, the way in which pavement damage models can be modified, and how to use the damage models when selecting from alternative pavement maintenance strategies.

Data collection will be a major expense item in the pavement effectiveness study. Highway maintenance organizations cannot afford to develop the detailed data needed to evaluate pavement maintenance effectiveness using the measurement processes normally associated with research. Faster, more accurate, automated and cost-effective measurement procedures are needed. Therefore, the best way to assist maintenance organizations to conduct pavement maintenance effectiveness evaluations is to provide them with improved data collection processes. The second research project statement, entitled "Measuring Systems and Instrumentation for Evaluating Pavement Maintenance Effectiveness" addresses this need.

PROJECT 3-1, QUANTIFYING PAVEMENT MAINTENANCE EFFECTIVENESS

Highway maintenance organizations are charged with the responsibility of keeping pavements safe and serviceable for the motoring public. They also try to extend pavement service life to the maximum extent possible albeit within resource constraints. Maintenance managers are curtailed in their efforts to achieve these objectives because they have insufficient information with which to objectively select the pavement

maintenance treatment that will prove the most cost-effective over the life of the pavement.

Pavements fall into two principal categories, rigid and flexible. The types of rigid pavement distress that are addressed by maintenance organizations include pumping, settlements, faults, cracks, blowups and holes. The activities executed to correct these distresses embrace crack and joint sealing, undersealing, partial and full depth patches, temporary patches, thin overlays, and pavement grinding. Of these activities, the ones that are considered preventive include crack and joint sealing and undersealing. The effectiveness of these preventive maintenance activities in extending pavement service life is not quantified. Unknown is the effectiveness of these preventive activities in reducing faulting, cracking, blowups, and the evolution of holes. Maintenance organizations feel that they could prevent many of these latter distresses if they had adequate information on conditions and the effectiveness of different treatments and timing on future pavement performance.

The types of flexible pavement distresses that are addressed by maintenance organizations include temperature and fatigue cracking, raveling, rutting, holes, surface permeability and roughness. The activities executed to correct these distresses embrace crack sealing, surface seals, surface and full depth patching, planing, and thin overlays. Again, the effectiveness of these activities in extending pavement service life has not been quantified. Of particular concern is the effectiveness of crack filling, seals, and thin overlays which are all potentially preventive maintenance activities.

Controlled studies are needed to identify the factors that influence the effectiveness of different pavement maintenance treatments in preventing or slowing the evolution of pavement damage. These studies will require that in-service pavement sections be monitored for a period of time following a maintenance treatment. The data base generated through such a monitoring effort can be evaluated to explain the effectiveness of the maintenance treatment. The factors that should be considered when selecting pavement sections for inclusion in the study are:

- Traffic Volume (low-medium)
- Temperature Zone (freeze-non freeze)
- Moisture Zone (wet-dry)
- Pavement Condition Cracking Distress (slight, moderate, severe)

Additionally, objective measures are needed of all pavement, climate and traffic variables that might influence the effectiveness of a maintenance treatment on pavement performance.

Objectives

- Develop a data base that will permit increased understanding of the effectiveness of different maintenance treatments in extending pavement service life or reducing the evidence of pavement distress.
- Evaluate the effectiveness of different pavement maintenance treatments in extending pavement service life.

- Establish a study methodology that can be followed by highway agencies to evaluate any maintenance treatment.

Scope

The study will generate and analyze data over a five-year period and complement the Long-Term Pavement Performance (L-TPP) studies. It will address both rigid and flexible pavements. The treatments studied will be limited to maintenance treatments that are expected to prevent or slow the deterioration of pavements. These treatments are classified as preventive pavement maintenance. Selected for inclusion in this research effort are the following activities.

- Flexible pavement
  - chip seals
  - thin overlays (under 3/4 inches)
  - slurry seals
  - crack sealing
- Rigid pavement
  - joint and crack sealing
  - undersealing

A maintenance treatment is a specific way in which a maintenance activity is performed. For example, a chip seal consists of applying an asphalt binder to a road surface and then covering the binder with aggregate. There are a number of binders and aggregates that can be used. A chip seal treatment includes a particular binder applied at a specific application rate. Also, the aggregate is a specific aggregate type and gradation applied at a specific application rate. A single treatment, based on most prevalent practice, is to be chosen for each of the study activities.

Approach

Define a controlled experiment using the principles of scientific experimental design to develop a data base to evaluate pavement maintenance effectiveness. Include a plan to collect data.

Include the environmental and traffic factors that influence pavement performance in the data base. Develop criteria and select in-service pavement sections to receive a treatment application. These sections are to be in a condition warranting a maintenance treatment. The data base is to include measures of each pavement section's condition prior to treatment and at intervals over time following a treatment. Include in the data base characterization information on each pavement section.

Execute the plan, analyze the data base and evaluate the effectiveness of each maintenance treatment on pavement performance.

Workplan

Task 3-1.1 - Develop A Detailed Experimental Plan.

1. Evaluating pavement maintenance effectiveness requires an understanding of pavement performance. The Long-Term Pavement Performance (L-TPP) study will establish in-service pavement sections to create this required understanding.

It will be necessary to interface all activities with the L-TPP studies. The information required to support an evaluation of pavement maintenance effectiveness will be addressed in the L-TPP experimental plan for in-service pavement studies and will have included site selection criteria that considered:

- Pavement type
- Rehabilitation type
- Climate zones
- Subgrade type
- Drainage type
- Loading
- Section age
- Maintenance data
- Available historical records
- AASHTO region
- Ability to obtain monitoring data

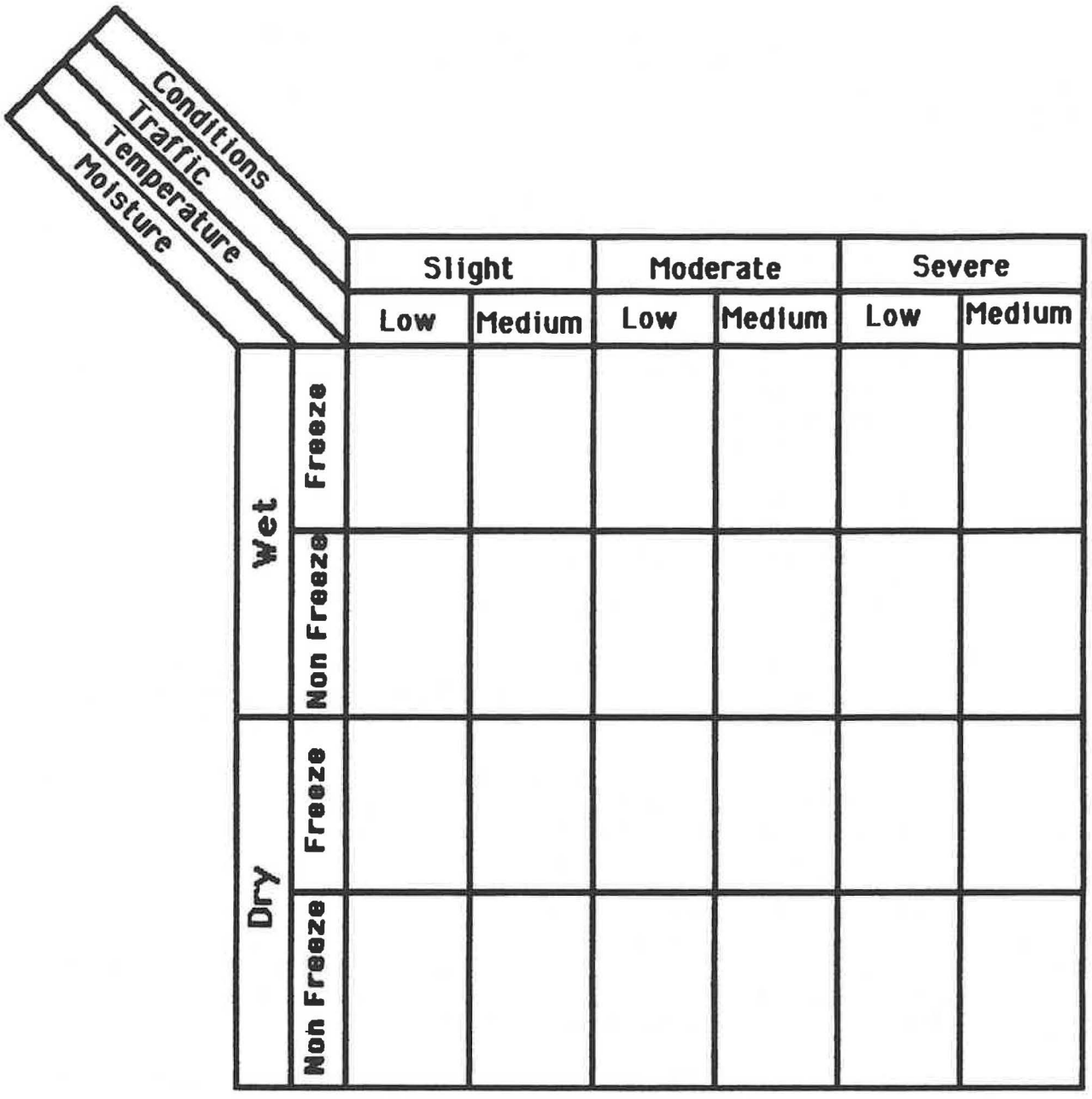
Critically examine the L-TPP plans, particularly with respect to maintenance data. Make recommendations on complementing the data collection plan and for establishing sections not included in the L-TPP program.

2. Design a controlled experiment to develop a data base to use in evaluating pavement maintenance effectiveness. A controlled experimental study means a complete experimental design directed at achieving an understanding of pavement maintenance effectiveness. To effect economy in the experiment and to produce a maximum return, the principles of scientific experimental design must be embraced. This includes defining all factors and levels to be used in the experiment. Each variable must be well-defined, and the inference base for the experiment must be specified. The analysis procedures must be defined prior to initiating the collection of data. As a minimum, satisfy the design factorial shown in Figure 3.

3. Develop a plan to collect data paying particular attention to the procedures established in the L-TPP study. Address the need to have both inventory and condition data. Consider the sufficiency of existing highway inventory data. In many organizations it is extremely difficult, if not practically impossible, to re-create from records the exact character of the pavements in the field. This is particularly true for older roads. Therefore, provide procedures to validate existing information or to develop it from direct measures such as coring.

4. Specify the type and quantity of materials that are to be used in each maintenance treatment. Further, develop standards to control and ensure the uniformity and the quality of each maintenance treatment.

TREATMENT NO. 1



24 X 5 X 2 = 240

FIGURE 3. DESIGN FACTORIAL FOR MAINTENANCE COST-EFFECTIVENESS STUDIES

5. Prepare a time schedule for acquiring data. Establish the data collection procedures, define the data units, the measurement methods and procedures. Address the need to ensure the accuracy of the data and provide calibration criteria and methods as needed.

6. Document the Phase I activities. Address the study's interface with the L-TPP studies. The experimental plan and analysis procedures should be covered in detail. Include complete descriptions of the data to be collected including the data units. Documentation is to include procedural manuals for data acquisition and validation.

Task 3-1.2 - Develop an Implementation Plan for the Pavement Maintenance Effectiveness Study. Develop a plan to implement the study. The plan should consider the status of the L-TPP at the expected time of implementation. Steps should be delineated for cooperating and interfacing with the L-TPP contractor(s), particularly the regional data center contractors.

Establish an implementation schedule and consider the time needed to brief the data collection staff. The schedule must account for the status of the L-TPP, funding availability and the possible effect of seasonal constraints on certain data measurement processes. Also consider the lead times required to interact with highway agencies expected to cooperate in the study effort.

Identify any instrumentation requirements not covered by the L-TPP studies and select for purchase or develop specifications to fabricate this supplemental instrumentation.

The plan is to be submitted to SHRP in a written document that details how the consultant proposes to implement the maintenance effectiveness studies.

Task 3-1.3 - Implement the Maintenance Effectiveness Study. The L-TPP pavement studies are expected to be underway by the time this task is ready to be executed. The L-TPP Plan envisions four regional contractors being retained to collect and process pavement related data. These same contractors should be used to collect pavement maintenance data. Therefore, this task is broken down into five subtasks. Task 3-1.3a outlines the responsibilities of the coordinating contractor and Task 3-1.3 b, c, d, and e the responsibilities of each of the four regional contractors.

Subtask 3-1.3a Coordinate Field Data Collection Activities.

- Meet with the L-TPP regional contractor(s) and highway agencies and brief everyone on the study.
- Select any supplemental test locations.
- Identify data collection responsibilities between the highway agency, regional L-TPP contractor(s) and the consultant.
- Define formal information channels and data handling procedures.
- Continually screen, edit and validate data elements.

- Conduct preliminary analyses of data to identify trends, improve the data acquisitions processes and refine the study design.

Subtask 3-1.3 b, c, d and e Collect Test Location Data.

- Establish if the highway agency can and will execute the maintenance treatments in accordance with specifications, provide assistance in complementing their capabilities as needed, schedule treatments and arrange for quality control monitoring.
- Arrange to acquire any required computer equipment and instrumentation.
- Check out all instrumentation and data collection procedures.
- Pilot test all data monitoring activities.
- Collect and process data.
- Continually screen, edit and validate data elements.

Task 3-1.4 - Evaluate the Effectiveness of Maintenance Treatments Being Studied.

1. Complete the data base at intervals and establish a data analysis file.

- Identify from the L-TPP studies, the models and their forms selected for predicting pavement distress and serviceability.
- Identify the variables included in the models and incorporate data on each variable from the test sections being monitored for maintenance effectiveness study into the data base.
- Validate the accuracy of the data analysis file.

2. Structure the analysis file to accommodate the proposed analysis procedures and generate summary statistics on the data base to guide the evaluation process.

3. Analyze the data base and evaluate the effectiveness of different maintenance treatments being studied on pavement conditions. Effectiveness is expected to be related to:

- The pavement's design and material characteristics.
- The operational (traffic volume and loads) and climatic factors.
- Pavement condition at time of treatment.
- Maintenance treatment.
- Timing and work quality.

4. Make a sensitivity study of the modified damage models to determine the impact of each independent variable on the predicted distress or serviceability over a realistic inference space.

5. Repeat the analysis process at intervals as the data base expands during the study or as new damage models evolve from the L-TPP studies.

6. Detail the analysis procedures. Identify the parameters influencing maintenance effectiveness, and the inference space where the evaluation is valid.

Task 3-1.5 - Develop a Training Short Course to Acquaint and Guide Highway Agencies in Implementing a Study to Evaluate the Effectiveness of Maintenance Treatment Used by Their Agency.

1. Develop a course outline.

2. For each topic in the course outline, establish

- Training objectives,
- lesson plan,
- student guide,
- instructor guide, and
- visual aids.

3. Make a pilot presentation of the course to the SHRP advisory panel.

4. Revise the course material based on the pilot course review comments.

5. Prepare a 15-20 minute video and slide/audio tape version of the course.

Deliverables

- An explanation of the effectiveness of chip seals, slurry seals, thin overlays and crack sealing on flexible pavement performance and the effectiveness of crack and joint sealing and undersealing on rigid pavement performance.
- A methodology that can be followed by highway agencies to evaluate the effectiveness of different pavement maintenance treatments, including the specific information that needs to be collected.

PROJECT 3-2. MEASURING SYSTEMS AND INSTRUMENTATION FOR EVALUATING PAVEMENT MAINTENANCE EFFECTIVENESS

Maintenance organizations have a continuing need to evaluate the effectiveness of different pavement treatments in extending pavement life. A better understanding of maintenance treatment effectiveness will permit these organizations to study and objectively evaluate maintenance strategies. They can select strategies and set maintenance service levels that minimize pavement life cycle costs and thereby enhance the cost-effectiveness of their maintenance programs. Maintenance service levels reflect the pavement's average condition over its service life. The conditions that reduce service levels include distresses such as cracks, holes, faults, bumps and slippery spots that can be corrected or improved using maintenance treatments.

The effectiveness of a maintenance treatment in addressing pavement distress is determined by the immediate condition of the pavement following a

treatment and by the extent that the distress or deterioration process is slowed in the future. Currently available pavement condition data (distress, serviceability) cannot be aggregated to evaluate pavement performance because it lacks uniformity in the way it is measured and interpreted. This lack of uniformity is due to poor measurement repeatability or because pavement conditions are determined subjectively by field investigators. Even with objective measurement processes, interpretation is nonuniform because there is wide variation in calibration processes and in the way final measurements are scaled or aggregated. This means that data from different sources cannot be pooled and, therefore, analyzed to develop meaningful assessments of pavement performance. Further, most of the currently used mechanical devices or instruments are slow and permit only limited sampling of conditions. Finally, the information obtained is generally reduced manually, which discourages undertakings that could produce adequate data bases.

To help maintenance organizations evaluate maintenance effectiveness better measuring methods are required, particularly nondestructive measuring or sensing procedures that can be used to quantify pavement conditions and the factors that influence pavement conditions. Needed are measurement devices that are fast, simple to use, generate reproducible measurements, are more cost-effective, and are capable of covering more extensive areas.

The objectives of the study are to:

- Identify pavement conditions and factors influencing these conditions that must be measured to evaluate the effectiveness of pavement maintenance treatments.
- Identify equipment, instrumentation or methods that can be used to measure the items identified above.
- Develop equipment or instrumentation where no suitable devices exist.
- Develop standard procedures to be followed in making measurements with each identified or developed device.
- Develop standard procedures to be followed in reducing each measurement.
- Prepare instruction and training materials for operating devices and reducing measurement data.

Scope

All pavement conditions and factors that affect pavement maintenance treatment effectiveness are to be considered. For each item, the specific characteristics to be measured are to be identified and the measurement units defined. Emphasis is to be placed first on using existing equipment and instrumentation; next, modifying available devices; and finally, for a few critical items, design, fabricate and test new devices that use contemporary nondestructive measurement technology. The items to be considered shall include but not be limited to the following:

- Holes in pavement
- Voids under pavement or in pavement
- Edge drop offs
- Reinforcement corrosion

- Pavement disintegration
- Water in base, surfacing or joints
- Asphalt stripping
- Asphalt oxidation
- Pavement rutting and depressions
- Surface texture/skid resistance
- Cracks (extent, type and underlying cause)
- Joint/crack sealant deterioration and condition

Approach

Identify the characteristics of pavements and other factors requiring measurement. Search out and identify existing devices and processes that will measure these items. Evaluate each in terms of performance characteristics, initial costs, operating costs, precision/accuracy, portability, ruggedness, durability, maintainability, and stability. Where feasible, modify existing devices to improve their utility.

Investigate the feasibility of developing measurement instruments, equipment or procedures using current nondestructive sensing technology for important items that cannot be evaluated with existing or modified devices.

For two or three feasible techniques, prepare terms of reference to design, fabricate and test new devices or processes. Contract for developing new devices.

Workplan

Task 3-2.1 - Evaluate Existing Measuring Systems and Instrumentation.

1. Identify the factors and pavement conditions that need to be measured over time to evaluate pavement maintenance effectiveness. All such measures are candidates to be measured with rapid and automatic measuring systems or instrumentation.

2. Define the measurement units that will effectively characterize the factors and conditions selected for measurement.

3. For each measurement requirement, determine and evaluate presently available instrumentation, either currently used by state highway agencies or commercially available (off the shelf). The desired measurement instrumentation must meet the following criteria:

- Reproduces values precisely when used by different operators,
- economical to use,
- inexpensive to purchase, reproduce or manufacture,
- able to make measurements quickly and safely,
- produces measurements readily reducible to usable information without extensive interpretation or modification,
- reliable, maintainable, and capable of accurate measurements through proper calibration,
- flexible, i.e., a variety of measurements can be made with one equipment system, and

- easy to store and durable under a variety of field and climatic conditions.

4. Prepare a test plan for evaluating each measurement device identified that considers:

- Criteria that will be used to select field test sites.
- Procedures that will be used to evaluate the precision and accuracy of each measuring device.
- Procedures that will be used to collect, process and evaluate the measurements obtained.
- Climatic extremes under which measurements can be made.

5. Implement the evaluation test plan and determine the suitability of existing measurement instrumentation in terms of:

- Performance characteristics
- Initial costs
- Operating costs
- Precision/accuracy
- Portability
- Ruggedness
- Durability
- Maintainability
- Stability

The devices must also be evaluated for long-term reliability. This means that the contractor will be required to analyze each device's ability to withstand field use by many operators, the stability of the device over time and the cost to collect information.

6. Document the measurement systems evaluated, the results obtained, and identify existing systems that are suitable for collecting pavement maintenance effectiveness information. Recommend measurement systems that are candidates to be developed.

Task 3-2.2 - Prepare Terms of Reference for Developing New Measurement Systems and Instrumentation.

1. Conduct a literature survey to determine the state-of-the-art techniques that can be used to sense measurable characteristics of materials. Evaluate each technique and determine its applicability to the factors and conditions needed to evaluate pavement maintenance effectiveness. Place an emphasis on nondestructive techniques and consider as a minimum, the use of sonics, ultrasonics, infrared, microwave interferometry, wave propagation, eddy currents, lasers, radar, nuclear radiations, infrared reflectivity, video, acoustics, and thermal approaches.

2. Investigate the feasibility and costs of developing measuring systems and instrumentation. Identify the systems/procedures that are the most practical and cost-effective to develop. Include the potential of each device in terms of:

- the importance of the factor or condition that the device will measure,
- the potential, precision and accuracy of the measures that will be obtained,
- the scope of the measuring process, i.e., measurement speed and extent,
- technical operator qualifications, if any,
- the estimated prototype costs, and
- the expected production costs.

3. Recommend to SHRP the techniques and applications that appear feasible for developing measurement instrumentation for factors and conditions not adequately monitored using existing systems. Prioritize and detail the reason(s) for each recommendation.

Task 3-2.3 - Fabricate and Test Prototype Devices.

Subtask 3-2.3 a, b, c - Fabricate a Prototype Device.

1. Develop a measuring system and instrumentation prototype which meets the specifications established in Task 3-2.2 for measuring a factor or condition not adequately handled with existing systems.

2. Prepare documentation on the development of the prototype: include complete specifications for the production of each unit, estimated production costs, and recommendations on the use of each system.

Subtask 3-2.3d - Test Prototype. Subject each test prototype system to the same testing and evaluation program used for existing systems and instrumentation, as outlined in Task 3-2.1 and prepare documentation on the evaluation. Prepare documentation on the development of the prototype: include complete specifications for the production of each unit, estimated production costs, and recommendations on the use of each system.

Task 3-2.4 - Develop Training Guides. For each device that has been demonstrated to be useful and practical, develop a training manual that can be used by operators. The manual as a minimum shall:

- Provide a simple explanation of how to use and operate the device system.
- Identify the characteristics of materials that the device can measure and the way the measures are reduced to meaningful information.
- Detail the manner in which the device is to be operated.
- Discuss the precision and accuracy of the device and (when necessary) the procedures to be followed in calibrating the device.
- Review any limitations of the device and restrictions on its use.
- Cover the care and maintenance of the device.
- Provide a failure checklist to take in case the device is not functioning.

The training guide will be supplemented with a video tape and slide/audio tape that provides a fifteen minute review of the material covered in the manual.

Deliverables

- Training guides on the operation of all measuring systems.
- Specifications for all modified or newly developed instrumentation.
- Procedural guides for converting all measures into information for use in quantifying pavement conditions, setting maintenance service levels and evaluating pavement maintenance effectiveness.

TECHNOLOGICAL IMPROVEMENTS

Projects 3-1 and 3-2 address the need to understand the effectiveness of pavement maintenance. This understanding will allow maintenance organizations to select the maintenance treatment expected to be the most cost-effective for given pavement conditions. Another way to improve maintenance cost-effectiveness is to improve the treatment process through the use of improved materials, equipment and methods. Since pavement maintenance has already been identified as the activity generating the greatest maintenance expenditures, improvements to pavement treatment processes also offer substantial payoff.

Over the years, numerous studies have been directed toward improving pavement maintenance productivity. Also, efforts have been made to identify and use more permanent repair materials, more efficient equipment and operational processes suitable for a variety of climatic and traffic constraints. In spite of these efforts, there is still a perception throughout the maintenance community that better and more cost-effective ways can still be found or developed to repair pavements.

Localized surface pavement defects are still considered a national problem. Although most agree that these defects can be prevented, there is also agreement that the financial resources will not be available to implement the preventive programs required to cope with an aging pavement system subject to increased traffic loadings. Since surface defects will continue to exist, better ways are needed to eliminate them.

The cause of most surface failures and holes is well understood. Further, the repair procedures are well documented and, when followed, will produce a permanent and acceptable pavement repair. Unfortunately, surface holes usually appear at a time when it is difficult to follow good practice, i.e., when the weather is bad, the traffic is heavy, or the workload is extensive. Maintenance crews are faced with the need to rapidly fill holes that are creating a hazard to the motorist. The need for speed precludes the use of good practice and results in temporary patches that require frequent replacement.

Research is warranted to develop surface failure repair methods that will produce permanent corrections quickly under all pavement and climatic conditions and with a minimum impact on the motoring public.

Another pavement activity warranting additional attention is joint and crack sealing. Sought are better and more permanent seal materials, more efficient procedures and less interference with traffic.

The shorter pavement occupancy times created through improvements in pavement maintenance productivity will minimize traffic interference. Also needed are improved traffic controls to reduce traffic interference. SHRP provides an opportunity to investigate innovative approaches to worker and motorist safety in conjunction with pavement maintenance activities. Some of the things that can be considered include:

- Portable and lightweight barriers that can be rapidly installed or made part of an integrated self-contained traffic control system.
- Equipment that can automate the installation and removal of the devices used to control traffic for maintenance work areas.
- Procedural guides that outline simpler and more efficient traffic control installation and removal procedures.

Maintenance equipment can be equipped with barriers and warning devices that may permit workers to have immediate protection when occupying a traveled way. Units can be equipped with sensing instrumentation that monitors approaching traffic. Various warning systems can be installed to:

- Alert the motorist to alter his behavior if his approach exceeds threshold values of speed and proximity.
- Seriously alert the motorist in time to take emergency evasive action if he fails to respond to first alert.
- Cause the workers to protect themselves in case of an impending collision based on the serious alert.
- Activate crash attenuation processes.

Two research projects are recommended for improving operational procedures. The first addresses the need for improved materials, methods and equipment for executing two different pavement maintenance activities: patching localized surface failures and joint and crack sealing. The second project addresses the need to have better traffic controls and traffic control installation procedures for these two pavement maintenance activities.

PROJECT 3-3. IMPROVED MATERIALS AND EQUIPMENT FOR PAVEMENT SURFACE REPAIRS AND CRACK FILLING

Maintenance requirements on the nation's highways are increasing annually as the system ages and changes in complexity and size to handle ever-increasing traffic loads and user demands for higher levels of highway service. At the same time resources are eroding due to lower per vehicle fuel consumption caused by the increased use of lighter and more fuel efficient vehicles. Improved maintenance materials, equipment and methods can reduce resource requirements through increased productivity and minimized roadway occupancy requirements. Further, mechanization can replace labor-intensive practices, reduce maintenance activity unit costs and enhance safety by minimizing the number of personnel exposed to traffic. Maintenance

workloads can be reduced if improved processes raise the quality of maintenance, since the repairs will be more permanent.

The need for more permanent and productive maintenance is particularly acute in urban areas that depend on high-volume, high-speed highway facilities, most of which were provided through the construction of the interstate system. These facilities are now aging, some of them being over 20 years old. Urban areas will continue to grow and it is problematic at this time whether that growth will be paralleled by the construction of new freeway facilities. Thus, we can expect these aging facilities to not only require higher maintenance expenditures due to age, but because they also will be serving ever-increasing volumes of traffic. Dealing with maintenance operations under high-speed, high-volume urban conditions, often with extremely difficult physical accessibility restrictions presents a real challenge. New equipment, materials, and more efficient procedures by which maintenance can be carried out on high-volume, high-speed facilities with minimum disruption to traffic flow is a major need.

Pavement and shoulder problems faced by highway maintenance organizations include:

- repairing holes,
- filling voids under the pavement or shoulder,
- eliminating the presence of water in and under the pavement,
- repairing critical drop-offs between the pavement and the shoulder,
- filling/sealing cracks, and
- replacing pavement markings.

Pavement maintenance has been shown to represent over a third of the total maintenance expenditures in the country. Two specific pavement activities that contribute significantly to this total are hole repairs and crack/joint sealing. Since both are activities that require occupancy of the pavement, improvements in the materials, methods and equipment used for these two activities offer great potential for cost-effective improvements.

Improved maintenance equipment can reduce resource requirements through increased productivity, can minimize roadway occupancy requirements, and can enhance safety by minimizing the number of personnel exposed to traffic.

The availability of materials which are more durable than those currently used under prevailing environments and that are more efficient in a material-method-equipment system, have the potential to increase the safety of maintenance operations, increase the cost-effectiveness of maintenance, and to improve the permanence of the repair.

Maintenance materials and equipment have tended to be the same as those used in the construction process, perhaps modified to meet specific maintenance agency need. Such use is in spite of the fact that maintenance is required at sites where these same construction-based materials have already failed. Cost reductions through improved equipment efficiency seem feasible by having equipment available that is designed and constructed to meet equipment specifications drafted to address highway maintenance demands

in repairing surface distress and filling cracks. Materials used in highway maintenance have also traditionally been the same materials specified for construction processes. Since about 20 percent of the costs of conducting a maintenance activity is, on the average, attributable to material costs, consideration should be given to using available materials previously deemed too expensive.

The characteristics of the materials sought for patching and sealing include that they:

- set up or cure out more quickly,
- permit application at significantly colder temperatures than now permissible,
- are stable under traffic and severe environmental conditions,
- can be applied quickly,
- bond well to in-place pavement,
- enhance (or retain adequate) surface skid resistance,
- are compatible with existing or improved equipment application systems application,
- are more effective in preventing the intrusion of water into the pavement structure than existing materials,
- not represent a safety hazard to personnel during application, and
- are environmentally sound.

There is the simultaneous need to modify existing equipment systems or create new equipment system prototypes designed to:

- allow surface repairs or crack filling operations from a position off the roadway,
- permit surface repairs or crack filling at a more rapid rate than is currently possible,
- reduce personnel requirements,
- create repairs or filled/sealed cracks that are more durable, and
- be compatible with improved materials that may be applied to these maintenance activities.

<u>Objectives</u>

- Identify materials, procedures and equipment for patching localized holes in flexible and rigid pavements that are more effective in preventing pavement deterioration and more efficient than existing methods.
- Identify materials, propose procedures and specify equipment to use in filling/sealing cracks in flexible pavements and joints in rigid pavement that are more effective in preventing the intrusion of water into the pavement structure and that are more efficient than existing methods.
- Provide estimates of material and labor resources required for each material/equipment/method system for unit quantities of work accomplished (performance standards).

Scope

Address improvements to materials and equipment used to repair pavement holes, shoulders, and fill/seal pavement cracks and joints. Holes are those evident at the surface of the pavement, not those requiring full-depth repair, and those considered localized with regard to needed repair. Both flexible and rigid pavements are to be addressed. Holes caused by utility cuts or construction deficiencies are excluded. Consider maintenance operations associated with both urban and rural pavement networks, exposed to high and low-volume traffic streams and all climatic zones, particularly frequent freeze-thaw zones. The interface of the pavement edge with the shoulder is to be included where it represents a longitudinal hole problem for repair and a joint to be filled/sealed. Consider existing and commercially available materials. Screen candidate materials based on physical and chemical performance criteria (desired characteristics). Use laboratory testing to select the materials to be field tested to validate material performance and to estimate effectiveness.

Examine all publicly funded equipment innovations underway and private sector equipment innovations, if applicable, to pavement repair or crack/joint filling. When an innovative equipment need is identified, create functional specifications in close consultation with the private equipment sector. Offer the development of a prototype meeting specifications to the private sector. If the private sector is not responsive, propose joint public/private financing. As a last alternative, consider public funding to develop prototype.

Workplan

Task 3-3.1 - Survey of Available Materials.

1. Review ongoing research by state departments of transportation, other highway agencies and material suppliers and manufacturers seeking more rapid and permanent repair of holes in pavements and interested in more effective filling/sealing of cracks in pavements for candidate materials. Compile a data base of the materials currently used for pavement repairs and seals. This should include not only the most commonly used materials but also all others which have been tried and for which there is some documentation. Evaluate the experience and elaborate the conditions under which the materials were used.

2. The surface repair and joint/crack sealing activities should be reviewed in terms of the desired characteristics of maintenance materials for either preventive or emergency maintenance functions. To the maximum degree possible, these definitions should be given in terms of physical and/or chemical material properties and should be related to desirable performance characteristics resulting from the maintenance activity. In other words, the material properties should be defined in terms of strength, durability, adhesion, cohesion, acidity, durability, and so on.

3. Survey publications and other documents, suppliers, manufacturers, national laboratories, chemical producers, established material science researchers and other information sources to establish a list of materials to be subjected to laboratory tests. The search is to be

based on a knowledge of the materials currently used, those on which experiments have already been conducted, and with a definition of physical and chemical material properties desired for surface repairs and seals.

4. Define the laboratory tests necessary to determine if a candidate material provides any or all of the desirable physical and chemical properties. Initial testing is to be conducted on promising materials to verify their properties for potential maintenance use. It will also be necessary to evaluate the processes required to apply or otherwise use the material and to identify, to the fullest degree possible, the material limitations under field maintenance conditions.

Task 3-3.2 - Survey of Available Equipment and Equipment Research

1. Review ongoing research, equipment experimentation, and equipment modification by public agencies that is deemed potentially applicable to pavement surface repairs and to improving maintenance crack filling/sealing.

2. Review ongoing research, equipment experimentation, and equipment modification by private sector organizations that is deemed to be potentially applicable to improving pavement surface repairs and maintenance crack filling/sealing.

3. Survey the maintenance profession at the engineering and operating levels to determine deficiencies perceived in the equipment systems currently used in maintenance organizations when making pavement surface repairs and crack filling/sealing.

4. Define the desired equipment characteristics to address the perceived equipment deficiencies. Prepare general specifications on the capacity, capabilities and operating characteristics of each unit. Contact manufacturers and public agencies and determine if equipment has been developed that satisfies or can be modified to satisfy the specifications delineated.

5. Investigate each unit which promises to satisfy an identified equipment specification need.

- Study the unit's specifications, operating instructions and performance data.
- Inspect the unit under field operating conditions.
- Calculate the costs savings that are possible with equipment.
- Estimate the maintenance activity safety improvement potential of using equipment.
- Document the unit's capacity, and capabilities to meet specifications.

6. Conduct a systems analysis to evaluate the public and private sector equipment innovations (if any) offering probable success in satisfying perceived equipment deficiencies.

7. Design experiments to test the effectiveness of any innovations judged to offer success based on the systems analysis. The experiments are

to provide measures of changes in labor required, personnel, traveling public safety, and quality control improvements with respect to existing maintenance activity methods.

8. Conduct the equipment evaluation experiments. (Note that this may be done by others as a part of the ongoing research underway by developers and innovators on a shared basis.)

9. Analyze equipment evaluation data to determine whether perceived equipment deficiencies have been adequately addressed. If further work is needed, proceed to prototype concept design, otherwise proceed to integrate equipment research with materials research.

10. If needed, develop functional requirement specifications as a concept design for a prototype equipment system to meet perceived equipment deficiencies.

11. Document the findings of Task 3-3.2 with recommendations on existing equipment units that have potential to satisfy equipment needs and recommend units to be developed. Include specifications, evaluation results, and all warrants created to justify the development of new equipment.

For each unit to be developed, prepare a prototype evaluation test plan that addresses the equipment operating characteristics and costs, capabilities to perform required maintenance tasks, and its expected reliability, maintainability, ruggedness, and ease of operation.

Also detail an equipment development plan including the proposed development schedule, resource requirements, testing and evaluation procedures, and demonstrations as appropriate.

Task 3-3.3 - Laboratory and Field Testing of Select Materials.

Subtask 3-3.3a, Coordinate Short-Term Material Field Test.

1. Conduct physical and chemical laboratory tests to evaluate each material by itself and/or as an additive or component as appropriate. In addition, conduct those laboratory tests necessary to evaluate each material when used as a component of the maintenance activity. Example, how does a new binding material act when combined with typical aggregates? Many of the laboratory tests will involve abrasion, strength, heat resistance and those other quantitative parameters which can be quickly tested. Some new tests may need to be developed.

2. Prioritize candidate materials for each pavement type for short-term field testing to establish their effectiveness when applied to pavements. Consider application compatibility with available equipment, personnel training, quality control, environmental hazards, and the safety of the traveling public and maintenance personnel.

3. Arrange for controlled short-term field tests as appropriate. These tests should not extend more than one year. Do not include materials that cannot be effectively placed using available or developed equipment.

4. Document a review and evaluation of laboratory and field data following completion of field testing.

Subtask 3-3.3b - Conduct Short-Term Field Tests. The initial field test evaluation should investigate the processes andtechniques used in the maintenance activity as well as the performance of the candidate material. The procedures and techniques should be reviewed and, where appropriate, modified to improve the acceptability of the material.

Task 3-3.4 Develop Equipment.

Subtask 3-3.4a - Coordinate the Development, Evaluation and Refinement of Prototype Equipment.

1. Distribute the functional specifications to private sector equipment developers for detailed design and production of testable prototypes.

2. If no private organization will design and produce a prototype, solicit responses to a public contract to develop a prototype.

3. Following the selection of equipment development contractors, meet with each participating contractor to help initiate the development of prototype equipment.

- Formalize a detailed development plan and schedule for each unit.
- Arrange to coordinate the consultant's participation with the development effort.

4. Monitor the development of prototype equipment units by visiting the contractors at milestone points. Evaluate progress, prepare recommendations to improve the development process and help with problems that might be encountered.

5. When the prototype becomes operational, implement the testing plan and evaluate the performance of the prototype equipment. Identify deficiencies and deviations from specifications, and recommend modifications that will enhance the unit's capabilities.

6. Following any required modification to prototype equipment, re-evaluate performance and establish if the unit successfully complies with specifications.

7. Develop a final set of equipment specifications on all successfully developed equipment to be used by highway organizations in getting bids from private contractors to fabricate units or to build the units in-house with agency resources.

The consultant will also provide cost estimates for manufacturing, operating, and maintaining each prototype equipment unit that is successfully demonstrated to satisfy an equipment need.

8. Develop operational guide and training manuals to assist highway agency personnel to effectively use the new equipment. Include a description of the equipment's components, their replacement or repair requirements, a recommended preventive maintenance program, and proper procedures for operating the equipment efficiently. The manual shall include suitable illustrations and be in easily understandable text.

9. Establish recommended procedures and specifications to be used by highway agencies for equipment acceptance testing.

10. Since each unit has been developed to address a specific maintenance need or to handle a newly identified material, prepare a guide performance (work) standard for each of the maintenance activities on which the newly developed equipment can be used, including labor, other equipment as needed, and materials. Based on the use of equipment in field trials, determine the expected productivity of each activity using appropriate work units.

11. Document the final equipment designs for modification, equipment ordering, etc., as a part of the recommended material-equipment-method system to repair surface distress and fill/seal cracks in pavements.

Subtask 3-3.4b - Develop and Refine a Prototype Equipment Unit.

Subtask 3-3.4c - Develop and Refine a Prototype Equipment Unit.

Task 3-3.5b - Long-Term Material Field Tests.

Subtask 3-3.5a - Arrange for Long-Term Field Testing of Select Materials.

1. Based on the short-term field test evaluations and other information available, identify those materials requiring further performance evaluation and design field tests for Long-Term Pavement Performance studies and/or Maintenance Effectiveness studies for these materials.

2. Identify potential test site locations for each of the maintenance materials and operations selected for further testing. Adequate locations should be selected to provide, to the maximum degree possible, for a scientifically controlled experiment and evaluation. This should include parameters such as climate, road characteristics, traffic characteristics and others related to the specific maintenance activity. Use the study design of Project 3-1 on maintenance effectiveness as a guide.

3. Select the contractor to conduct the controlled long-term tests. The duration of these tests should be from one to three years depending on the expected and/or desirable life of the repair or seal. In many cases (possibly most) the complete evaluation may require a longer time span and arrangements should be made for continued observations and documentation.

4. Evaluate field test results to estimate the effectiveness of each recommended material. The final evaluation of laboratory and all

field test results should result in appropriate recommendations with regard to the conditions under which the materials will perform satisfactory.

Subtask 3-3.5b - Conduct Long-Term Material Field Test.

Task 3-3.6 - Documentation and Training.

1. Since new materials, procedures and possibly equipment will be identified as beneficial to maintenance activities, an integral part of the project will be the preparation of manuals on the use, application and critical factors concerned with the new materials. The manuals will be developed with full knowledge and appreciation of field conditions and clearly illustrate training requirements for users.

2. In addition to the manuals, a training course should be developed for using the new materials, equipment and procedures identified for adoption. These training courses would rely on the user manuals but would supplement them by using other media and direct instruction. The training courses (and manuals) should be tested on representative groups and modified where appropriate. In some cases it may be desirable to develop different levels of training courses. One might address those individuals who may need to evaluate the appropriateness of the material and to determine when and where it might be used. Another could focus on those who conduct the maintenance activity.

Deliverables

- An assessment of available materials within the spectrum of existing materials science technology to improve pavement patching and filling/sealing of cracks.
- A specification by which equipment can be modified or new equipment acquired to reduce the labor required, increase the safety to personnel, increase the safety to the traveling public, and/or reduce the environmental impact associated with surface repairs and filling/sealing cracks in pavements.
- A guideline on how to implement a material-equipment-method system to increase the effectiveness of pavement surface repairs.
- A guideline on how to implement a material-equipment-method system to increase the effectiveness of crack filling/sealing.

PROJECT 3-4, PAVEMENT MAINTENANCE WORK ZONE SYSTEMS TO IMPROVE WORKER AND MOTORIST SAFETY

According to the National Safety Council, approximately 500 maintenance workers are killed each year. This makes highway maintenance work second only to refuse collection as a hazardous occupation. Maintenance work areas on or close to the pavement also create hazards to highway users. One study covering 140 construction and maintenance work zone sites in 11 states, counties and cities showed accident rates, on an aggregation of road types, increasing 28 percent. Short-duration and short-length construction zones were found to have even higher accident rates.

Maintenance work crews occupy the travelway when they perform pavement maintenance. This occupancy is hazardous since it exposes workers to traffic and presents the motorist with unexpected or unusual conditions. Handling traffic during such pavement occupancies is a critical part of the maintenance operation.

The Manual on Uniform Traffic Control Devices (MUTCD) provides general guidance and minimum standards for a variety of pavement occupancy situations. Additionally, extensive literature and training material on proper traffic control techniques is available to complement the MUTCD. Most of this information addresses construction work sites or maintenance activity requiring some duration of pavement occupancy. As improved materials, methods, and equipment increase the productivity of pavement maintenance activities, pavement occupancy duration is shortened. The traffic control part of the activity becomes a major time component. Improved procedures are needed to reduce the time required to provide protection to the motorist and the maintenance worker and yet create an efficient workspace on the pavement without creating major disruptions to the flow of traffic. The new procedures must be easy to implement by small maintenance crews and suitable for a variety of traffic control situations, including rural low-volume roads, high-speed high-volume freeways, and urban streets.

Motorists approaching a traffic control site will usually be required to alter their vehicle speed and/or path to safely pass through the work zone. Critical to traffic control is the information the motorists receive relating to their required actions. Advance warning signs are not always effective in getting the motorists to reduce their speed in driving lanes, particularly when the work site is not visible. Flashing beacons and other attention getting mechanisms prove more effective, which suggests there are opportunities to experiment with various attention getting mechanisms to improve driver response. Changeable message signs seem to have good potential for short-duration closures, as do flashing arrow boards in some applications.

There are two fundamental alternatives to traffic impact in work zones. The first is energy absorption or in other words, crash barriers of one type or another which can bring a vehicle to a stop. The second is redirection of the vehicle, back onto a proper course. Positive traffic barriers are needed to protect maintenance work crews. For short-duration work activity they must be extremely portable. Such barriers can not rely on foundation restraints that are both costly and time-consuming to install and move. Further, a barrier must have the structural capability to redirect vehicles without undue vehicle damage. Existing barriers systems consist of precast concrete safety shapes, W-beam-on-barrel systems and timber W-beam barriers. Crash tests have shown that barrier performance improves as barrier length increases. The precast concrete seems to have the greatest acceptance. However, existing barrier systems are too costly and time consuming to install, particularly for short-duration pavement closures.

Portable energy-absorbing devices also can be used to provide protection to motorist and workers. A number of energy-absorbing devices that are attached to maintenance vehicles or trailers have been tested. Some only provide adequate protection for slow moving traffic (under 30 mph). Accommodating higher speeds requires greater attenuation length, inhibiting

their use on winding roads. A Connecticut DOT attenuation device that consists of four 2 foot diameter steel pipes connected in series and cantilevered from the rear of the service vehicle has been reported to perform satisfactorily in full scale crash testing. California DOT lightweight aluminum crushable material attenuations have been reported as helpful in reducing vehicle damage and deceleration. Opportunities exist to improve on such systems and to consider ways to incorporate the attenuation concept for rapid installation and removal of traffic controls.

There is a need to prevent rear end accidents due principally to driver error in addition to developing new controls to protect workers and motorist from serious injury or death when the traffic controls fail to engage a proper response on the part of the motorist. Rear end accidents predominate in the work zone approach area and have been reported to represent around 55 percent of the accidents in this area. Most are due to the slowing of preceding vehicles.

Uniform and objective procedures are needed to evaluate the effectiveness of different traffic control installations. The most acceptable measure of effectiveness is the traffic accident rate. However, accidents are rare events. Due to the stochastic nature of traffic accidents, large samples are needed and this requires collecting accident information over long periods of time. This is not possible for traffic control installations, particularly those of short duration associated with pavement maintenance activities. In lieu of accident experience, interim effectiveness evaluations must be devised. These must be based on changes in nonaccident measures of effectiveness.

Since the objective of traffic controls is to minimize the hazard to the maintenance worker and motorist, accidents are to be prevented or their severity reduced. Traffic controls are used to eliminate the safety deficiencies inherent in occupying a pavement to perform maintenance. A key to the nonaccident approach to safety effectiveness is the identification of the measures of effectiveness (MOEs) that need to be quantified for a given traffic control installation. MOEs must relate to the specific traffic operational or driver behavior characteristics that are expected to be affected by the installation of traffic controls. Each MOE should be a quantitative measurement that can be collected in the field in conjunction with any specific evaluation objective. These nonaccident measures used to evaluate a specific traffic control item or a configuration's effectiveness include such things as travel time, delay, traffic conflicts and erratic maneuvers, to cite a few examples.

Research results that can minimize roadway occupancy time for maintenance work will have a significant and positive impact on both worker and motorist safety. The research result sought should produce longer lasting and more permanent repairs, more productive repair processes, and more effective traffic controls to protect workers and the traveling public.

Objective

Develop improved materials, equipment and procedures to minimize the hazard to motorist and maintenance workers during pavement maintenance activities.

Scope

Emphasis is to be placed on improved traffic control for pavement surface repairs and joint and crack sealing. Minimizing hazards means rapid installation and removal of any traffic control devices. It also means striving for conditions as near to normal as possible so as not to inhibit traffic flow by providing positive guidance when altering traffic flow. It further means protecting the motorist and worker to the maximum extent possible should the traffic controls fail.

Consideration should be given to the automatic placement and removal of work zone delineators. Consider mobile traffic controls that are suitable for both moving operations and ones of short duration. Investigate traffic monitoring technology and alert and warning systems for the motorist and worker. Develop lightweight barriers to deflect motorists from head-on collisions and to protect workers. Investigate different crash attenuation systems. Create procedures to rapidly install and remove barriers, or possibly attach them to maintenance equipment where they can be rapidly deployed as needed. Minimize the labor requirements associated with traffic controls. Address both low and high traffic volume traffic control needs. Consider both daytime and nighttime installations. Establish standard procedures for evaluating the effectiveness of all devices and procedures. Provide guides for different work zone areas.

An objective evaluation is to be made on all recommended procedures and covering a variety of traffic control situations. Crash tests will be required to demonstrate the effectiveness of any barrier or attenuation systems.

Workplan

Task 3-4.1 - Evaluate Existing Devices and Procedures.

1. Conduct a literature review to determine the effectiveness of existing traffic control strategies and devices being used to improve safety and traffic operations in maintenance work zones, the measures of effectiveness (MOE) used to evaluate the traffic control strategies and devices and the methods used to collect the data to determine the MOEs.

2. Determine the work area requirements for pavement surface repairs and joint and crack sealing activities (relates to crew size, distress area or activity procedures).

3. Define the motorist behavior sought through the traffic controls that will be used to create a work zone.

4. Define any barrier requirements for different size work areas.

5. Prepare quantitative criteria to use in determining the effectiveness of traffic controls in terms of minimizing hazards. Consider accident avoidance as the basis for criteria. Use nonaccident measures to quantify MOEs such as conflicts, lateral placement, brake applications, erratic maneuvers, head turns, and work zone encroachments. Establish new MOEs to use in evaluating traffic control effectiveness. Evaluate compliance

with traffic controls by using speeds, speed changes and speed profiles. Apply the quantitative evaluation criteria to existing field study data, and assign effectiveness values to the devices and procedures studied. Establish the factors that are the most effective in getting motorist compliance. Based on the factors identified, develop guidelines to use in searching out and developing improved devices and procedures to use in protecting the motorist and worker when travelways are occupied to perform pavement maintenance.

6. Develop improved procedures to collect data on traffic volumes, speeds and motorist behavior in response to the presence of work zones. In planning for field evaluation it will be necessary to determine the types of field data that will be required to quantify each MOE. This includes the exact data, their units, time of data collection, data-collection procedures, and range of traffic conditions. Also needed is the amount of each data element required to establish statistically reliable samples.

Provision should be made to train field data collectors and to secure suitable data collection equipment. Also any instrumentation installations or other activities that require roadway occupancy must be coordinated with the appropriate highway agency.

7. Conduct field studies where there are gaps in existing knowledge to establish the effectiveness of currently used traffic control procedures and devices.

- Determine the effectiveness of a variety of common traffic control configurations. Emphasis is to be on traffic controls for spot locations and moving maintenance activities for both low and high traffic volume situations, day and night operations on rural and urban roads and expressways.
- Every care should be taken to ensure that no accidents occur during the evaluation of different devices and installation configuration. The steps that will be taken to minimize the probability of an accident shall be delivered as part of the field evaluation plan. It should be possible to create a work zone installation that if encroached upon as a result of a traffic control failure will not have any detrimental impact on the motorist.

Task 3-4.2 - Create Guides for New Traffic Controls. Use the guidelines delineated as a result of Task 3-4.1 and:

1. Identify or design new devices to use in traffic control operations on at least three different basic facilities. Consideration should be given to two-lane, high-speed, low-volume roads; urban and rural freeways; and multi-lane urban arterials which have low speeds and carry large volumes of traffic. These latter roads have unique characteristics such as the effect of signalized intersections, the fact that shoulders generally are not available to work from, and the presence of pedestrian traffic. With reference to barriers, it might well be that an energy absorbing barrier would be much better suited to the arterial street where it might prevent the longer-term tie-up and have a reduced probability of

involving others in a collision with a redirected vehicle. Also lower speeds are involved.

2. Conceptualize different approaches to protecting the motorist and worker including an automated warning system.

3. Develop specifications for a lightweight, rapidly implemented barrier and with attenuators to protect worker and motorist. An effective barrier might be one that prevents the occurrence through adequate driver reaction rather than one which is a part of an impact. It might also lead to examining multi-stage barriers where there is some initial warning, possibly more than visual, including audio or even a slight impact (a traveling speed bump) which would alert the driver to take a corrective action prior to impacting the second portion of the device which would then stop or redirect the vehicle.

4. Assemble a panel of from six to eight experts and critique the new devices and procedures. Prepare recommendations for developing and testing new devices and procedures.

Task 3-4.3 - Develop and Test New Traffic Controls.

Subtask 3-4.3a. Develop and fabricate portable rapidly installable barrier/attenuation systems as set forth in the specification developed in Task 3-4.2 and subject it to crash tests to determine its ability to deflect motorists and protect workers.

Subtask 3-4.3b. Conceptualize, fabricate and make available for field testing a detection system to alert motorists of workzone presence and to warn maintenance workers of a impending crash due to traffic control failure.

Subtask 3-4.3c. Test new devices and applications using the evaluation criteria established in Task 3-4.1. Testing may be in the field, under laboratory conditions, or both. Computers might be used to simulate the probability of accidents at a work zone. Possibly the type of accident and the speed and direction of errant vehicles could be simulated from known accident records. This could lead directly into some form of risk analysis to evaluate one of the major tradeoffs, i.e., protection costs versus the probability of an occurrence. Consider the use of modern simulators such as those available to FHWA in Washington to measure drivers' response to different types of devices, both existing and those which may be developed under the project. Some type of controlled field test will probably be required to simulate the degree of damage at impact.

Task 3-4.4 - Documentation for Implementation.

1. Develop specifications that can be used by highway agencies to have new traffic control devices, materials and instrumentation fabricated.

2. Prepare training courses on the use of the evaluation process and the use of any new traffic controls and procedures. The training courses should be tested on representative groups and modified where appropriate.

Deliverables

- Specifications for the fabrication of a lightweight barrier or attenuation system that will deflect motorists and protect workers when pavements are occupied to perform maintenance.
- An objective methodology to evaluate traffic control processes and devices.
- Objective measures of the effectiveness of existing and newly developed devices, materials and traffic control procedures for a variety of pavement occupancy situations.
- Specifications for a warning system to alert motorists and workers when traffic controls fail to get proper motorist response.
- Traffic control installation and removal procedures.

IMPLEMENTING RESEARCH RESULTS

A fundamental concern expressed continuously during each of the Maintenance Advisory Committee meetings was that existing knowledge does not get used by the highway maintenance community. It was clear that conducting training as an implementation process was not a part of SHRP. However, the creation of new and innovative ways to implement research results and to train maintenance personnel to use research results is considered to be within the scope of SHRP. Therefore, an important part of the maintenance cost-effective research design should be a project that can apply contemporary marketing technology innovatively to the problem of getting the results from the other maintenance projects in the SHRP program actually used.

The project should develop improved mechanisms to achieve wider application of research results. Novel ways need to be developed to package results so that they will be really accepted within the maintenance community. In particular, a need exists to reach technicians and hourly employees who have little opportunity to participate in training other than on-the-job. Maintenance personnel in these categories develop their skills through job experience. They do not depend on literature to gain technical expertise. Their knowledge is obtained through trial and error and interactions with supervisors, vendors and peers. The way to get research results used by such personnel is to have them participate in demonstrations, lectures, and to be involved in hands-on experience under instructor guidance.

As envisioned by the Advisory Committee, this project should be given to a contractor whose expertise included contemporary marketing technology and the capability to develop training and implementation information dissemination packages. The contractor would interface with each of the other maintenance contractors and together they would formulate the procedures and format of the implementation and training package that offered the best potential to get the research results from each project used. The actual creation of the packages would be handled by this consultant. The following research project was structured to satisfy this need.

PROJECT 3-5(3), MEDIA EVALUATION AND IMPLEMENTATION RESEARCH IN HIGHWAY MAINTENANCE

The goal of all applied research should be to improve the quality and/or efficiency of the work in the field or office. Thus, research is ineffectual if the solutions are not carried through to implementation. Too often, inadequate attention is given to placing the research results in a context and form which will enhance chances for acceptance and implementation.

Decisions regarding maintenance involve a broad range of the population, from the general public, elected officials, agency administrators, maintenance engineers, and field supervisors, to the individuals in the laboratories, offices or field who are charged with ultimate application. Every level has a need for different kinds of information regarding a specific maintenance improvement in order to accommodate their effective decision-making.

The printed word (though highly effective for complete documentation) is a greatly overloaded media. There are numerous alternatives which have not been fully used in the maintenance field. These include, but are not limited to, photographic media, video tape, radio, television broadcast, computer-based systems and others.

If the results of the maintenance research effort are to be effectively implemented, a separate project is needed to research the effectiveness of various media and develop implementation information packages. This effort should include communication and media professionals as well as technical researchers.

Objectives

- Coordinate with SHRP contractors in developing their information and implementation materials to achieve greater effectiveness and continuity and identify the most appropriate user constituencies for the results of each project.
- Evaluate the effectiveness of various media in communicating the needs and benefits identified in SHRP maintenance research to each of the appropriate constituencies.
- Produce for each SHRP maintenance technical research project, a range of specialized implementation modules to maximize communication effectiveness. These will be individualized for various constituencies using technical information from the SHRP maintenance research projects and the most effective media for each of the maintenance constituencies.

Scope

Include all maintenance operations and maintenance activities related to any of the SHRP maintenance projects; maintenance agencies at state, county and city level must be in the constituency groups. Also include effective communication of accepted research results from each SHRP maintenance project.

Investigate all available media, including various computer-based media and electronic systems. These are to be evaluated as to cost and effectiveness in communicating different types of information to different constituencies.

SHRP technical researchers are to be supported as they develop the manuals and short course materials that are required deliverables in their individual technical projects. The technical researchers are to be encouraged to create innovative materials.

The most important and extensive task will be the development and delivery of information and implementation modules relating to the new information, techniques, materials and strategies developed from the SHRP maintenance research. Separate implementation modules using appropriate media will be developed for the different constituencies reflecting different levels of technical knowledge and the implementation concerns of these constituencies.

Workplan

1. Gather information on existing implementation materials to use in disseminating SHRP maintenance project results.

- Inventory relevant materials from National Highway Institute, technology transfer centers, state departments of transportation, APWA, and other existing providers of training materials.
- Categorize existing materials as to their target population, information content and media.

2. Evaluate various contemporary media as applied to implementation of SHRP maintenance activities.

- Survey users of existing materials as to their perception of effectiveness.
- Using an interdisciplinary group, including public relations and communication experts, formulate factors relating the most effective use of media as directed to specific target groups with appropriate message content. Compare these to existing materials.
- Based on views of users, producers and communication specialists, evaluate the best of the existing materials. Enumerate the strengths and weaknesses of each material or media form for each level of constituency.

3. Coordinate and support SHRP technical maintenance researchers in the development of information and implementation products.

- Coordinate implementation with all SHRP technical maintenance contractors. Define specific deliverables being developed by each research contractor and identify intended users.
- Identify information needs for those audiences not covered by the technical deliverables and establish responsibilities regarding information needs.

- Evaluate desirable degree of common format, media, etc., to be used by all SHRP technical maintenance researchers.
- Explore new or innovative approaches with technical researchers to be considered for their deliverables.
- Provide media and graphics support to technical researchers as appropriate within technical responsibilities and budget.

4. Develop information to characterize the user of research results.

- Survey target groups as to informational needs, detail desired, media preference, duration of exposure, perceived importance of subject to their work, etc., for each SHRP technical maintenance research area.
- Develop a computerized data base of information obtained.
- Using marketing and communication experts, evaluate the results of the users' survey to select promising training and implementation methods for each maintenance research contractor.
- Based on the preceding, develop a general format of content, media, etc., to be employed in the development of the implementation module for each specific group.

5. Develop and deliver information and implementation modules for the SHRP maintenance research projects using appropriate media for the specialized, individual constituencies concerned.

- For each technical maintenance research area, identify the target groups, their information needs, and preferable media, based on Task 4. Not all target groups may be included in each research area. Interest, need and probable effectiveness should be used to eliminate those groups where implementation modules would not be cost-effective.
- Prepare and produce multiple information and implementation modules as designed in item 1 above.
- Test the modules on appropriate target groups. Test should include an estimate of each module's short and long-term effectiveness.
- Evaluate test results and modify modules as appropriate.
- Deliver final versions of the information and implementation modules.

Deliverables

A series of implementation units using appropriate media (including print) which have been tested, evaluated and modified to ensure their effectiveness in reaching the target constituencies.

SECTION 5
RESULTS TO BE ACHIEVED

The maintenance cost-effectiveness research design was developed to generate a maximum payoff to the maintenance community. All of the projects have been directed at pavement maintenance, an activity that nationwide consumes over one-third of all highway maintenance expenditures. By concentrating the entire maintenance research program on pavements, the prospects for success should be high.

Each project addresses issues that are considered important to highway agencies so there should be good acceptance on the part of the nation's highway organizations of the results produced by the research.

The research program is designed to improve the maintenance community's ability to maintain highway pavements. The approach is three-pronged. Two projects address the need to improve maintenance organizations' ability to administer maintenance funds for highway pavements. This means providing management with better ways to plan, budget, and program pavement maintenance expenditures. Two projects attack the problem of execution efficiency by searching for better materials, methods, and equipment to perform pavement maintenance and by developing traffic control devices and procedures to ensure that any pavement activity can be performed as quickly and safely as possible. A final project is structured to get the results from the first four projects actually used.

The general benefits expected from the successful completion of the projects proposed include:

- Eliminating or minimizing pavement hazards to the motorist by anticipating and treating pavement distress before it becomes serious.
- Improving pavement lifetime serviceability (minimizing user costs) by implementing maintenance treatments offering the maximum extension of pavement service life.
- Minimizing agency pavement maintenance costs by selecting the optimum time to implement pavement maintenance treatments and by executing the treatments efficiently.
- Minimizing the hazards to maintenance workers and motorists when occupying a pavement to perform maintenance by executing the maintenance quickly and having rapidly implemented traffic control procedures that ensure maximum protection to both the worker and the motorist.

The way in which the general benefits will be acquired can be shown by examining the specific improvements that will be realized through the successful completion of each project.

PROJECT 3-1. QUANTIFY PAVEMENT MAINTENANCE EFFECTIVENESS

This project is expected to explain the effectiveness of six specific pavement maintenance treatments: flexible pavement chip seals, thin overlays, slurry seals and crack sealing, plus rigid pavement joint and crack sealing and undersealing.

Effectiveness means the extent to which a pavement's deterioration process is retarded and its life extended in terms of both surface distress and serviceability. Further, these assessments of effectiveness are expected to be related to (1) the pavement's condition at the time of a treatment, (2) the structural characteristics of the pavement, (3) the traffic to which it will be exposed and (4) other environmental and local factors to which the pavement will be subjected. With this type of information, highway organizations can examine a variety of maintenance options over a pavement life cycle period and select a strategy that will maximize pavement service life at a minimum cost to either or both the agency and road users.

Another result of this study will be that the principal factors affecting the effectiveness of different pavement maintenance will have been identified. These factors represent data items that are candidates to be monitored by highway organizations. This represents important information that can be used to improve the management processes.

In the process of monitoring effectiveness, the different conditions must be quantified. Specific measurement units must be defined for each distress condition, i.e., cracks, ruts, faults, bleeding, and so on. Since distress ranges from slight to severe and in the extent of area affected, ways must be developed to define the expected variations in the distribution of distress. This process should create a basis for establishing objective definitions for pavement-related maintenance service levels.

The SHRP L-TPP studies are expected to produce models to explain pavement performance as a function of pavement characteristics, traffic and the environment. It should be possible to modify these models to reflect the influence of optional pavement maintenance treatments. Once this capability is in hand, maintenance managers will have another important tool. They will be able to predict pavement distress, define the conditions of distress that will activate a specific maintenance response and the extent of that response (maintenance service level). This means that the maintenance manager will have the ability to compute future maintenance workloads (based on objective predictions of need) to meet current maintenance level policies. This will substantially improve the planning, budgeting, programming and scheduling processes for pavement maintenance.

PROJECT 3-2. MEASURING SYSTEMS AND INSTRUMENTATION FOR EVALUATING PAVEMENT MAINTENANCE EFFECTIVENESS

Expected from this project will be implementable procedures to obtain periodically the factors and pavement condition information needed to

evaluate pavement maintenance effectiveness. Project 3-1 will define the specific information needed. This project will either identify or produce the equipment, devices, instrumentation and procedures required to collect and reduce data to meaningful information.

The actual implementation of the data gathering and reduction procedures will allow maintenance managers to continuously monitor pavement conditions and verify or modify the distress prediction models mentioned under Project 3-1. This information will permit managers to monitor the pavement maintenance service levels actually achieved from their programs. The information generated is also basic inventory data needed for maintenance workload predictions, an integral part of the maintenance budgeting process. Finally, the monitoring process provides management with definitive information indicating the onset of pavement failures or at least to anticipate a failure. With such information, managers can execute preventive maintenance that should delay or prevent more costly corrective maintenance and rehabilitation.

PROJECT 3-3, IMPROVED MATERIALS AND EQUIPMENT FOR PAVEMENT LOCALIZED SURFACE REPAIR AND CRACK FILLING

For two types of pavement maintenance activity, i.e., repairing localized pavement surface defects and joint/crack sealing, improved materials are expected to be identified, new or modified equipment developed and better methods devised to perform those activities. The improved materials are expected to be easier to place or use, cure more quickly so that maintenance sites can be opened to traffic within minutes of work completion, and be more permanent so that the maintenance work need not be repeated. The need to find faster methods for performing the individual tasks of the two maintenance activities to be studied will be addressed by creating new ways to use existing equipment, possibly modifying existing equipment or even developing new equipment. The resulting equipment will replace expensive, slow, and labor-intensive work activity, will hopefully improve the quality of the maintenance work thereby enhancing its permanence, and most importantly, should substantially reduce the time required to complete the maintenance tasks on which the equipment is used. Maintenance methods can be restructured to capture the benefits realized from improved materials and equipment. We can expect to increase maintenance work productivity and reduce its unit costs. Most importantly, we will be able to minimize the time that maintenance work crews spend on a pavement, not only for a given pavement occupancy, but by minimizing the frequency that pavements are occupied. This translates directly into improved safety for both the maintenance crews and the motorist since their exposure to the hazardous conditions created by pavement occupancy will be less.

Another result of minimizing the frequency and time of pavement occupancy will be to reduce motorist traffic interface expense, in terms of vehicle operating costs and travel time.

One example of the magnitude of the problem being addressed was summarized from the Road Information Program (TRIP) survey. It showed that in 1985 there was an average of 29 potholes per mile on pavements nationally. With over 2 million miles of paved roads this is 56 million potholes. At an estimated cost of $224 million dollars, a 10% improvement in the productivity

and unit cost of just pothole repairing would save over 20 million dollars annually, given the current condition of the nation's pavements.

PROJECT 3-4, PAVEMENT MAINTENANCE WORK ZONE SYSTEMS TO IMPROVE WORKER AND MOTORIST SAFETY

As the title indicates, the results from this effort should improve both maintenance worker and motorist safety. This will be achieved in three ways. First, more efficient traffic control installation and removal procedures will be created. Both the maintenance worker and the motorist will realize less exposure time. With improved devices, the traffic controls will be more effective, gain better motorist response and thereby reduce accidents. Finally, the ability to use portable barriers and attenuators will minimize the seriousness of any mishap and thereby reduce motorist and worker injuries and fatalities.

PROJECT 3-5(3), MEDIA EVALUATION AND IMPLEMENTATION RESEARCH IN HIGHWAY MAINTENANCE

A major concern expressed by the maintenance community is that many of their problems have already been solved by somebody, someplace, at some time. If these solutions could only be made known at the right time, substantial improvements could be made in maintenance administration and operational procedures. This project will not implement study results, but it will identify contemporary marketing communication and training techniques that can be used to enhance the chances that the results produced in the first four projects will be implemented and used. Further, these concepts will be incorporated into readily implementable training packages on each project and directed to maintenance personnel at all levels.

The concepts and procedures developed as a result of this research are expected to have wide application, not only for the maintenance community but in providing guidance on training and implementation processes covering the entire spectrum of highway disciplines.

ISSUES ADDRESSED BY SHRP

SHRP is a study that is concerned with issues that impact on highways nationally. This program for research in the maintenance area addresses each of the criteria set forth to guide the selection of SHRP research.

- The maintenance cost-effectiveness program will achieve maximum payoff. With 1985 maintenance expenditures at an expected 18 billion dollar level and with pavements maintenance representing over a third of these expenditures, a savings of 1% to highway organizations will produce benefits of 60 million dollars a year for an investment of 4 million dollars per year.
- Maintenance is a neglected area since expenditures represent nearly one-third of total annual highway direct costs. Less than one percent of the Federally Coordinated Program of Research addresses maintenance. Since so little has historically been invested in maintenance research, it is an area offering maximum opportunity for improvements.

- There are no maintenance organizational barriers to experimenting with different maintenance processes, materials, or equipment. However, experimentation results tend to be confined to the agency that does the experiment. The reason is that different terminology, units of measure and environments raise serious questions concerning the applicability of the results to other jurisdictions. Each project defined in the maintenance cost-effectiveness program addresses serious issues that have been considered previously, but in a fragmented, informal manner by numerous highway organizations.
- Each project in the maintenance cost-effective research program will produce deliverables that are urgently wanted by the maintenance community. Also addressed by the program is the need to standardize measurement units, data reduction process, and terminology that can establish a standard for the maintenance community. This national and agency unbiased approach should promote the ready acceptance of study results and enhance the probability that research results will be used.
- The maintenance cost-effective research program is a massive undertaking to address numerous facets of a single maintenance problem area, namely pavement distress. Only with such a large scale effort can this problem be successfully studied and produce meaningful results that can and will be applied nationally.
- The research plan presents a coordinated attack on pavement distress. This includes developing methods to anticipate it; quantifying the effectiveness of alternative treatments in preventing or eliminating it; devising the best combination of material, equipment and procedures to treat it; creating the safest possible conditions to perform the treatment; monitoring the subsequent performance to validate the adequacy of different treatments; providing basic information and relationships to manage the process; and finally, establishing implementation processes to get all the improvements used.
- Changes in national policies have been anticipated in formulating the research projects. The effectiveness of a pavement maintenance treatment will be quantified for different traffic loading conditions so changes in permissible axle loadings in the future can be handled. In evaluating alternative repair materials, the impact on the environment is considered and thereby accommodates changes in environment pollution policies. The study's emphasis on mechanization for maintenance work and traffic control will circumvent future concerns of OSHA for workmen safety, as does the emphasis on automated equipment to replace survey teams who walk along the roadway evaluating pavement conditions.
- The entire study program is concerned with improving safety. Selecting the best pavement treatment for measured conditions will minimize the frequency that the pavement is occupied by preventing distress such as potholes which create a hazard to the motorist. Performing the work quickly by having highly productive work methods and instantly installed traffic controls will minimize the time motorist and workers are exposed to hazardous pavement work-sites. Enhanced barriers,

attenuators and warning systems will minimize the frequency of injuries and fatalities when there is a mishap. Getting the results used will ensure that all of the safety benefits will be realized.

SECTION 6
IMPLEMENTATION OF RESULTS

Project 3-5 directly addresses the issue of study results implementation and will produce training and implementation packages to cover the maintenance cost-effectiveness Projects 3-1 thru 3-4. These packages will provide a basis for transmitting the research results. Also needed will be some mechanism to assemble the necessary receivers of the packaged material. This will require the identification of specific people who are interested in the subject results, capable of understanding it, and want to be exposed to the information. Further, a suitable environment must be established for the actual exposure to the implementation/training packages.

The technology transfer program for local transportation agencies(T^2 for Locals Program) can provide useful guidance for structuring an implementation program. In particular, the T^2 programs emphasis on getting information disseminated close to an employee's work place is particularly germane for maintenance workers. Related to local agencies, the T^2 Centers throughout the country would seem to be an ideal place to initiate the implementation of the maintenance cost-effectiveness study results for local highway agencies. In this regard, it would probably be necessary to provide financial support to the centers to achieve the maximum level of implementation.

It will be desirable to establish feedback on the effectiveness of the implementation packages relating to inaccuracies, inconsistencies, media appropriateness, pace, content and so forth, so that appropriate revisions and modifications can be made to enhance the quality of the implementation packages. This would suggest that some centralized SHRP organization be available to handle this function, possibly with support from a contractor with marketing and material preparation expertise.

SECTION 7
SCHEDULE OF PROJECTS, TASKS AND SUBTASKS

The timing of the five projects making up the Maintenance Cost-Effectiveness research plan is shown in Figure 4.

Project 3-1, "Quantify Pavement Maintenance Effectiveness" consists of five contracts. The main contract includes Task 3-1.1 thru Task 3-1.5 and is concerned with the formulation of the study's experimental and implementation plans, coordinating the collection of data, evaluating the effectiveness of each treatment study and providing guidance on the development of a training implementation package. Under Task 3-1.3 are contracts for Subtask 3-1.3b, c, d, and e. These contracts are required to support the actual data collection and reduction process expected to be implemented in conjunction with the L-TPP studies and in each of the four regions established for L-TPP. The data collection effort can start as soon as the test section sites are identified and the appropriate interfacing arranged with state highway agencies in each L-TPP study region. The actual timing may be constrained by the status of the L-TPP studies.

Project 3-2, "Measuring Systems and Instrumentation for Evaluating Pavement Maintenance Effectiveness" consists of four contracts. The main contract consists of all Tasks 3-2.1 thru 3-2.4 and addresses all facets of the project. If it should be determined that prototype instrumentation is to be developed, up to three different prototypes can be built using the funds that have been allocated to Subtasks 3-2.3a, b, and c. The schedule envisions that it will require between one and two years before any requirements for instrument prototypes will be formulated.

Project 3-3, "Improved Materials and Equipment for Pavement and Surface Repairs and Crack Filling" is designed to have one contractor examine materials, equipment, and procedures since the Advisory Committee felt separating these components is undesirable. The main contract includes Tasks 3-3.1 thru 3-3.6. It is the coordinating contract where new or improved materials and equipment are identified, evaluation programs formulated and recommendations with specifications drafted for equipment prototype development. Subtask 3-3.3b is to be a separate contract to fund short-term material testing by L-TPP regional contractors. If in Task 3-3.2 it is determined that new equipment is warranted, specifications are developed for the desired units. Private industry is first to be approached. If they are not responsive, contracts to support Subtasks 3-3.4b and 3-3.4c can be executed to provide public support to a private equipment manufacturer to help develop the desired prototypes. As currently envisioned, the equipment prototype development phase would not be initiated until about halfway through the five year study program. Subtask 3-3.5b provides funds to

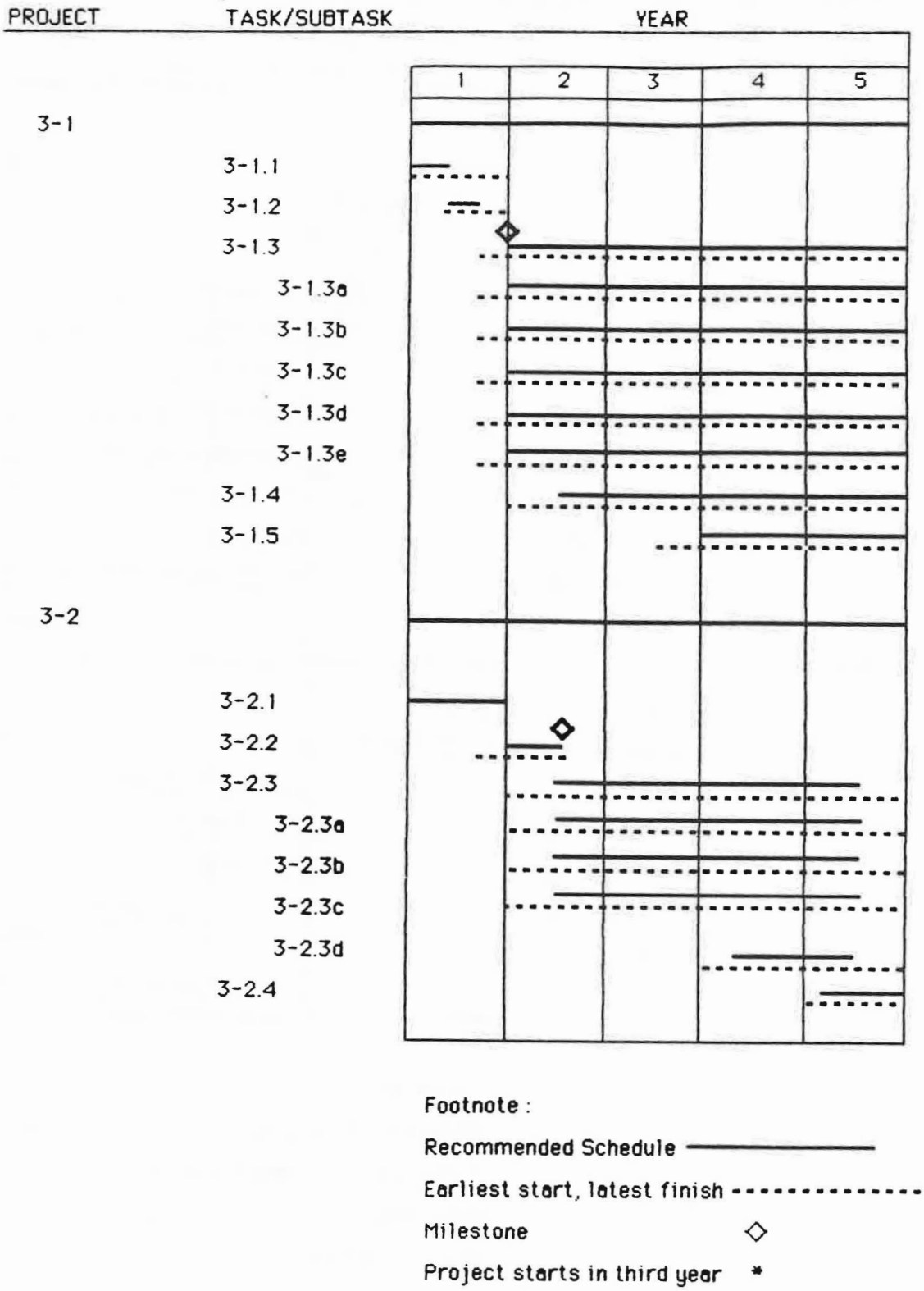


FIGURE 4. PROJECT SCHEDULE FOR RESEARCH STUDY ON MAINTENANCE COST-EFFECTIVENESS

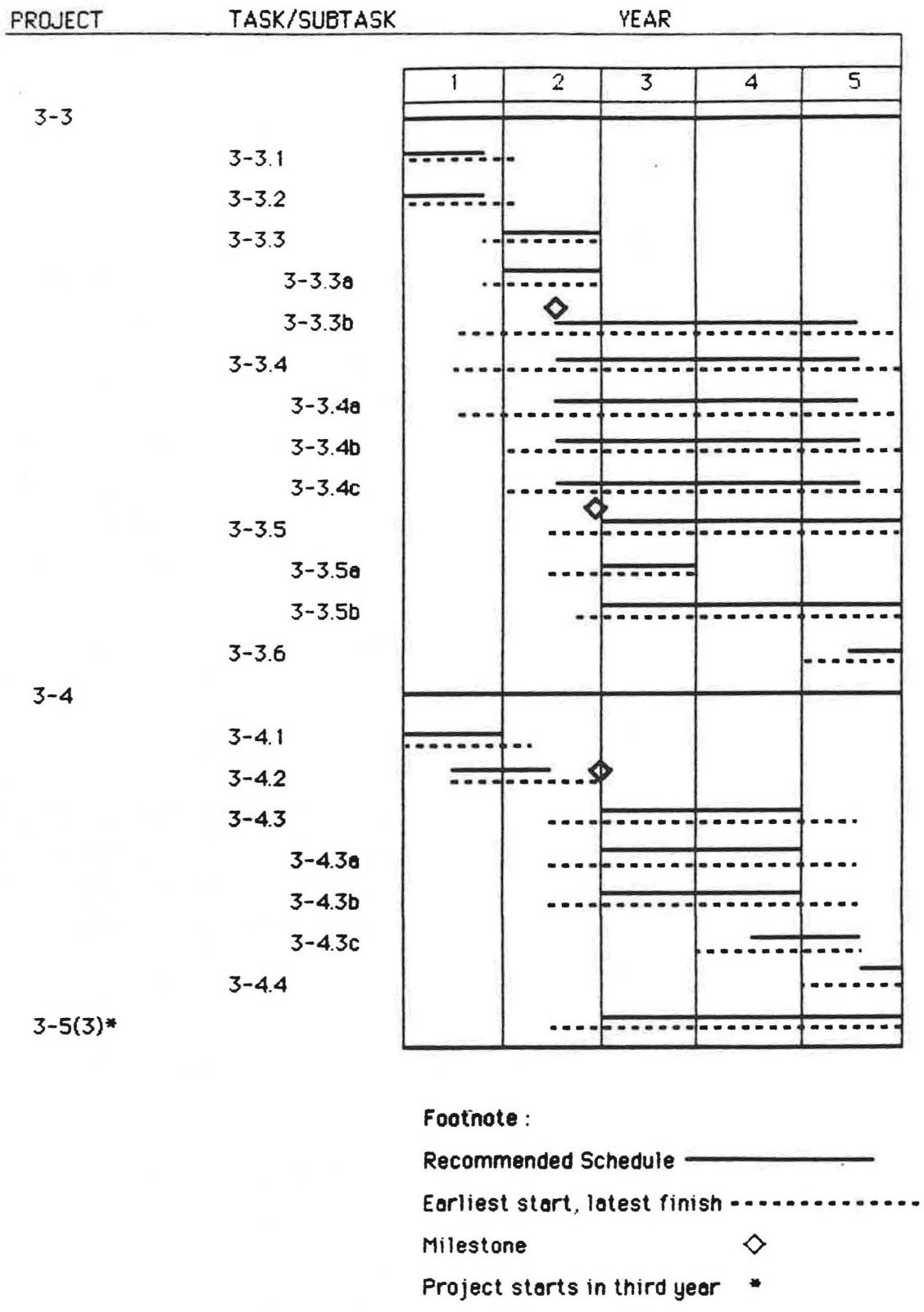


FIGURE 4. PROJECT SCHEDULE FOR RESEARCH STUDY ON MAINTENANCE COST-EFFECTIVENESS

support the L-TPP regional contractors as they implement field tests of select materials as designated by the coordinating contractor.

Project 3-4, "Pavement Maintenance Work Zone Systems to Improve Worker and Motorist Safety" consists of three contracts. The overall project involves all tasks; 4-4.1 thru 4-4.4. Provision is made for two contracts, Subtask 3-4.3a to develop, fabricate and crash test portable rapidly installable barrier/attenuation systems and Subtask 3-4.3b to conceptualize, fabricate and make available for field testing a detector system to alert motorists of work zone presence and warn motorists of an impending crash due to traffic control failure.

Project 3-5(3), "Media Evaluation and Implementation Research in Highway Maintenance" is one contract. This contract will be delayed until there is substantive research results available to package for implementation. Present estimate is this will be at least two years into the research program.

SECTION 8
BUDGET

The budget is summarized in Table 4. As indicated earlier, most of the projects consist of a number of tasks and generally each project is envisioned as a single contract. The exception is that there are certain portions of some project tasks that lend themselves to separate contracts. For this reason, some of the tasks are broken down further into subtasks.

In the Project 3-1, there are five tasks, all conducted by a single contractor. Task 3-1.3 is broken down into five subtasks. This data collection task includes the main coordinating contractor and four $1,300,000 contracts to support regional contractors who are responsible for collecting and reducing field data. The regional contractors are assumed to be the same as those envisioned by TRA-2 on L-TPP.

Project 3-2 consists of four tasks with Task 3-2.3 broken down further to four subtasks where provision is made for three different prototype development subtasks, each with budgets of $1,000,000.

Project 3-3 consists of six tasks. Subtask 3-3.3b and Subtask 3-3.5b are budgeted to support the field evaluation of select improved materials in both short- and long-term field tests. These tasks are expected to be handled by one or more of the TRA-2 L-TPP regional contractors. Subtasks 3-3.4b and 3-3.4c are budgeted to support the development of improved equipment in support of private industry should the latter decline to undertake prototype development at their own expense.

Project 3-4 consists of three tasks, having $1,600,000 to identify, conceptualize and evaluate improved traffic control devices and procedures. Subtask 3-4.3a is budgeted to support the development and crash testing of a barrier/attenuation system. Subtask 3-4.3b is funded to fabricate an early warning system and conduct preliminary field tests to demonstrate its utility.

Project 3-5(3) is a single task to provide technical expertise on marketing and to develop training/implementation packages to get the maintenance cost-effectiveness research results used.

TABLE 4
TRA 3 BUDGET

Project	Task/Subtask		Year 1	2	3	4	5	Cost $ in thousands	
3-1									6,050
	3-1.1		40	---	---	---	---	40	
	3-1.2		40	---	---	---	---	40	
	3-1.3							5,570	
		3-1.3a	170	50	50	50	50	370	
		3-1.3b	200	350	250	250	250	1,300	
		3-1.3c	200	350	250	250	250	1,300	
		3-1.3d	200	350	250	250	250	1,300	
		3-1.3e	200	350	250	250	250	1,300	
	3-1.4		---	50	50	85	175	360	
	3-1.5		---	---	---	15	25	40	
3-2									3,500
	3-2.1		100	---	---	---	---	100	
	3-2.2		---	50	---	---	---	50	
	3-2.3							3,310	
		3-2.3a	---	50	100	100	60	310	
		3-2.3b	---	100	300	300	300	1,000	
		3-2.3c	---	100	300	300	300	1,000	
		3-2.3d	---	100	300	300	300	1,000	
	3-2.4		---	---	---	---	40	40	
3-3									6,300
	3-3.1		450	350	---	---	---	800	
	3-3.2		450	350	---	---	---	800	
	3-3.3							700	
		3-3.3a	---	400	100	---	---	500	
		3-3.3b	---	100	100	---	---	200	
	3-3.4							3,030	
		3-3.4a	---	---	250	170	150	570	
		3-3.4b	---	---	230	500	500	1,230	
		3-3.4c	---	---	230	500	500	1,230	
	3-3.5							900	
		3-3.5a	---	100	150	130	120	500	
		3-3.5b	---	---	100	200	100	400	
	3-3.6		---	---	---	20	50	70	
3-4									2,900
	3-4.1		325	25	---	---	---	350	
	3-4.2		---	325	50	---	---	375	
	3-4.3		---	---	---	---	---	2,115	
		3-4.3a	---	---	350	350	---	700	
		3-4.3b	---	---	300	300	---	600	
		3-4.3c	---	---	100	300	415	815	
	3-4.4		---	---	---	20	40	60	
3-5			---	---	200	500	600		1,300
								Total	$20,050

APPENDIX A
TRA 3 - POTENTIAL PROJECTS CONSIDERED BUT NOT INCLUDED IN RECOMMENDED RESEARCH PROGRAM

The contractor and the Maintenance Advisory Committee, during its meeting to develop projects for the Maintenance Cost-Effectiveness Research Area, identified a number of studies not included in the final research design. They were deemed important areas of research need but were excluded since there were resource limitations. The Committee also identified elements of the proposed study plan that were eliminated to reduce the scope of the proposed research. These problem areas and project elements are discussed below:

PROJECT A-1. DEVELOP PORTABLE NONDESTRUCTIVE SENSING EQUIPMENT TO EVALUATE MAINTENANCE CONDITIONS

Corrective highway maintenance could be eliminated or minimized if maintenance is conducted in a more timely manner. This means anticipating needs and applying preventive maintenance treatments. Current information on the maintainable highway components condition is insufficient.

Distress measuring or sensing procedures are needed to detect maintenance element characteristics that indicate the onset of failure or can anticipate failure. Devices or procedures are needed to detect:

- voids under culverts, pipes and conduits,
- extent of hidden defects in bridge joints,
- the condition of concrete and steel in culverts or drainage pipes, particularly in unaccessible locations,
- steel paint adequacy,
- steel fatigue cracks,
- sign and marking reflectivity,
- defects in monolithic decks on box beam bridges,
- bridge deck distress and delamination,
- prestressed concrete steel condition,
- crack detection in structural concrete and steel.

PROJECT A-2. QUANTIFY THE PUBLIC CONSEQUENCES OF PAVEMENT CONDITIONS

It is important to assess both the costs and benefits of any proposed maintenance activity and objectively evaluate the economic and other consequences of different actions. The influence of pavement roughness on vehicle operating costs is not well established. Not enough is known about the potential for potholes and shoulder dropoffs to cause accidents. Therefore, establish quantitative models to explain the impact of pavement

conditions on vehicle operating costs, lost time, accidents, pollution, and user comfort.

PROJECT A-3. IMPROVED AND MORE EFFICIENT MAINTENANCE EQUIPMENT

Improved mechanization and better equipment is needed for many maintenance activities. Major payoffs can be realized by identifying modifications that will optimize the utility and productivity of equipment.

Sought by maintenance organizations are more compact and efficient hydraulic and air tools that can be attached to conventional maintenance equipment units, tree trimming devices, chipping hammers, guiderail post drivers, signpost drivers, compactors, guiderail straightening devices and post straightening devices. Needed are equipment to repair, sleeve or replace pipes and culverts under deep fills that are deteriorating and will require substantial repair or replacement in the near future. There is a need for the removal and replacement of structural steel protective materials. Present sandblasting and high-pressure water jetting are seen as expensive and damaging to the environment. Equipment is wanted to improve the mechanization of litter removal and to recycle all types of binders. Improved equipment also includes units for mowing, ditch cleaning, painting, sweeping, culvert cleaning, hazardous waste removal and woody vegetation elimination.

PROJECT A-4. EQUIPMENT MANAGEMENT NEEDS

A model is needed to select the optimal range and mix of equipment for highway maintenance activities. Also, standard criteria and test procedures are needed for equipment acceptance as well as guidelines on future equipment maintainability. Finally, guides are required on equipment replacement, component standardization, preventive maintenance practices and operator training aimed at improving safety and motivating operator respect to avoid equipment abuse.

PROJECT A-5. STRATEGIC MODEL TO GUIDE MANAGEMENT DECISIONS

Top management needs help to weigh all the factors affecting decisions. Given the proliferation of information and the desire to make good decisions quickly suggests that computers and automation can be applied to help top managers. Both expert systems and simulation are techniques that can be used in computer programs to assist managers make decisions. Questions, alternatives and consequences that can be addressed encompass variations in:

- Frequency of performing maintenance activities
- Size and number of work crews assigned to an activity
- Number and size of different types of equipment assigned to an activity
- Interruptions of scheduled maintenance activity due to sick leave, vacation, equipment breakdown, equipment maintenance, natural disaster storms, power supply failures, etc.
- Labor work rules
- Material supply costs and material availability
- Equipment fuel cost and fuel availability

- Education level and training of personnel
- Sophistication of equipment and maintenance methods
- Traffic levels and methods of traffic control

The range of situations and scenarios that may be tested in the expert system/simulation method can include:

- Changes in safety regulated work rules
- Changes in union contract work rules
- Changes in equipment fleet purchase or lease or selling policies
- Changes in equipment fleet fuel type
- Changes in vacation or sick leave rules
- Changes in retirement or recruitment policies
- Changes in scheduling of overtime for snow/ice removal, for hurricane response, for major flood response and similar repetitive large area special maintenance impact situations
- Testing plans for maintenance response to tornado cleanup, earthquake repair, train derailment repair, air crash cleanup, hazardous material spill containment and cleanup and similar special event of a catastrophic nature in a limited area that requires a special maintenance response
- Changes in general budget allocations to maintenance
- Changes in dedicated fund allocations to maintenance
- Changes in safety requirements for traffic control

PROJECT A-6. AUTOMATED INTERACTIVE FIELD SCHEDULING AND REPORTING

Highway maintenance is a very labor-intensive activity. As highway agencies reduce their labor forces there are fewer personnel to handle a growing workload. With fewer personnel, allocation and assignment practices become more critical. This points to the need for increasing the first-line supervisor's capacity to organize, allocate and control the resources he has at his disposal.

Automated interactive graphic computer software systems can be developed that will permit first-line maintenance supervisors to enter and extract management data and information in real time that is useful in managing maintenance resources. The objective would be to provide first-line supervisors with the automated, interactive and user-friendly capabilities to:

- record maintenance element conditions and maintenance work needs,
- optimize scheduling of available resources to priority work activities, and
- record work performance, resource utilization and costs, by activity, route location, management unit.

APPENDIX B
BIBLIOGRAPHY

AASHTO Select Committee on Research, "Strategic Transportation Research Study Technical Design." Report to the AASHTO Executive Committee (May 7, 1984).

American Public Works Association, "Street and Highway Maintenance Manual." American Public Works Association (1985).

American Public Works Association, "The Hole Story: Facts and Fallacies of Potholes." Chicago, Illinois (1983).

"An Investigation of Asphalt Cement Subsealing and Lime-Cement Jacking." State of New York Dept. of Public Works, Physical Research Report RR 65-2 (May 1965).

"Ants and agency choose silicone over neoprene." Engineering News Record (April 18, 1985).

Beason, W.L. and Ross, H.E., "A Truck-Mounted Portable Maintenance Barrier." Transportation Research Record 1024 (1985).

Beason, W.L. and Ivey, D.L., "Structural Performance Levels for Portable Concrete Barriers." Transportation Research Record 1024 (1985).

Bellock, E., "Sealcoating and Surface Treatment for Pothole Prevention." Public Works (April 1985).

Blais, E.J., "Value Engineering Study of Crack and Joint Sealing." FHWA-TS-84-221 (December 1984).

Bronstad, M.E., Michie, J.D. and Mayer, J.B., Jr., "Minicar Crash Test Evaluation of Longitudinal Traffic Barriers." Transportation Research Record 1024 (1985).

Bryer, T.E., "Risk Management Analysis: Highway Maintenance Operations." Transportation Research Record 979 (1984).

Bukowski, M.E., Tucker, R.L. and Fowler, D.W., "Detection of Voids Underneath Concrete Pavements Using Infrared Thermography." Center for Transportation Research, University of Texas at Austin (1983).

Burke, J.E., "Administration of Research, Development, and Implementation Activities in Highway Agencies." NCHRP Synthesis of Highway Practice 113 (December 1984).

Butler, B.C., Carmichael, R.F. and Flanagan, P.R., "Impact of Pavement Maintenance on Damage Rate: Volume 1." Final Report (September 1985).

Byrd, Tallamy, MacDonald and Lewis, "Techniques for Reducing Roadway Occupancy During Routine Maintenance Activities." NCHRP Report 161 (1975).

Byrd, Tallamy, MacDonald and Lewis, "Traffic Control for Street and Highway Construction and Maintenance Operations: Participant Notebook." Falls Church, Virginia (2nd Ld. 1977).

Cable, J.K., "Iowa Pavement Performance." Paper Prepared for Civil Engineering 391 at the University of Texas at Austin (July 1985).

Carney, J.F. III, Dougan, C.E. and Hargrave, M.W., "The Connecticut Impact-Attenuation System." Transportation Research Record 1024 (1985).

Casner, D., Anderson, D. and Thomas, H.R., "Evaluation of Equipment Used for Localized Repair of Pavements." Transportation Research Record 985 (1984).

Choate, P., "Bad Roads: The Hidden Costs of Neglect." National Asphalt Pavement Association (1983).

Chong, G.J., Phang, W.A. and Jewer, F.W., "Choosing Cost-Effective Maintenance." Ministry of Transportation and Communication (January 1981).

Cold Regions Research and Engineering Laboratory, "Pothole Primer: A Public Administrator's Guide to Understanding and Managing the Pothole Problem." Special Report 81-21 (September 1981).

"Concrete mix adds strength." Engineering News Record (November 20, 1980).

Cooper, F.F., "Utilization of Interactive Graphics for Quality Assurance and Pavement Management." Session No. 168, 1985 Annual Meeting of Transportation Research Board, Washington, D.C. (January 14-17, 1985).

"Corrosion Detection." New Scientist, Vol 105, No. 1437 (January 3, 1985) p. 24.

Creech, M.F., "Partial-Depth Precast Concrete Patching." Virginia Highway and Transportation Research Council (December 1974).

Darter, M.I., "Patching of Continuously Reinforced Concrete Pavements." Paper Prepared for Presentation at the Annual Meeting of Transportation Research Board (January 1981).

Darter, M.I., Barenberg, E.J. and Yrjanson, W.A., "Joint Repair Methods for Portland Cement Concrete Pavements: Final Report." Research Report, Design and Construction Guidelines and Guide Specifications, Research Report 1-21 (February 1985).

Darter, M.I., "CRCP Rehabilitation Needs and Methods." Proceedings of the Continuously Reinforced Concrete Pavement Workshop.

Delannoy, H., et.al., "Routine Maintenance of Highways in Member Counties of PIARC." Transportation Research Record 864 (1982).

Del Val Inc, "Concrete Pavement Jacking of Airports and Highways." (1980).

Del Val, "Grouting, A Handbook of Applications." (1978).

Dudek, C.L., Richards, S.H. and Buffington, J.L., "Improvements and New Concepts for Traffic Control in Work Zones: Vol. 1, Four-Lane Divided Highways." FHWA/RD-85/034 (January 1985).

Eaton, R.A., Wright, E.A. and Mongeon, W.E., "The Engineer's Pothole Repair Guide." Cold Regions Technical Digest No. 84-1 (March 1984).

"Effects of Preventive Maintenance on Pavement Serviceability." Research Project 161-1 Engineering Research and Development Bureau (1980).

Eighmey, L., "Surface Recycling Enhances Preventive Maintenance." Roads and Bridges (March 1985).

"Evaluation of a Ground Probing Radar Device for Detecting Voids Within and Beneath Concrete." State of California Department of Transportation (April 1985).

"Evaluation of Several Maintenance Methods for Continuously Reinforced Concrete Pavements." Joint Highway Research Project (1980).

Faulkner, M.J.S. and Dudek, C.L., "Flashing Arrowboards in Advance of Freeway Work Zones." Transportation Research Record 864 (1980).

Faulkner M.J.S. and Dudek, C.L., "Field Evaluation of Moving Maintenance Operations on Texas Urban Freeways." Transportation Research Record 864 (1982).

Federal Highway Administration, "Highway Statistics 1976-1983." Washington, D.C. (1976-1983).

Federal Highway Administration, "Highway Statistics Summary to 1975." Report No. FHWA-HP-HS-S75 (1975).

Federal Highway Administration, "Our Nation's Highways: Selected Facts and Figures." Washington, D.C. (1983).

Federal Highway Administration, "Repair and Rehabilitation of P.C.C. Concrete Pavements." (June 1983).

Federal Highway Administration, "Synthesis of Safety Research Related to Traffic Control and Roadway Elements Vol. 2." FHWA-TS-820-233 (December 1982).

Federal Highway Administration, "Transverse Cracking of Asphalt Pavements." Report No. FHWA-TS-82-205, Final Report (July 1982).

Fernau, E.A., "Subsealing Specifications." New York Dept. of Transportation (November 1984).

Fontana, J.J. and Bartholomew, J., "Polymer Concrete Patching Manual." FHWA-IP-82-10 (June 1982).

Garza, I.F. and Sylvia, M., "Improvements and New Concepts for Traffic Control in Work Zones: Vol. 2 - Implementation of Controls." FHWA/RD-85/035 (January 1985).

Graham, J.L. and Hardwood, D.W., "Effectiveness of Clear Recovery Zones." National Cooperative Highway Research Program Report 247.

Graham, J.L. and Migletz, J., "Collection of Work-Zone Accident Data (Abridgement)." Ref. pg. 15, Transportation Research Record No. 933 (1983).

Hartvigas, L., "Patching Flexible and Rigid Pavements." FHWA/NY/KR-79/74 (October 1979).

Hathaway, C.W., "Technology Transfer Program for Local Transportation Agencies: An Evaluation Report." (June 1985).

Her, I., Henry, J.J. and Wambold, J.C., "Development of a Data Acquisition Method for Noncontact Pavement Macrotexture Measurement." Transportation Research Record 100 (1984).

Hicks, R.G., Rosenbaum, D. and Covault, D.O., "Field Maintenance Manual for Georgia Counties, Local Roads and Streets." FHWA-TS-79-218 (August 1979).

Highway Research Board, "Pavement Performance: Methods for Evaluation." HRB Bulletin 187 (1958).

Highway Research Board, "Standard Nomenclature and Definitions for Pavement Components and Deficiencies." HRB Special Report 113 (1970).

Highway Research Board, "Traffic Control for Freeway Maintenance." NCHRP Synthesis of Highway Practice 1 (1969).

Highway Users Federation and Automotive Safety Foundation, "Highway Fact Book." Washington, D.C. (1985).

Huchingson, R.D., Dudek, C.L. and Woods, D., "Improvements and New Concepts for Traffic Control in Work Zones: Vol. III Pavement Marking Patterns." FHWA/RD-85/036 (January 1985).

Huddleston, N.D, Richards, S.H. and Dudek C.L., "Driver Understanding of Work-Zone Flagger Signals." Transportation Research Record 869 (1982).

Indahl, G., Quinn, J.J. and Afferton, K.C., "Pavement Patching Techniques and Materials." Report No. 75-010-7742 (May 1975).

Indahl. G., Quinn, J.J. and Afferton, K.C., "Pavement Patching Techniques and Materials." New Jersey Department of Transportation (June 1975).

(Indiana D.O.H. Specs) Specification for Undersealing Portland Cement Concrete Pavement With Asphalt, Indiana Department of Transportation.

International Road Federation, "A Policy for Road Maintenance." Washington, D.C. (1985).

Kelley, J.F., "Formulating and Justifying Highway Maintenance Budgets." NCHRP Synthesis of Highway Practice 80 (October 1981).

Kukacka, L.E. and Fontana, J., "Polymer Concrete Patching Materials: Volume II, Final Report." Implementation Package 77-11 Vol. I and II (April 1977).

Kukacka, L.E. and Fontana, J., "Polymer Concrete Patching Materials: Vol. 1 Users Manual." Implementation Package 77-11 Vol. I (April 1977).

Kulkarni, R.B. et.al., "A Systematic Procedure for the Development of Maintenance Levels of Service." Transportation Research Record 781 (1980).

Kulkarni, R. et.al., "Maintenance Levels of Service Guidelines." NCHRP Report 223 (June 1980).

Lewis, R.M., "Performance Criteria for Channelizing Devices Used for Two-Lane, Two-Way Operations: Final Report." FHWA/RD-83/057 (August 1983).

Lewis, R.M., "Review of Channelizing Devices for Two-Lane, Two-Way Operations: Interim Report." FHWA/RD-83/056 (June 1983).

Ltr., Mudjacking Information from R.H. Heedum of State of Nebraska (December 1984).

Mahone, D.C. and Lisle, F.N., "Identifying Maintenance Needs." Transportation Research Record 781 (1980).

Majidzadeh, K. and Luther, M.S., "Pavement Patching Guidelines." FHWA-TS-82-221 (February 1983).

Manning, D.G. and Holt, F.B., "Detecting Deterioration in Asphalt Covered Bridge Decks." ME-82-03, The Research and Development Branch/Ontario Ministry of Transportation and Communications (September 1982).

Markow, M.J., "Incorporating Quality Standards and Impacts Within Highway Maintenance Management." Transportation Research Record 781 (1980).

Maxcy, D.J., Darter, M.I. and Smiley, S.A., "Evaluation of Patching in Continuously Reinforced Concrete Pavements." Transportation Research Record No. 727 (1979).

McKeel, W.T., "Evaluation of Epoxy Compounds As A Material for Patching and Protecting Concrete." Virginia Highway Research Council (March 1971).

"Millings, seal used instead of overlay." Roads and Bridges (March, 1985).

Muncaster, J.W., "Asphalt Underseal State of the Art." Trumbull Asphalt (July 26, 1985).

National Safety Council, "Accident Facts." Chicago, Illinois (1984).

Niessner, C.W., "Optitimizing Maintenance Activities: Fifth Report: Bituminous Patching." Report No. FHA-TS-78-220 (May 1978).

North American Pavement Management Conference, Toronto, Ontario, Canada. Proceedings: Volume 3 (March 18-21, 1985).

Organization for Economic Condition and Development, "Hazardous Road Locations: Identification and Counter Measures." OECD Road Research (September 1976).

Organization for Economic Operation and Development, "Maintenance Techniques for Road Surfacings: Assessment, Choice of Treatment, Planning, Implementation." OECD Road Research (October 1978).

Pavement Deflection Improvement Due to Asphalt Undersealing in 1983, Indiana Dept. of Highways (1983).

"Pavement Undersealing Principles and Techniques." Chem Grout Inc., (1985).

Perkins, D.D. and Bowman, B.L., "Effectiveness Evaluation by Using Non Accident Measures of Effectiveness (Abridgement)." Transportation Research Record No. 905 (1983).

Peterson, D.E., "Evaluation of Pavement Maintenance Strategies." NCHRP Synthesis of Highway Practice 77 (September 1981).

Pigman, J.G., Agent, K.R., and Creasey, "Analysis of Accidents Involving Crash Cushions." Transportation Research Record 1024 (1985).

Poister, T.H. and Moyer, W.R.," The Pennsylvania DOT Trained Observer Survey: Design and Preliminary Results." Transportation Research Record 781 (1980).

"Pothole Prevention Possible With Road Diagnostic Device." Roads and Bridges (March 1985).

"Potholes losing ground nationwide." ENR (March 28, 1985).

Powell, W.D., et.al., "The Structural Design of Bituminous Roads." TRRC Laboratory Report 1132 (1984).

Pruett, J.M. and Lan, K.K., "Working With a Highway Maintenance Simulation Model Using An Interactive Input Module." Transportation Research Record 781 (1980).

Pruett, J.M. and Ozerdem, E., "Systematic Development of a Highway Maintenance Simulation Model." Transportation Research Record No. 727 (1979).

Public Technology, Inc., "Street Patching Operations, Field Test Evaluation Program, Sylvax Upon Improved Street Patch Material." NSF/RA-770582 (1977).

Quinn, W.J. and Boecroft, G., "The Evaluation of Pavement Patching Materials in Oregon." Oregon Department of Transportation (November 1980).

Rauhut, J.B., et.al., "Data Collection Guide for Long-Term Pavement Monitoring." Federal Highway Administration (May 25, 1984).

Ray, G.L., "Louisiana's Equipment Replacement Dilemma." Transportation Research Record 864 (1982).

Richards, S.H. and Dudek, C.L., "Sight-Distance Requirements at Lane-Closure Work Zones on Urban Freeways." Transportation Research Record 864 (1982).

Rutherford, N.F., "Pavement and Shoulder Maintenance Performance Guides." FHWA-TS-84-208, Final Report (August 1984).

Salt, G.F., "Recent Full-Scale Flexible Pavement Design Experiments in Britain." 2nd Int. Conf. on Structural Design of Asphalt Pavements, Proceedings (1967).

Schoon, J.G., "Highway Quality and Maintenance: Concepts and Qualification." Transportation Research Record No. 927 (1979).

Sharaf, E.A. and Sinha, K.C., "Analysis of Pavement Routine Maintenance Activities in Indiana." Transportation Research Record 985 (1984).

Shober, S. and Johnson, K., "Experimental Rehabilitation of Jointed Portland Cement Concrete Pavement." FHWA/WI-83/2 (February 1983).

"Sign Maintenance Pays Off in Norway." World Highways, Vol XXXVI, No. 2 (February 1985).

"Slabjacking Concrete Pavements." Portland Cement Association (1967).

Slifer, J.C.; Peter, M. and Burns, W.E., "Illinois Investigates Undersealing." Public Works (July 1985).

"Special Provision, Modification of the Standard Specifications." Section 450 Pressure Grouting Portland Cement Concrete Pavement, Department of Transportation, State of Georgia (1983).

State Department of Highways and Public Transportation, "Part VI - Traffic Controls for Street and Highway Construction and Maintenance Operations." Texas Manual on Uniform Traffic Devices, Manual No. 802406 (1980).

The Texas Engineering Extension Service, Texas A&M University. "Preventive Maintenance of Traffic Control Devices: Signs, Signals and Markings." (September 1982).

Thomas, H.R., Zahuroddin S. and Anderson, D.A., "Cost-Effective Use of Manpower for Manual Pothole Repair." Transportation Research Record 985 (1984).

Thomas, L. W., "Legal Implications of Regulations Aimed at Reducing Wet-Weather Skidding Accidents on Highways." Research Results Digest, Digest 95 (August 1977).

Thomas, L.W., "Legal Implications of Highway Departments Failure to Comply with Design, Safety, or Maintenance Guidelines." NCHRP Research Results Digest, Digest 129 (October 1981).

Thomas, L.W., "Liability of State and Local Governments for Snow and Ice Control." NCHRP Research Results Digest, Digest 83 (February 1976).

Thomas, L.W., "Liability of State Highway Departments for Design, Construction, and Maintenance Defects." NCHRP Research Results Digest, Digest 80 (September 1975).

Thomas, L.W., "Liability of State and Local Governments for Negligence Arising Out of the Installation and Maintenance of Warning Signs, Traffic Lights, and Pavement Markings." NCHRP Research Results Digest, Digest 110 (April 1979).

Thompson P.D., Croney, D. and Currer, E.W.H., "The Alconbury Hill Experiment and Its Relation to Flexible Pavement Design." 3rd Int. Conf. on the Structural Design of Asphalt Pavements, London, Proceedings Vol. I (1972).

Thornton, J.B., and Gulden, W., "Pavement Restoration Measures to Precede Joint Resealing." Transportation Research Board, TRR 752 (1980).

Thurgood, G.S. "Proceedings: Workshop in Pavement Rehabilitation." FHWA-TS-84-224 (September 17-20, 1984).

Torres, F. and B.F. McCullough, "Void Detection and Grouting Process." Center for Transportation Research, University of Texas, Research Report 249-3 (May 1982).

"Transition Plan for Strategic Highway Research Program on Long-Term Pavement Performance." Development at the February 6-8, 1985, Technical Advisory Panel Meeting.

Transport and Road Research Laboratory, "Working Party on Highways Maintenance Research: Working Group on Performance of Maintenance Treatments: Proposals for Further Work on the Performance of Maintenance Treatments." PT5 (July 1985).

Transportation Research Board, "America's Highways: Accelerating the Search for Innovation." Special Report 202 (1984).

Transportation Research Board, "Consequences of Differed Maintenance." NCHRP Synthesis of Highway Practice 58 (May 1979).

Transportation Research Board. "Detecting Defects and Deterioration in Highway Structures." NCHRP Project 20-5, Topic 1503 (January 1985).

Transportation Research Board, "Highway Maintenance Research Needs - 1980: Final Report." FHWA/RD-81/502 (September 1981).

Transportation Research Board, "Highway Maintenance Research Needs: Final Report." FHWA-RD-75-511 (March 1975).

Transportation Research Board, "Management and Selection Systems for Highway Maintenance Equipment." NCHRP Synthesis of Highway Practice 52 (1978).

Transportation Research Board, "Practical Guidelines for Minimizing Tort Liability." NCHRP Synthesis of Highway Practice 106 (December 1983).

"Undersealing Pavement Cuts Noise, Vibration." Roads and Bridges (March 1985).

Vance, J.C., "Liability of the State for Injury-Producing Defects in Highway Surface." NCHRP Research Results Digest, Digest 135 (July 1982).

Vance, John C., "Personal Liability of State Highway Department Offices and Employees." NCHRP Research Results Digest, Digest 79 (September 1975).

Vyce, J.M., "Bituminous Resurfacings on Flexible Pavements." Research Report 31 (August 1975).

Vyce, J.M., "Flexible Pavement Performance in New York State." Research Report 5 (March 1972).

Weller, D.E., "Proposed Warning Levels for the Structural Maintenance of Flexible Roads." TRRL Supplementary Report 550 (1981).

Wright, P.H., Hall, J.W. and Zader, P.L., "Low-Cost Counter Measures for Ameliorating Run-Off-The-Road Crashes." Ref. pg. 1-6. Transportation Research Record No. 926 (1983).

Yoder, E.J., Florence, R.H. Jr. and Virkler, S.J., "Evaluation of Several Maintenance Methods for Continuously Reinforced Concrete Pavements." Joint Highway Research Project, Purdue University (1981).

Yoder, S.R., "Rehabilitation by Undersealing." Proceedings of the Continuously Reinforced Concrete Pavement Workshop (1978).

Zimmer, R.A. and Ivey, D.L., "Holes in the Pavement - An Assessment of Their Influence on Safety." Transportation Research Record 1000 (1984).

Zimmer, A. and Ivey, D.L. "Pavement Edges and Vehicle Stability - A Basis for Maintenance Guidelines." A Technical Paper for Presentation at 61st Annual Meeting of TRB (January 1983).

Zimmer, R.A. and Ivey, D.L., "Pavement Edges and Vehicle Stability A Basis for Maintenance Guidelines." Research Report No. 328-1 (September 1982).

TECHNICAL RESEARCH AREA 4
DETAILED PLANNING FOR RESEARCH ON BRIDGE COMPONENT PROTECTION

Prepared for:
NCHRP Project Number 20-20(6)
Pre-Implementation Activities for the
Strategic Highway Research Program (SHRP)

January 1986

Prepared by:
David G Manning
Georgetown
Ontario, Canada

TABLE OF CONTENTS

		Page
	LIST OF FIGURES	TRA 4-ii
	LIST OF TABLES.	TRA 4-iii
	ABSTRACT.	TRA 4-iv
	ACKNOWLEDGEMENTS.	TRA 4-v
SECTION 1	STATEMENT OF THE PROBLEM.	TRA 4-1
SECTION 2	GOALS AND OBJECTIVES OF THE PLAN.	TRA 4-3
SECTION 3	FORMULATION OF THE PLAN	TRA 4-5
SECTION 4	TRA 4 RECOMMENDED RESEARCH PLAN	TRA 4-8
SECTION 5	RESULTS TO BE ACHIEVED.	TRA 4-42
SECTION 6	IMPLEMENTATION OF RESULTS	TRA 4-45
SECTION 7	SCHEDULE OF PROJECTS, TASKS AND SUB-TASKS	TRA 4-47
SECTION 8	BUDGET.	TRA 4-56
APPENDIX A	RELATED RESEARCH NOT FUNDED	TRA 4-A-1
	BIBLIOGRAPHY.	TRA 4-B-1

LIST OF FIGURES

		Page
FIGURE 1	RESEARCH PROJECTS FOR TRA 4, BRIDGE COMPONENT PROTECTION.	TRA 4-48
FIGURE 2	PROJECT AND TASK START YEAR AND ELAPSED TIME FOR PROJECTS 4-1 AND 4-2.	TRA 4-49
FIGURE 3	PROJECT AND TASK START YEAR AND ELAPSED TIME FOR PROJECTS 4-3 AND 4-4.	TRA 4-50
FIGURE 4	PROJECT 4-1, INSPECTION AND ASSESSMENT OF THE PHYSICAL CONDITION OF CONCRETE STRUCTURES.	TRA 4-51
FIGURE 5	TASK 4-2.1, ELECTROCHEMICAL REMOVAL AND PROTECTION. . .	TRA 4-52
FIGURE 6	TASK 4-2.2, CATHODIC PROTECTION	TRA 4-53
FIGURE 7	PROJECT 4-3, PROTECTION AND REHABILITATION BY OTHER THAN ELECTROCHEMICAL METHODS.	TRA 4-54
FIGURE 8	PROJECT 4-4, METHODOLOGY FOR PROTECTION AND REHABILITATION OF CONCRETE BRIDGE COMPONENTS.	TRA 4-55

LIST OF TABLES

		Page
TABLE 1	TRA 4 - BUDGET, PROJECTS 4-1 AND 4-2	TRA 4-57
TABLE 2	TRA 4 - BUDGET, PROJECTS 4-3 AND 4-4	TRA 4-58
TABLE 3	TRA 4 - STAFFING AND FACILITIES, PROJECTS 4-1 AND 4-2. .	TRA 4-59
TABLE 4	TRA 4 - STAFFING AND FACILITIES, PROJECTS 4-3 AND 4-4. .	TRA 4-60

ABSTRACT

This report documents the detailed planning activities for research on bridge component protection. The study, which was identified as Technical Research Area (TRA) 4, was carried out as part of the pre-implementation activities for the Strategic Highway Research Program (SHRP).

The report presents the recommended plan for $10 million of research studies. It describes the goals and objectives of the plan and the concepts used in its development. The recommended research plan comprises four projects which address the needs of protecting existing reinforced and prestressed concrete components against corrosion and of rehabilitating corrosion-induced distress.

Project 4-1 will develop reliable methods of inspecting the physical condition and assessing the service life of concrete bridge components. Project 4-2 will develop electrochemical methods of protection and rehabilitation and Project 4-3 will develop non-electrochemical solutions. Project 4-4 will develop the methodology to identify the protection strategy which will result in the lowest anticipated life-cycle costs for a specific bridge. This will result in the optimum utilization of the products of the other three projects A schedule, budget, the requirements for staffing and facilities, and a task-by-task description for each project are presented.

ACKNOWLEDGEMENTS

The research reported herein was performed under NCHRP Project 20-20(6). David G. Manning was the contractor for this study and also the principal investigator.

The other members of the contract team, and the co-authors of this report, were: Charles J. Arnold, DeWitt, Michigan; Kenneth C. Clear, President, Kenneth C. Clear Inc., Sterling, Virginia; and Roger A. Dorton, Willowdale, Ontario.

SECTION 1
STATEMENT OF THE PROBLEM

Few problems in the operation of the nation's highway system aggravate the driver more than the poor ride quality of deteriorated bridge decks and the delays and detours which inevitably occur when repairs are made. The principal cause of the rapid and premature deterioration of bridge decks is the use of salt in winter maintenance operations. The salt penetrates the concrete and causes corrosion of the embedded reinforcement. Once initiated, corrosion is extremely difficult to arrest. As the steel corrodes, it expands and develops stresses which eventually induce spalling of the concrete and result in the potholes familiar to the road user.

It is not only bridge decks which have experienced the ravages of corrosion-induced distress. In those parts of the country where de-icing chemicals are used, chloride ions have penetrated beams, piers, and abutments which are exposed to surface run-off or spray from passing vehicles. Many concrete components in bridges located in a marine environment have also been penetrated by chloride ions and are exhibiting serious corrosion problems. This is especially true of components in the splash zone. Although the deterioration of these components is less obvious to the road user than the deterioration of bridge decks, it is, in many ways, much more serious. Not only is the deterioration much more difficult and expensive to repair, but the safety of the structure is more likely to be affected.

Bridges built during the post World War II period have deteriorated rapidly. Thousands of concrete components were constructed without positive protection against corrosion. Most were designed to have a concrete cover over the reinforcement (typically 1-1/2 inches) which has subsequently been found to be inadequate. Even the specified cover was often not achieved because of imperfections during construction. As a result, the bridge building boom of the 1950's and 1960's has generated the repair and replacement crises of the 1980's.

The precise costs of corrosion damage to reinforced and prestressed concrete components are not known. However, it is possible to develop a reasonable estimate. Of the more than 500,000 bridges in the United States, 253,196 were classified as deficient at the end of 1982. It was estimated that $48.9 billion in current dollars will be required to repair or replace them. It has been further estimated that about 3500 bridges become deficient each year. The federal definition of "deficient" includes both structurally deficient and functionally obsolete bridges. The 1982 status report shows that deficient bridges are almost equally divided between these two categories. While corrosion of reinforcement is not the cause of all structural deficiencies (the figures also include steel bridges), it is a substantial contributor. Offsetting these reductions is the fact that there

are many concrete bridges which are exhibiting corrosion problems but would not be rated as deficient. Consequently, a figure of $24 billion represents a reasonable upper-bound estimate of the costs of correcting corrosion-induced distress. A lower bound figure can be derived from the estimated figure of $16.1 billion plus $400 million per year for bridge deck restoration needs (not including beams, piers and abutments) since corrosion-induced deterioration is the biggest contributor to bridge deck deterioration. The figures indicate that the unfunded liability to correct corrosion-induced distress in bridges is approximately $20 billion and the figure is increasing at almost $500 million annually. The repair or replacement of deficient bridges will demand greater expenditures over the next decade than any single requirement of the highway system. The costs are truly staggering and potential pay-off from an extension of service life of concrete components in a corrosive service environment resulting from the $10 million for research in the SHRP is extremely high.

Although the subject of bridge protection includes consideration of both new and existing bridges, the bridges being built today have considerably better corrosion protection than those built as recently as ten years ago. Research has resulted in epoxy coated reinforcement, specialized concretes, improved membranes and sealants, together with identification of the need for quality concrete, increased concrete cover and improved quality assurance practices. While further research would result in further incremental improvements, the greater challenge is to identify methods of corrosion protection for bridges already in service before they deteriorate to the extent that they must be replaced. Further, products of research in other technical research areas can be expected to improve the performance of new bridges. Specifically, the development of low-permeability concretes and improved quality assurance practices in Technical Research Area 5 will have application to concrete in bridges. Technical Research Area 1 may provide more durable and effective seal coats and bituminous surfacings for bridges. Any reductions in salt usage arising from developments in Technical Research Area 6 will also benefit new bridges but will not remove the chlorides already in place. As Special Report 202 notes succinctly:

> "The key problem is to develop economically feasible methods of saving thousands of bridge decks built before the use of present day protective systems."

> "Most existing concrete bridge decks and pier caps are contaminated with chlorides. Those that are currently sound are facing inevitable premature deterioration unless the corrosive process already underway can be halted or reversed."

In recent years, research has made important strides in developing protective treatments for existing, chloride contaminated decks. However, other components have received little attention and the technology for repair is in its infancy. Much more work needs to be done, and needs to be done quickly if existing concrete components are to be protected before the deterioration progresses to the stage where replacement is necessary.

Consequently, for the reasons of need, urgency, and potential pay-off, a research plan has been developed for Technical Research Area (TRA) 4 which addresses the needs of protecting existing reinforced and prestressed concrete components against corrosion.

SECTION 2
GOALS AND OBJECTIVES OF THE PLAN

The overall objectives of TRA 4 are to provide methods to protect chloride-contaminated concrete components against deterioration and to rehabilitate and protect those components which are already exhibiting corrosion-induced distress.

The key question which must be answered by bridge owners is how and when to protect existing bridges against corrosion to minimize life-cycle costs. Consequently, the final goal will be the development of a decision model which is applicable at the project level and will lead to the most appropriate protective treatment for any structure under an agency's jurisdiction. In order to be useful to all agencies, the decision model must be simple and able to be modified to accommodate individual agency practices and conditions. The use of such a model is predicated on the availability of reliable methods of determining the condition of bridge structures and a range of options which are effective in protecting any specific bridge. The use of the model then determines, on the basis of the existing condition and the service life of each potential treatment, the predicted future condition of the bridge for each of the options. This, in turn, permits the selection of the option which leads to minimum life cycle costs. Consequently, reliable methods of inspection and assessment and an arsenal of options for protection need to be developed within TRA 4 and these become significant objectives.

There are a number of methods which can be used in the inspection and assessment of the physical condition of existing structures but there are also serious limitations in terms of speed, reliability and the significance of results of many of the existing test procedures. The greatest single need is the development of a field procedure which will measure the rate of corrosion (as opposed to the presence or absence of corrosion measured by the standard half cell test) of embedded reinforcement under field conditions. This test method is essential for assessing the service life of existing field installations as well as evaluating the performance of new protection procedures to be developed within TRA 4.

Other, specific deficiencies with existing test methods can be identified and will be addressed by TRA 4. These include determining the effectiveness of membranes and sealers, the permeability of concrete, the presence of delaminated concrete in beams and substructure components and the condition of concrete deck slabs which have a bituminous surfacing. The objective of TRA 4 is to address these needs, and develop the most promising solutions into field-proven test procedures.

The objective in developing methods of protection and rehabilitation is to produce a range of options which can be implemented by user agencies.

The immediacy of the task is emphasized by the passing of the 1982 Federal-Aid Highway Act which included a major increase in funding for bridge repairs and replacements. A range of options is essential because the type, condition and location of structures is so varied that protective methods which are applicable in one location may be inappropriate in another location. For example, some methods which are presently used on bridge decks such as concrete overlays and waterproofing membranes are not directly applicable to concrete beams, piers and abutments. Some sophisticated techniques which require specialized equipment and contractor expertise may be well suited to locations where the volume of work can support contractor investment and promote competitive bidding but would be prohibitively expensive in remote locations. In high volume traffic locations, user delays may dictate that construction times be kept to a minimum and this would exclude consideration of some options which could be used if the time available were not critical. Similarly, if work must be done when low temperatures are a factor, some options may be excluded. Some jurisdictions have found bituminous surfacings on bridge decks to be unsatisfactory while others have found them to give excellent performance in combination with membranes. For all these reasons, it is essential that a range of options be available so that bridge owners can determine which is the most economically and technically feasible approach for a specific structure.

Although the objectives are essentially the same, differences in technology mean that the options can be conveniently divided into those which involve electrochemical techniques and those which do not. At the present time, a field procedure which can be used to remove chloride ions from contaminated concrete members does not exist. Limited experimental work has shown electrochemical removal to be a promising technique and the objective is to develop cost-effective methods of removing chlorides from salt-contaminated components and protecting them against future corrosion. Unless all the chloride-contaminated concrete is removed, cathodic protection is the only method (with the possible exception of deep polymer impregnation) which is known to stop corrosion but bridge owners have been slow to adopt a technology which is alien to highway personnel. Furthermore, cathodic protection methods developed in other fields (mainly pipelines, buried tanks and chemical plants) cannot be applied directly to above-ground reinforced concrete structures and a number of significant technical questions remain to be answered. These questions focus on the life of system components and establishing protection criteria. It is the objective of TRA 4 to develop cost-effective cathodic protection systems for concrete bridge components and produce a manual which will contain specifications and procedures. Such an approach is expected to result in more widespread acceptance of cathodic protection, more reliable, longer life systems and reduced costs.

The problems associated with the more conventional approaches to protection and rehabilitation are those of high cost (largely because of the cost of concrete removal), unknown service life because of the inability to stop corrosion, long construction times and the fact that there are few options for components other than bridge decks. TRA 4 has the objectives of resolving these problems by identifying less costly and more effective methods of concrete removal, and developing options which are applicable to decks, beams, substructure elements and prestressed components.

Successful completion of the goals and objectives of TRA 4 will produce the results and benefits described in Section 5.

SECTION 3
FORMULATION OF THE PLAN

The research plan contained in Section 4 was developed primarily from the policy, objectives and discussion contained in Chapter 7 of Special Report 202 "America's Highways, Accelerating the Search for Innovation". The AASHTO Select Committee on Research Report "Strategic Transportation Research Study Technical Design" to the AASHTO Executive Committee, dated May 7, 1984 was also used as a resource document on technical matters.

Using the above two reports as basic source material, the research plan was formulated through an iterative process of input, review and modification. The input was from six major sources:

- Literature research
- Expert knowledge of the contract agency staff
- Contact with experts in the United States and abroad
- Expert knowledge of the Advisory Committee
- Expert knowledge of the invited guests at the National Workshop
- Expert knowledge of the Task Force, SHRP staff and the principal investigators for the other TRA's and the Overview and Integration Planning Study

Numerous publications relevant to the subject of bridge protection were reviewed to define the state-of-the-art and identify promising areas of research as well as those already known not to be rewarding.

The contract agency team consisted of four individuals each having different but complementary backgrounds and areas of expertise. Each member had been involved in bridge protection research for more than ten years. All members of the contract team were active in technical committees of both North American and European organizations which facilitated the identification of research in progress and communication with other researchers. During the development of the research plan, personal visits were made to agencies having related research programs in the United States and Europe. In addition, discussions were held with professional peers at conferences and by telephone.

The Advisory Committee on Bridge Protection appointed by NCHRP Project Panel SP 20-20 consisted of twenty-eight persons representing federal, state and local agencies, industry, consultants and universities. During the development of the research plan the Advisory Committee met on four

occasions: in Washington in May, Toronto in July, in conjunction with the National Workshop in Dallas in September and in Chicago in December, 1985. On each occasion, the research plan was subjected to a detailed review and valuable input provided to the contractor. The diverse membership and broad perspective of the Advisory Committee ensured that the research plan will meet the needs of the user agencies and, at the same time, contains a measured balance between tasks which are reasonably pragmatic and higher risk endeavors which have the potential for a larger pay-off.

The input from the Advisory Committee was supplemented by the suggestions from the guests invited to participate in the National Workshop. The guests, who also had a wide range of experience and varied backgrounds, were able to review and comment on the draft research plan at a time when a framework had been established but there was still the opportunity to make changes. Their advice proved to be very useful.

The Task Force, SHRP staff and the Overview and Integration contractor were especially helpful in defining the scope of the activities which could appropriately be included in the program. In addition, the concepts of the plan were endorsed by the Task Force at its meeting in Charleston in November. Finally, the principal investigators for the other TRA's provided input and assisted in defining interactions with other research areas to ensure that TRA 4 can be integrated into the final program without gaps or duplication.

The Advisory Committee supported the contractor's position that in order to ensure the achievements envisaged by Special Report 202, the scope of TRA 4 had to be limited to the above-grade and above-the-waterline reinforced and prestressed concrete components of existing highway bridges. This decision was taken for the following reasons:

- Well funded, highly focused research is needed to develop methods of protecting existing structures before they deteriorate to the extent that replacement is necessary.
- A number of options are available for providing corrosion protection in new bridges; such is not the case for most existing components.
- Developments applicable to existing structures are likely to have application to new construction but not vice versa.
- The product of other technical research areas such as Asphalt, Cement and Concrete and Snow and Ice Control will benefit new structures but will have little impact on existing structures.
- The budget of $10 million for TRA 4 is insufficient to tackle the problems of both new and existing bridges and, since the needs of existing, chloride contaminated bridges are greater, the existing bridges must be given a higher priority.
- Below-grade and below-the-waterline components are less susceptible to corrosion damage, and therefore the potential pay-off is less than for components which are above grade and above the waterline.

The scope of TRA 4 means that there are major areas of bridge research which are not being addressed in this program. These include the corrosion protection of concrete components in new bridges, for the reasons given above. Research on steel bridges and on the design and analysis of concrete bridges is excluded from the plan since these subject areas were not identified in Special Report 202. A further discussion of projects not included in the research plan is contained in Section 4 and Appendix A.

The concept used to formulate the research plan was to identify the overall goal for the research area by answering the basic question: What should the research deliver in a 5-year period? The overall goal was defined as the development of the technology and methodology, in a form usable by operating agencies, to protect existing concrete bridge components for the minimum life cycle costs. Such a capability requires a means of determining how and when to protect and the vehicle for doing this was identified as a simple decision model. In order for such a model to be useful, there must exist a means of determining the in-service condition of concrete bridge components and a range of options for providing protection and rehabilitation. Recognizing these needs led to the logical development of three inter-related projects, the products of which are essential to completion of the fourth project and to satisfying the overall goal of the technical research area.

Within each project, tasks and sub-tasks were developed using a systematic approach which consisted of:

i) A definition of the problems as identified by user agencies.

ii) A review of the historical development of the subject area and the current state-of-the-art to determine a suitable starting point for the research.

iii) Identify the desired solution.

iv) Identify activities (tasks and sub-tasks) which will develop a product which is essential to achieving the desired solution.

v) Develop a framework which establishes the inter-dependence and inter-relationships of the individual activities.

vi) Ensure that the products of the individual activities and the overall solution will solve the problems defined in step (i).

vii) Ensure that the project will result in products usable by operating agencies and that it can be accomplished within 5 years, and within the available budget.

This approach was used to develop flow charts for each of the projects identified and was found to be particularly useful in determining the desired products of the research. It was also found to be an effective method of establishing the priority and scope of tasks and sub-tasks since, if the activity were not found essential to achieving the desired solution for the project, the activity was not included in the research plan. The flow charts which were developed, together with a detailed explanation of the research plan is given in Section 4.

SECTION 4
TRA 4 RECOMMENDED RESEARCH PLAN

INTRODUCTION

The research plan for TRA 4, Bridge Protection, comprises four projects, viz.

4-1 - Inspection and Assessment of the Physical Condition of Concrete Structures

4-2 - Protection and Rehabilitation by Electrochemical Methods

4-3 - Protection and Rehabilitation by Other Than Electrochemical Methods

4-4 - Methodology for Protection and Rehabilitation of Concrete Bridge Components

The objectives and the inter-dependence of the four projects are shown in Figure 1 in Section 7.

Project 4-1 will develop economic and reliable methods for the inspection and assessment of the existing condition and for predicting the future condition of concrete bridge components. In addition to developing products which can be used by bridge owners to obtain more reliable information on the condition of bridges, the products are also required for the successful completion of the other three projects. In particular, the measurement of the rate of corrosion of embedded reinforcement is required to evaluate materials and procedures developed in both Projects 4-2 and 4-3. Other procedures such as the detection of delamination in substructure components, and the measurement of chloride content and concrete permeability also have application within Projects 4-2 and 4-3. Developments such as determining the condition of asphalt-covered deck slabs, the effectiveness of sealers and the integrity of membranes will be used in Project 4-3, especially in evaluating the service life of existing methods of protection. Project 4-1 will also generate the information for determining the existing condition and predicting the future condition of concrete components which will be required as part of the development of the Time-Deterioration Model in Project 4-4.

Projects 4-2 and 4-3 have essentially the same overall objective: to develop technically and economically viable options for protecting and rehabilitating existing concrete bridge components against corrosion. However, because of differences in technology, it is convenient to divide the research into electrochemical (Project 4-2) and non-electrochemical (Project

4-3) solutions to the problem. The treatment of members which were built without adequate corrosion protection, members which are chloride-contaminated but where the concrete is sound and those which are exhibiting corrosion-induced distress are specifically included in both projects. The term "rehabilitation" is not used in the context of restoring a component to its original condition since, by virtue of the fact that the component has deteriorated, the original condition was not sufficiently durable for the service environment. Consequently, rehabilitation is used to mean restoration to at least the original strength and dimensions of the component (though not necessarily with the same type of material) plus the provision of corrosion protection appropriate for the service environment and the future needs of the structure. The products of Projects 4-2 and 4-3 will be a range of cost-effective options for protecting and rehabilitating concrete bridge components. Some options will be more suited to certain components (e.g. piers rather than decks), others will require equipment and contractor expertise that may not be available in all parts of the country and still others will be most applicable where there are operational constraints (e.g. high traffic volumes, cold weather).

Project 4-4 is designed to bring together the products of Projects 4-1, 4-2 and 4-3 in a single usable form. It will develop a decision model which will be applicable at the project level as opposed to the network level. In other words, it will lead to the selection of the protection strategy which will result in the lowest anticipated life-cycle costs for a specific bridge based upon its existing condition and consideration of options for protecting its various components against damage. Project 4-4 has been conceived as a study which will be conducted largely in an office environment and will rely heavily on the products of the other three projects. Because of this dependence on the other projects, Project 4-4 will not begin until year 3 of the five year program.

PROJECT 4-1: INSPECTION AND ASSESSMENT OF THE PHYSICAL CONDITION OF CONCRETE STRUCTURES

Concept of the Project

Project 4-1 will develop economically viable procedures for determining the existing condition and predicting the future rate of deterioration of concrete structures.

Budget limitations preclude the development of entirely new items of equipment. The thrust of the project will therefore be the development of applications and procedures rather than equipment. The concept of Project 4-1 is that it will be a critical assessment and refinement of techniques which are needed (but the existing techniques are inadequate) to make decisions on how and when to apply corrosion protection to existing bridges. It is important to note that the methods of inspection and assessment which will be developed in Project 4-1 relate specifically to corrosion protection. They will be used when decisions must be made about the protection and rehabilitation of specific bridges. It is not the goal to develop methods which will become a component of the biennial inspection program of all bridges, though some of the procedures could be useful in routine inspections.

The approach which has been taken is to identify the areas in which the information is insufficient for decision-making purposes. Tasks have been

identified to address these deficiencies, except where there are already ongoing projects within the FCP and NCHRP. For most applications, inspection and assessment techniques complement each other and each supplies a little more information about the condition of a component. Rarely does one technique provide all the information which is required and it is for this reason that several test methods are used in most condition surveys. The results of one method can then be used to confirm the results of another or to identify anomalous results as the case may be. This approach, which constitutes sound engineering practice, has an important bearing on Project 4-1 because it means that the success of the project is not predicated on complete success in all the tasks. Providing that significant developments occur in a reasonable number of the early tasks in the project, the product will be the reliable field methods of inspection and assessment which are the goal. The exception to this statement is the development of a method to measure the rate of corrosion of embedded reinforcement. This method is needed in both Projects 4-2 and 4-3 to evaluate new materials, field validation trials and in-service installations. A number of different approaches will be pursued within the rate-of-corrosion task to ensure that at least one is successful.

The structure of Project 4-1 can be summarized in the following three steps:

i) Assessment and development of several techniques

ii) Field validation of the successful techniques identified in step (i)

iii) A procedural manual containing the criteria for use and interpretation of the test methods from step ii) and relevant test procedures developed outside this program

Only the successful techniques identified in the initial screening studies will progress to the field validation stage. The field validation phase will establish the capabilities and costs of each technique. Following the field trials is the important step of establishing the significance of the results of each test method, the interpretation which should be placed on the results, and the values which should trigger decisions.

Description

Although there are a number of test procedures which can be used in the inspection and assessment of existing structures, there are a number of deficiencies which have an impact on corrosion protection decision-making.

- Cannot measure rate of corrosion in the field
- Cannot ascertain the condition of pretensioned strand and post-tensioned cables and bars
- Cannot determine the effectiveness of membranes and sealers
- Cannot reliably determine the condition of asphalt-covered decks

- Many existing methods are slow, unreliable and the significance of the results is unclear
- Unable to predict future rate of deterioration and future condition

The tasks which have been identified to resolve these deficiencies are listed below and are shown in Figure 4 in Section 7.

4-1.1 Rate of Corrosion

4-1.2 Detecting Delamination in Beams, Piers, and Abutments

4-1.3 Detecting Deterioration in Asphalt-Covered Decks

4-1.4 Integrity of Membranes

4-1.5 Sealer Evaluation

4-1.6 Permeability of Concrete

4-1.7 Chloride Content of Concrete

4-1.8 Field Validation and Calibration

4-1.9 Existing Methods

4-1.10 Procedural Manual for Existing and Future Condition

Investigating the condition of prestressed concrete components has not been included in Project 4-1 because it cannot be adequately addressed within the available budget and there are projects within the FCP and the NCHRP dealing with pretensioned and post-tensioned components. This is not intended to diminish the importance of prestressed members; in fact, there is increasing concern for the condition of prestressed concrete components because of the potential consequences of corrosion of the prestressing steel. The decision not to include the subject in this program is a reflection of the much greater number of reinforced concrete components and the realization that the difficulties involved in determining the condition of prestressing steel are so great that they would consume the entire budget for Project 4-1. Prestressed components will not be neglected entirely because the results of the FCP studies will be consolidated in the methods identified in Task 4-1.10 for determining the existing condition and predicting the future condition of concrete components.

As already noted, the development of a method of measuring the rate of corrosion of concrete reinforcement is an essential component of TRA 4. A substantial budget has been assigned to this task to permit consideration of a number of techniques and pursue the more promising simultaneously until it becomes clear which is the most suitable for field use. The task will also make use of the latest progress in developing a rate-of-corrosion device in the FCP.

The other task for which there is a related project in the FCP is Task 4-1.2, which involves the detection of delamination in exposed concrete

members. The FCP studies have been underway for a number of years and have been concerned primarily with bridge decks. Duplication will be avoided by developing methods of detecting delamination in bridge substructure components in Task 4-1.2. The requirements for a method used on substructure components differ from those on decks since speed is less important and access is often the greatest problem. Furthermore, some methods, particularly infrared thermography, which work well on decks may not be applicable to substructure components.

Task 4-1.3 involves determining the condition of concrete deck slabs which have a bituminous surfacing. The use of bituminous surfacings on bridges ranges from zero in some southern and mountain states to almost 100% in some north-eastern states. An individual's assessment of the need for such a project is therefore influenced by the extent to which bituminous surfacings are used within the individual's home state. There are, however, many thousands of asphalt-covered decks in service and a determination of the condition of the concrete deck slabs is of vital importance to the owners of such bridges. A related task is 4-1.4 to determine the condition of membranes since their use is also subject to regional variations. Membranes are, however, used in approximately twenty states and 8 to 10 million square feet will be installed in 1985.

Task 4-1.5 on sealer evaluation is designed to develop a test method for the presence and effectiveness of sealers. The use of sealers has increased substantially in recent years. Although it is known that additional applications of new sealer must be made periodically to maintain corrosion protection, agencies do not have a means of determining the optimum interval between applications.

Task 4-1.6 has been included because of the difficulty of predicting the future condition of concrete components on the basis of their existing condition. It is believed that a measurement of concrete permeability, in combination with a chloride ion determination, offers the most promising method of predicting the future condition of components which are in good condition at the time of testing. The task to develop a method of determining the chloride content of concrete (4-1.7) differs from the other tasks in that it is reasonably straightforward and this is reflected in the budget. It is included because there is currently no standard field method of chloride measurement and, if one were developed, it could reduce the cost of chloride testing substantially. It could also influence the scope of condition surveys while the crew is still on site, and so lead to more effective surveys.

Task 4-1.8 involves the field validation and calibration of the products of Tasks 4-1.1 to 4-1.6 (Task 4-1.7 is itself a field validation study). The task also includes establishing the costs of the test procedures and, where appropriate, preparing a draft standard test method.

Project 4-1 also includes a task (4-1.9) which consists of a critical review of existing procedures. It is important that in the quest for new methods, the existing methods are not discarded. In fact, the tasks in Project 4-1 are not designed to replace existing methods such as concrete cover measurements or ultrasonic techniques. This task will therefore ensure that the best of the existing procedures are included in the procedures to be identified for determining existing and predicting future condition in Task 4-1.10. This task will follow the field validation and calibration studies

and will specifically address the questions of the physical significance of the measured values and establish when intervention is necessary. The final activity in Task 4-1.10 consists of consolidating the results of the earlier tasks in a single user document containing both standard and recommended practices.

The task statements which follow should be viewed as a direction which the research could take with reasonable assurance of making significant progress. However, it is not the only approach and there is a danger that innovative approaches could be stifled if a specific approach is dictated. While this is applicable to most of the task statements in all four projects, it is particularly true of Project 4-1. In this case, it is essential that the research contractor develop a clear understanding of the problem which is to be solved and the use of the product of the research in order to apply creative thinking to the development of a solution.

Task Statements

4-1.1 Rate of Corrosion

Objective: To develop a field method of measuring the rate of corrosion of steel in concrete.

Scope: The task will begin by a thorough assessment of the device developed in the FCP studies and of the various methods which can be used to measure the rate of corrosion of steel in concrete (e.g. linear polarization, AC impedance, cyclic voltammetry and electrochemical noise measurements). The more promising approaches should be investigated progressively through laboratory, exposure plot and small scale field evaluations. Development of the alternative options should not be discontinued until it is clear which method should be included in the full field validation and calibration studies in Task 4-1.8. This approach has been assumed in preparing the budget and should increase the probability of success significantly. Success in this task has a major impact on the evaluation of new materials, field trials and existing installations in Projects 4-2 and 4-3. The final product of the task should be a test method suitable for adoption by ASTM.

Product: Standard field procedure for rate of corrosion measurements.

4-1.2 Detecting Delamination in Beams, Piers, and Abutments

Objective: To develop a method of detecting delamination in concrete beams, piers, and abutments.

Scope: Several investigations have been carried out (in the FCP and elsewhere) to develop rapid, non-contact methods of detecting delamination in bridge decks. These studies have led to the identification of impulse radar and infrared thermography as promising techniques. This task involves a parallel investigation to identify and develop techniques applicable to other components. It should be noted that speed is less important when evaluating most beams, piers, and abutments than it is on decks (because the activity is less likely to cause traffic delays) but access can present serious operational problems. Thermography may not be applicable to components which are continuously shaded. Consequently, the task should begin by an assessment of all possible approaches. The task includes the development of data

reduction techniques (if necessary) and preliminary field evaluations.

Product: A potentially economical and reliable method of detecting delamination in bridge substructure components.

4-1.3 Detecting Deterioration in Asphalt-Covered Decks

Objective: To develop a method of determining the condition of concrete deck slabs which have a bituminous surfacing (with or without a membrane).

Scope: The task will build upon the work on both exposed concrete and asphalt-covered deck slabs and other related investigations, rather than develop new equipment. The task is concerned exclusively with the condition of the concrete deck slab and not the condition of the bituminous surfacing. The project should not be limited to detecting corrosion-induced deterioration because firstly, it is necessary to distinguish corrosion problems from other forms of deterioration and secondly, the other deterioration may influence the selection of the corrosion protection treatment. Data reduction procedures are included in the task if this is appropriate.

Product: A potentially economical and reliable method of detecting deterioration in asphalt-covered deck slabs.

4-1.4 Integrity of Membranes

Objective: To develop non-destructive procedures to determine the effectiveness of membranes.

Scope: The task is needed because there is not a reliable method to determine whether and to what extent a membrane is punctured. Electrical resistivity tests have not worked well because of an inability to discriminate between membranes which have a few pinholes and those with large punctures. This is important because membranes with even a few pinholes have been found to offer good protection to bridge decks. The test procedure will be non-destructive to the membrane though, as a last resort, selective removal of the bituminous surfacing at test locations would not be excluded. If a direct approach is not feasible, the effectiveness of the membrane may have to be assessed indirectly from the condition of the concrete deck slab.

Product: A potentially economical, reliable test method for determining the effectiveness of membranes.

4-1.5 Sealer Evaluation

Objective: To develop a non-destructive procedure to determine the presence and effectiveness of sealers.

Scope: The use of sealers has increased substantially in recent years with the advent of a new generation of more effective products for non-trafficked areas. Many of the products are colorless and degrade with time. A field test method is needed to determine whether a sealer is present and effective in order to schedule the optimum interval between applications. The task should examine different approaches (e.g. permeability, absorption) for measuring depth of penetration and effectiveness and develop a test method.

Product: A potentially economical, reliable, non-destructive field method for determining the presence and effectiveness of sealers.

4-1.6 Permeability of Concrete

Objective: To develop a field procedure to measure the permeability of concrete.

Scope: The existing test method for the chloride permeability of concrete is too lengthy and unreliable under field conditions. The task should examine the possibility of improving the existing procedure and applying new approaches. If the difficulties of determining chloride permeability prove insurmountable, air and water permeability methods should be examined.

Product: A potentially economical, reliable field method for measuring the permeability of concrete.

4-1.7 Chloride Content of Concrete

Objective: To develop a field method of measuring the chloride ion content of concrete.

Scope: The task will develop a quick reliable test method for field use. Possible approaches include use of a chloride selective electrode in-situ or analysis of a pulverized sample. Less precision than given by standard laboratory techniques would be acceptable. The task includes field validation testing since the task is relatively straightforward and all activities can be completed in a single task. Task 4-1.7 also includes preparation of a standard test procedure suitable for adoption by ASTM and AASHTO.

Product: A standard field test procedure for the measurement of the chloride ion content of concrete.

4-1.8 Field Validation and Calibration

Objective: To prove the test methods developed in Tasks 4-1.1 to 4-1.6 under field conditions and establish the significance of the test results.

Scope: This task involves validation and calibration of the products of the earlier tasks under operating conditions. It is for this reason that the products of Tasks 4-1.1 to 4-1.6 have been described as potentially economical and reliable since they must be proven in field conditions. The testing of more than one promising approach identified in an earlier task is not excluded. The field validation studies should examine the applicability of the test procedures to both reinforced and prestressed concrete components. In order to complete Project 4-1 in time for the products to be usable in Projects 4-2, 4-3 and 4-4, it is necessary that Task 4-1.8 begin in year 2. It is intended that field validation studies begin as soon as products are available from any of the Tasks 4-1.1 to 4-1.6 while those tasks which do not result in a product in the first year will continue simultaneously. The cost of the test procedures will be established. The task also includes preparation of draft standard test procedures where appropriate.

Product: Field proven methods of known cost and significance.

4-1.9 Existing Methods

Objective: To identify existing methods which can usefully contribute to Task 4-1.10

Scope: This task consists of a critical evaluation of existing test methods not included in other tasks (e.g. potential measurements, ultrasonics, magnetic methods for locating reinforcement) and a determination of their usefulness in assessing the existing condition and predicting future deterioration. The task is intended to be a paper study and not involve physical testing. Where standard test procedures do not already exist, they should be drafted in a format suitable for adoption by standards organizations such as ASTM or AASHTO.

Product: Standard test procedures.

4-1.10 Procedural Manual for Existing and Future Condition

Objective: To document procedures which can be used to determine the existing condition and the methodology for predicting the future condition of concrete components.

Scope: This is an important task which describes:

i) the successful products of the earlier tasks,
ii) the relevant test procedures identified in Task 4-1.9 and
iii) applicable procedures developed outside this program, particularly those suitable for use on prestressed concrete components.

Except for the publishing elements, the task is viewed primarily as a desk activity requiring a high level of technical expertise. The document which is produced should describe what test procedures to use, under what circumstances, and the meaning of the results. It should also summarize techniques which have have been tried but found to be unsuitable and give the reasons. The document should explain how the results of the relevant test methods can be interpreted to predict future performance. The possibility of developing a predictive model should be examined. The results of this task are important to the success of the time-deterioration model in Project 4-4. In order to satisfy the overall time-frame for TRA 4, Task 4-1.10 will need to begin in Year 3 which is before all the field validation studies have been completed. This may be less than ideal but is not expected to create insurmountable difficulties.

Product: A procedural manual.

PROJECT 4-2: PROTECTION AND REHABILITATION BY ELECTROCHEMICAL METHODS

Concept of the Project

Project 4-2 will develop technically and economically feasible methods of protecting and rehabilitating concrete bridge components using electrochemical methods. The project comprises two tasks:

4-2.1 Electrochemical Removal and Protection,

4-2.2 Cathodic Protection

Task 4-2.1 is significant because there is currently no method by which chloride ions can be removed from salt-contaminated concrete. Limited experimental work has shown electrochemical removal to be a promising technique but much remains to be done to develop a routine, operational procedure. The technique consists of the application of a large direct current between an anode on the member's surface and the reinforcement for a relatively short period of time to migrate the chloride ion away from the reinforcing steel. However, this migration may induce undesirable side effects in the concrete and, if inert anodes are used, chlorine gas will be generated at the concrete surface. Either following or concurrent with the electrochemical removal, the concrete must be sealed against the further ingress of chloride ions. Task 4-2.1 is designed to determine the feasibility of electrochemical removal and, if feasible, to develop procedures and specifications for its use.

Task 4-2.2 is important because, with the possible exception of deep polymer impregnation, cathodic protection is the only treatment which is known to stop corrosion in reinforced concrete components. Cathodic protection normally consists of the continuous application of a very small direct current to the surface of the reinforcing steel. However, there also exists the interesting possibility of using intermittent power supplies, possibly in combination with partial electrochemical removal. The principles of cathodic protection are well established in other fields (e.g. pipelines, buried tanks, industrial plants) but methods and criteria for protecting above-ground reinforced concrete structures are still in the developmental stage. In addition, there are serious organizational barriers to the use of cathodic protection by the highway industry. Task 4-2.2 is designed to develop a number of field proven cathodic protection systems and prepare an implementation package so that cathodic protection can be used by agencies previously unwilling to employ this method of corrosion protection.

The structure of Tasks 4-2.1 and 4-2.2 is very similar and consists of a progression through four steps.

i) background studies,

ii) development of components and criteria (including small scale field trials in some cases),

iii) full scale field trials of complete systems,

iv) documentation in a usable form,

As in the case of Project 4-1, the philosophy is that Project 4-2 should not be used to develop entirely new materials or pieces of equipment. It is the intent that Project 4-2 will evaluate existing products and establish the criteria for the acceptance of both existing and future materials and equipment. This approach has two major attributes: it maximizes what can be accomplished within the budget for TRA 4 and it encourages private sector involvement and complementary studies in other research programs (including the FCP). It is envisaged that the private sector will develop new products during the time Project 4-2 is underway and establishing acceptance criteria has the important advantage of encouraging product development long after the program is completed. Furthermore, this approach does not preclude materials and equipment development projects within

the FCP and elsewhere. Such studies are encouraged since they will contribute to the achievements of Project 4-2 but cannot be accommodated within the budget. A close analogy can be drawn between the philosophical approach described for Project 4-2 and that which was used to develop epoxy coated reinforcement in the early 1970's. In that case, the Federal Highway Administration contracted with the National Bureau of Standards to evaluate all candidate coatings for reinforcing steel and prepare specifications for the materials, their application and use. The private sector responded by developing a number of potential coatings during the course of the study but even more significant is the fact that since the study was completed, improved coatings and increased competition has occurred in the marketplace because the mechanism for acceptance of the new products was established.

TASK 4-2.1: ELECTROCHEMICAL REMOVAL AND PROTECTION

Description

The overall objective of Task 4-2.1 is to develop methods of preventing the premature deterioration of sound, chloride contaminated components and also as one of the options of treating deteriorated components without removing substantial quantities of concrete. Previous research work resulted in the treatment of a portion of a bridge deck in Ohio and was successful in moving chloride away from the reinforcing steel. Other work resulted in the experimental treatment of bridges in Kansas. However, a number of problems remain to be solved and these are summarized below:

- Optimum combination of equipment and anodes not defined and field proven
- Treatment parameters unknown
- No provision for dealing with chlorine gas generated if inert anodes are used
- May induce undesirable effects in the concrete such as an increase in permeability, reduction in the bond between the cement paste and the reinforcing steel, the migration of ions other than chlorides, and high temperatures may be developed in the concrete
- Lack of post-treatment protection

There are two interesting potential applications for electrochemical removal which have not previously been investigated. The first is the possibility of using lower currents for a longer duration than the currents and treatment times in earlier work. If feasible, this approach would be more useful on piers, beams and abutments than decks because treatment of the former components is less likely to cause traffic delays. The use of a low power source would have the important advantages of reducing equipment costs and minimizing temperature build-up. The second possibility is to partially remove the chlorides from a member and then apply intermittent cathodic protection. This could reduce the cost of cathodic protection by permitting the use of sacrificial anodes or intermittent power supplies (e.g. wind generator or solar cells or situations where the only economical source of

power is from bridge illumination circuits).If continuous cathodic protection were to be applied, then electrochemical removal would not be required.

The sub-tasks comprising Task 4-2.1 are as follows:

4-2.1,a Background Studies

4-2.1,b Electrochemical Removal

4-2.1,c Concurrent Protection

4-2.1,d Field Validation Studies

4-2.1,e Implementation Package

The background studies are required to determine the feasibility of electrochemical removal and establish the criteria for treatment. The sub-task includes investigation of chloride removal and re-migration rates, bond, permeability, gas generation and the effects of intermittent power application which are all important to Task 4-2.2 in establishing protection criteria for cathodic protection. Sub-task 4-2.1,a includes an important go/no-go decision point, 18 months after beginning the study. At this time the feasibility of electrochemical removal must have been determined. If found to be feasible, sub-tasks 4-2.1,b and 4-2.1,c will be initiated. If not feasible, the funding allocated to Task 4-2.1 will be used for sub-task 4-2.2,g and for Phase II of Task 4-3.7. However, sub-task 4-2.1,a must be completed because the results are needed to complete task 4-2.2.

Sub-tasks 4-2.1,b and 4-2.1,c involve the definition of the equipment needed and development of concurrent methods of sealing the concrete against chloride ingress respectively. Methods of post-treatment protection (e.g. by sealers or penetrants) will be developed in Task 4-3.4. This division is made necessary by the fact that if electrochemical removal were found not to be feasible, sub-task 4-2.1,c would not be funded but the development of methods for protecting and rehabilitating components without concrete removal is essential to the successful completion of Project 4-3. The split between concurrent and post-treatment protection fits well with the scope of Project 4-2 which is limited to electrochemical methods. Where electrochemical removal is to be applied to deteriorated components, the materials and methods developed in Task 4-3.3 for restoring and protecting the concrete will be applicable. Sub-tasks 4-2.1,b and c include the construction and shake-down testing of full scale equipment. This step is specifically mentioned because it is often omitted in research studies but is essential in order to ensure a smooth transition between small scale laboratory or exposure plot studies and the full scale field validation studies which will take place in sub-task 4-2.1,d. The test procedures developed in Project 4-1 will be useful in determining the performance of the treatments and in assessing the extension in service-life provided in order to establish the cost-effectiveness of the electrochemical removal and protection. Sub-task 4-2.1,e involves the preparation of an implementation package of operational procedures.

Sub-Task Statements

4-2.1,a Background Studies

Objective: To determine the feasibility and the criteria for removing chlorides electrochemically.

Scope: The study will investigate the effect of current density and time on reinforcement bond, hydrogen embrittlement, changes in concrete permeability, and the cement phase at the rebar (mainly alkalis), chloride removal rates and gas generation. It will determine if the effects are a function of the total charge and/or current density. It will also determine how quickly the chlorides move back if migrated away from rebar but not removed from the concrete. The sub-task contains a decision point 18 months after beginning the study, at which time it will be necessary to determine whether the electrochemical removal of chlorides is feasible. If the answer is affirmative, sub-tasks 4-2.1,b and c must begin. If the answer is negative, the funding assigned to the remainder of Task 4-2.1 will be allocated to additional work in Tasks 4-2.2 and 4-3.7. In either case sub-task 4-2.1,a must be completed. The data on chloride removal and re-migration rates will be used to determine if intermittent cathodic protection is feasible, either on its own or in combination with partial electrochemical removal. Data on reinforcement bond, hydrogen embrittlement, concrete permeability, and changes in the composition of the cement paste phase at the rebar at low current densities will be used in sub-task 4-2.2,b.

Products:
i) Documentation of the results.

ii) Determination of the feasibility of electrochemical removal and the criteria for its use.

iii) Determination of the feasibility of intermittent cathodic protection and the criteria for its use.

4-2.1,b Electrochemical Removal

Objective: To develop practical procedures for removing chlorides from salt-contaminated concrete components.

Scope: This sub-task is an engineering study to define the equipment needed (power supplies, heat dissipation devices, hardware, anode materials and configuration, gas traps, etc.), and develop the procedures for chloride removal. The sub-task will investigate if different procedures are required for decks and piers. The ability to deal with large areas quickly is necessary for decks. It is not important for most piers, beams and abutments where the ability to use smaller power sources may reduce costs and minimize problems associated with heating effects and gas generation. It will also determine how to deal with chlorine gas (e.g. trap it, ignore it or prevent its formation). This sub-task includes small scale trials, and the construction and shake-down of full scale equipment. Coordination with sub-task 4-2.1,c will be necessary to ensure the equipment is compatible with methods of concurrent protection.

Products: i) Documentation.

ii) Potentially economical and feasible techniques of electrochemical removal.

4-2.1,c Concurrent Protection

Objective: To develop sealing or impregnation techniques which can be used concurrently with electrochemical removal to prevent future corrosion.

Scope: This sub-task will develop methods which can be used concurrently with electrochemical removal to seal the concrete against the ingress of chlorides and reduce permeability. The study should include the investigation of polymer impregnation, and impregnation with penetrating sealants or corrosion inhibitors, including the possibility of using the heat generated in removal operations for thermal polymerization. The sub-task includes the construction and shake-down of full scale equipment. Coordination with sub-task 4-2.1,b will be required to ensure compatibility between the results of the two studies. Methods of post-removal protection will be developed as part of Project 4-3.

Products: i) Documentation

ii) Potentially long-life options for protecting chloride-contaminated components.

4-2.1,d Field Validation Studies

Objective: To develop the most promising products of sub-tasks 4-2.1,b, 4-2.1,c. and Tasks 4-3.3 and 4-3.4 into field proven techniques.

Scope: The sub-task will combine the most promising products of sub-task 4-2.1,b for electrochemical removal, 4-2.1,c for concurrent protection and Tasks 4-3.3 and 4-3.4 for post-removal protection and develop them for operational use. The treatment of a minimum of two bridge decks and two substructures (assuming that both are found to be feasible) should be included. The sub-task should include consideration of the safety of the techniques as routine procedures and a determination of their cost-effectiveness. The budget for 4-2.1,d includes limited agency involvement. Monitoring of the field trials will be required beyond the time of the program in order to ascertain their actual performance.

Products: i) Documentation.

ii) Economical, practical and safe methods of electrochemically removing chlorides from salt-contaminated concrete components.

4-2.1,e Implementation Package

Objective: To prepare an implementation package suitable for use by operating agencies.

Scope: The sub-task will define the equipment, procedures and the criteria for use and operation of those techniques identified as most suitable in sub-task 4-2.1,d. The implementation package should include a description of

the equipment and procedures and typical, non-proprietary specifications. The package must be suitable for use by personnel in operating agencies who have no previous knowledge of electrochemical removal techniques.

Product: An implementation package containing descriptive procedures and typical specifications.

TASK 4-2.2: CATHODIC PROTECTION

Description

The overall objective of Task 4-2.2 is to develop cost-effective cathodic protection systems for concrete bridge components and package the results in a "cookbook". It is more than ten years ago that the first application of cathodic protection was made to a bridge deck in California. Since that time, there have been several research studies in the FCP and elsewhere, new anodes have been developed and cathodic protection has been shown to stop the corrosion of reinforcing steel, but the number of installations remains relatively small. There has also been limited research work undertaken to develop methods of cathodically protecting bridge beams and substructure components (piers and abutments). This is significant because it is known that the volume of substructure repairs will increase substantially in the next few years, that the repairs will be more difficult and expensive than deck repairs, and there are few repair options available. Despite the promise of cathodic protection, it is not being used routinely. There are a number of technical questions to be answered, mainly concerning protection criteria and long term effects, but the larger barriers are its high cost and the lack of familiarity within the highway industry. Consequently, a concerted research effort is needed, not only to answer the unresolved technical questions but also to package the product in a form that will be accepted by highway personnel. The problems which Task 4-2.2 must address can be summarized as follows:

- Unknown life of components
- Unknown protection criteria to stop corrosion
- Limited options
- High cost
- Technically complicated
- Can prestressed concrete components be protected?
- Alien technology to highway personnel
- Few qualified practitioners

These problems can best be solved by undertaking research studies to resolve the technical issues and then producing a "cookbook" containing specifications and simple procedures for design, construction, activation and monitoring of cathodic protection installations on decks, beams, and substructure components.

The sub-tasks which have been identified as a means of reaching this goal are listed below and are shown in Figure 6 in Section 7.

4-2.2,a State-of-the-Art and Performance History of Field Installations

4-2.2,b Long Term Effects

4-2.2,c Testing and Criteria

4-2.2,d Life Prediction Techniques

4-2.2,e Field Test Systems

4-2.2,f Prestressed Concrete - Structural Effects of Cathodic Protection

4-2.2,g Prestressed Concrete - Methods of Applying Cathodic Protection

4-2.2,h Cathodic Protection "Cookbook"

While it is implicit that all tasks and sub-tasks will begin with a review of the state-of-the-art, a separate sub-task is defined in Task 4-2.2 for two reasons:

i) There is ongoing work within the FCP and the FHWA Demonstration Projects Program. Developments within those research studies could influence the starting point for Task 4-2.2

ii) Many of the recent developments, particularly those in the private sector, have not been documented in the literature. There is thus the need for a concerted effort to be made through personal contacts to determine the true state-of-the-art.

In addition to determining the state-of-the-art through personal contacts and field visits, there is much to be learned from the performance history of existing installations. Much of the data required are not available and must be collected because of the relevance to sub-tasks 4-2.2,c and 4-2.2,d in determining protection criteria and the performance of individual components under actual service conditions.

Sub-task 4-2.2,b complements sub-task 4-2.1,a and is intended to answer a number of the unresolved questions surrounding the long term effects of applying cathodic protection to a bridge structure and, if proven feasible, identify low cost options for power supplies. Sub-task 4-2.2,c will develop simple criteria for the activation and monitoring of cathodic protection systems. Sub-task 4-2.2,d will result in the identification of a number of qualified components (anodes, reference cells, rectifiers, etc.) and a definition of the acceptance requirements against which new products can be evaluated. Once the individual components have been developed and protection criteria established, it is necessary to field test cathodic protection systems using combinations of these components. Any developments in Project 4-3 which can be used in combination with cathodic protection to reduce cost or improve durability also need to be included in the field trials. For

example, one method of cathodically protecting a bridge deck is to place anodes in a grid on the deck surface followed by the application of a concrete overlay. Developments in Project 4-3 may lead to the identification of overlay materials which offer superior performance characteristics.

The application of cathodic protection to prestressed concrete components presents additional considerations, largely because of the possibility of hydrogen embrittlement of the prestressing strands which would preclude its use. Sub-task 4-2.2,f will determine whether the cathodic protection of pretensioned and post-tensioned concrete components is feasible. If not feasible, this will be recorded in the documentation of the study and cathodic protection will not be an option for the protection of prestressed components. Sub-task 4-2.2,g, which involves additional laboratory testing and the development of methods of cathodically protecting prestressed elements, will only be undertaken if the cathodic protection of prestressed concrete is shown to be feasible and if funding becomes available from Task 4-2.1. Without this funding, sub-task 4-2.2,g cannot be accomplished within this program.

In the unlikely event that funding becomes available from Task 4-2.1, and cathodic protection of both pretensioned and post-tensioned members is not feasible, the most appropriate use of the funding would be in developing methods of investigating the condition of prestressed components as part of Project 4-1. A specific task statement has not been prepared because the precise activities would depend upon the progress made in the related studies in the FCP and the NCHRP.

The final sub-task is the preparation of a cathodic protection "cookbook", applicable to both decks and substructure elements. The term "cookbook" is chosen deliberately because it implies that the design and installation of cathodic protection will be described in a series of simple step-by-step procedures. This approach has been taken to overcome the organizational barriers, the lack of familiarity of highway personnel with the technology and the fact that there are relatively few qualified practitioners. The intent is that a prescription approach will be used which is applicable to the majority of bridges. The criteria for selecting the types and condition of bridges for which the approach is valid must be clearly identified. The design and installation of cathodic protection on any bridge which does not meet the criteria for the "cookbook" to be used must be engineered individually by qualified personnel.

Sub-Task Statements

4-2.2,a State-of-the-Art and Performance History of Field Installations

Objective: To investigate progress in related R & D and field projects and to document the performance of selected field installations.

Scope: This sub-task will be used to define an appropriate starting point for the other sub-tasks in Task 4-2.2 and will provide a data base for sub-tasks 4-2.2,c and 4-2.2,d. Much of the progress which has been made in recent years in cathodically protecting above-ground reinforced concrete structures is not in the public domain. It is essential to undertake a thorough review of the state-of-the-art to ensure that this program begins at the leading edge of the technology. The data base which is required should be developed by monitoring

a relatively small number (typically two or three for each system, but including both impressed current and galvanic systems) of carefully chosen sites representing the range of cathodic protection systems which have been used on both bridges and substructures. The performance of sacrificial anodes should be carefully reviewed because of the advantages of the simplicity of galvanic systems without the danger of over-protection. The sites should be selected on the basis of good construction records and available data. The sub-task will include transcribing available data and taking additional measurements as necessary to define power requirements, protection levels, component life, and monitoring frequency and practices. It is also important to try to establish, where failures have occurred, if the failure resulted from a component failure or can be attributed to improper design, construction or maintenance.

Products: i) Documentation of the state-of-the-art.

ii) A data base of performance under actual service conditions.

4-2.2,b Long Term Effects

Objective: To identify and quantify changes which take place in cathodic protection systems with time.

Scope: The sub-task consists of a laboratory and exposure plot study to define any long term effects of cathodic protection which may have either an adverse or beneficial effect upon the performance of the cathodic protection system or the structure under protection. Possible positive effects include the migration of chloride away from the reinforcing steel and a reduction in power requirements. The latter would increase anode life and may render intermittent applications of cathodic protection feasible. Possible negative effects include a reduction in the bond between overlays and the concrete member and an increase in circuit resistance because of a reduction in conductivity at the interface between primary and secondary anodes or between anode and concrete.

This sub-task requires close coordination with sub-task 4-2.1,a which includes a determination of the effects of the range of current density used in cathodic protection on rebar bond, hydrogen embrittlement, concrete permeability and changes in the composition of the cement phase at the rebar. Sub-task 4-2.1,a will also determine the possibilities of using intermittent applications of cathodic protection (from the measurements of the rate of chloride movement away from the reinforcing steel when different levels of power are applied and the movement back to the rebar when power is switched off). and will examine the possibility of applying partial electrochemical removal followed by intermittent or low level cathodic protection. If sub-task 4-2.1,a determines that these approaches are feasible, this sub-task should examine alternative intermittent (e.g. wind, solar, switched line-power) and low (e.g. batteries, fuel cells) power options and determine their suitability for powering cathodic protection systems. The intention is not to develop power sources but to identify simple, reliable and inexpensive power sources which are available or can be developed in the private sector. Final suitability will be determined by the ability to meet the protection criteria defined in sub-task 4-2.2,c.

The work on power sources should be completed in the first two years of the sub-task so that the findings can be used in sub-task 4-2.2,e. The work on long term effects will continue for a total of 54 months, at which

time the findings will be required for input to sub-task 4-2.2,h.

Sub-task 4-2.2,b specifically includes field confirmation studies by investigating the condition of structures which have been cathodically protected for long periods of time.

Products: i) Assurance of the long life of cathodic protection systems without detrimental effects to the protected structure.

ii) Low cost, reliable power sources.

4-2.2,c Testing and Criteria

Objective: To evaluate, refine and establish protection criteria and test methods.

Scope: The sub-task involves fundamental laboratory and exposure plot studies, together with the data base developed in sub-task 4-2.2,a to investigate the technical validity of different protection criteria. The product will be the definition of protection criteria and a simple method of measurement. Criteria rather than a single criterion is used because different components may require different levels of protection. The goal of simplicity does not exclude sophisticated equipment providing that it is easy to use by relatively low level highway personnel. Two approaches should be investigated: the use of automated controls to satisfy technically precise criteria and the possibility of using simple, but acceptable criteria, for which the test methods are also simple.

Product: A simple method of establishing protection criteria for activation and monitoring.

4-2.2,d Life Prediction Techniques

Objective: To develop criteria for evaluating and predicting the service life of the components of cathodic protection systems.

Scope: Components will be evaluated for both their civil engineering (durability) and electrical properties, in the service environment (e.g. embedded in concrete or in contact with brine-laden coke). This sub-task is not intended to develop components but to evaluate the products of the private sector and other research studies and define acceptance requirements for new products. Although all components (e.g. reference cells, ground connections, rectifier-controllers) are included, emphasis will be placed on anodes and their connections. The study specifically includes both deck and substructure applications.

The sub-task has two goals:

i) to predict the service life of components which are available at the time of the study.

ii) to develop the acceptance criteria for products which will be developed in the future.

The following activities are envisaged:

1. Define the performance of existing installations and operating parameters, e.g. current densities, years of service. Data will be generated in 4-2.2,a.

2. Develop accelerated laboratory and test yard procedures to predict service life, including simulating the effect of traffic.

3. Validate 2. by testing the systems documented in 1. and comparing predicted to actual performance, i.e. validate the test methods.

4. Test all available components using 2.

5. Define acceptance criteria and test procedures for new products.

Product: Qualified products and acceptance criteria.

4-2.2,e Field Test Systems

Objective: To assemble the most promising components identified in 4-2.2,b, 4-2.2,d and 4-3.3 into cathodic protection systems and evaluate under field conditions when powered to satisfy the criteria developed in 4-2.2,c.

Scope: The field validation should involve a minimum of three systems for decks and three systems for substructures, each duplicated (i.e. a minimum of 12 test sites). The substructure applications should include one installation of each system in a marine environment and one in a location where deicing chemicals are used. The installations will be designed to optimize the use of the most promising results from sub-tasks 4-2.2,b and 4-2.2,d. Any developments from Task 4-3.3 which can be combined advantageously with cathodic protection should also be included. The sub-task should also develop a standardized method of data collection and investigate the feasibility of remote monitoring. The budget for this sub-task includes only the costs of the cathodic protection portion of a rehabilitation contract.

Product: Several options for simple, low cost, long life cathodic protection systems.

4-2.2,f Prestressed Concrete - Structural Effects of Cathodic Protection

Objective: To determine whether it is feasible to cathodically protect prestressed concrete components.

Scope: The sub-task comprises a literature study of the metallurgical factors involved in hydrogen embrittlement and a laboratory and exposure plot study to determine the feasibility of cathodically protecting pretensioned and post-tensioned components. Examination of post-tensioned components includes determining the effect of anchorages and of plastic and metal ducts. If it is not safe to apply cathodic protection to prestressed components this result will be contained in the "cookbook".

Product: Determination of feasibility.

4-2.2,g Prestressed Concrete - Methods of Applying Cathodic Protection

Objective: To develop methods of cathodically protecting prestressed components.

Scope: The sub-task will only be undertaken if the cathodic protection of prestressed components is found to be feasible in sub-task 4-2.2,f and if funding is available from Task 4-2.1. There will also be the need for close coordination with sub-task 4-2.2,e since many of the systems tested may also be applicable to prestressed components. The sub-task consists of studies to examine the combination of cathodic protection and dynamic load on large scale laboratory specimens followed by the development of methods of applying cathodic protection to pretensioned and post-tensioned members. Large scale exposure plot specimens should be used for development work followed by a minimum of eight field installations consisting of duplicate installations of two different systems on pretensioned members and two different systems on post-tensioned members. The budget has been developed using the same assumptions as in developing the budget for sub-task 4-2.2,g.

Product: Field proven options for cathodically protecting prestressed concrete components.

4-2.2,h Cathodic Protection "Cookbook"

Objective: To document the results of Task 4-2.2 in a user's manual for operating agencies.

Scope: The sub-task will develop a manual which should present a prescription or step-by-step approach to the design, construction, acceptance, activation and monitoring of c.p. systems on most (maybe 80%) of the existing highway bridges. C.P. systems for bridges not meeting the criteria for bridges covered by the manual will continue to require custom engineering. The "cookbook" should be written for highway personnel and should assume no prior knowledge of cathodic protection. It should be designed to overcome the barrier of alien technology which has resulted in high costs and relatively few installations of cathodic protection on bridges in the past. The "cookbook" will include separate sections on decks, substructures and prestressed components since the options, protection criteria and control modes may be different. Specifications and typical drawings will be included.

Product: Specifications and a simple explanation of the procedures for the design, construction, acceptance, activation and monitoring of cathodic protection systems.

PROJECT 4-3: PROTECTION AND REHABILITATION BY OTHER THAN ELECTROCHEMICAL METHODS

Concept of the Project

Project 4-3 will develop technically and economically feasible methods of protecting and rehabilitating bridge components using other than electrochemical methods.

Although there are a number of conventional approaches to bridge protection already in use, Project 4-3 is necessary because of the limitations of the existing methods. Most of the existing methods are applicable only to bridge decks and suffer the drawbacks of high cost and a relatively short service life. Very few methods are available for protecting beams, piers and abutments, yet it is known that substantial resources will be required to protect and rehabilitate existing, chloride-contaminated components in future years.

The project comprises nine inter-related tasks and represents an approach to bridge protection which is closer to methods now in use than the solutions to be developed in Project 4-2. Consequently, there are not the same problems of implementing alien technology which must be addressed in Project 4-2. Project 4-3 will therefore focus on the development of technology; implementation can be expected to be more straightforward since the products are more likely to be compatible with existing practices.

The structure of Project 4-3 consists of a progression through four steps.

i) background studies

ii) a development phase involving materials, equipment and procedures (including small scale field trials)

iii) full scale field validation studies

iv) user documentation

The products of Project 4-3 will be a range of methods for protecting bridge components. The methods will be field proven and of known cost and a first estimate of service life. Continued monitoring beyond the five years of the SHRP will be necessary to establish more reliable estimates of service life. This information not only has direct application to user agencies but is also required input to the decision model in Project 4-4. As noted in Section 2, a range of options is required to accommodate local conditions with respect to climate, user preferences and available expertise. Several options for protection are also required because of the need to select the optimum treatment for decks and substructure components which may be exhibiting differing degrees of deterioration.

The tasks have been structured to provide a balance between high risk endeavors and those which will result in a more pragmatic approach should the higher risk solution not prove entirely successful. Project 4-3 offers the potential for a significant breakthrough in the technology for protecting bridge components against corrosion and the potential will be pursued aggressively in the early phases of the project. It must also be recognized that, while desirable, it is not essential that a treatment arrest corrosion for the treatment to be cost-effective. It is only necessary that the treatment provide an extension of service life at a cost which is less than the cost of dealing with the consequences of undertaking no treatment. Most of the methods now in use (e.g. overlays, membranes, sealers) of protecting existing components do not stop corrosion but will often extend the service life of the component such that their use is cost-effective. Consequently, Project 4-3 will examine potential solutions which stop corrosion and also

techniques which may not stop corrosion but do provide a significant extension in service life.

Project 4-3 has also been developed with the philosophy that individual tasks should not develop entirely new materials or pieces of equipment. The reasons are those of budget, maximizing private sector involvement and encouraging complementary research programs discussed in Project 4-2. The statements that new materials and equipment will not be developed and that Project 4-3 has the potential for a significant breakthrough may appear contradictory and an explanation of the concept is in order. It is envisaged that the background study will examine the viability of different approaches to corrosion protection. The more promising approaches will be further examined in Task 4-3.3 or 4-3.4 to develop the approach to the stage where it is ready for field validation studies. This phase will evaluate products developed in the private sector (or through other research programs) and define the requirements for such products, thereby promoting further work in the private sector and creating the vehicle for user acceptance. Tasks 4-3.3 and 4-3.4 will also develop the procedures for using these new materials. If specialized equipment is needed to use the materials, the same philosophy will be applied.

Description

Project 4-3 has been formulated to address the following deficiencies with existing, conventional approaches to the protection of existing concrete components.

- Unknown life
- High cost
- Do not stop corrosion
- Long construction times
- Weather dependent
- Few options for components other than decks
- No methods of protecting prestressed concrete components

The tasks which have been defined to resolve these problems are listed below and are shown in Figure 7 in Section 7.

4-3.1 Concrete Removal and Surface Preparation

4-3.2 Background Studies

4-3.3 Post-Removal Protection

4-3.4 Protection and Rehabilitation Without Concrete Removal

4-3.5 Field Validation Studies

4-3.6 Rapid Rehabilitation and Protection of Bridge Decks

4-3.7 Improvements in Deck Joints

4-3.8 Service Life of Existing Methods of Protection

4-3.9 Manual

The most time-consuming and, frequently, the most expensive item in a bridge rehabilitation contract is the removal of concrete which is physically sound but is contaminated with chlorides. An inexpensive, rapid and environmentally acceptable method of concrete removal is needed which offers control of the depth of removal but which does not damage the concrete left in place. The last-mentioned requirement is important because some scarifiers are known to damage the surface concrete with the result that failures have occurred in the original concrete just below the bond line with the repair material. There are, however, a number of promising alternative pieces of removal equipment, especially water and shot-blasters, which have been introduced to the marketplace recently. There are also other approaches (e.g. vibration, lasers) which have not been fully investigated. These factors will be investigated in Task 4-3.1 which will lead to the identification of rapid, economical techniques for the removal of concrete.

The alternative to spending considerable effort and expense in removing sound, salt-contaminated concrete is to leave it in place. While the idea is attractive, this approach has had limited success in the past because, if conventional methods of protection are applied, the corrosion does not stop and may even be accelerated. There are a number of possible approaches such as oxygen and chloride scavengers, chemical dewatering and corrosion inhibitors which would allow the concrete to be left in place and these will be investigated in Task 4-3.2. These approaches have received no more than a cursory examination in the past. There is a relatively high risk factor associated with this task but, commensurate with the risk, is the potential for a significant breakthrough.

The more promising approaches identified in Task 4-3.2 will be the subject of further development in Tasks 4-3.3 and 4-3.4. Both tasks include a comparison of incremental advances in existing technology and the developments from Task 4-3.2..Task 4-3.3 will examine methods of protection which can be used in combination with the improved methods of concrete removal to provide potentially long-life and economical methods of protection. It is possible that Task 4-3.3 will result in the development of methods of protection which can be used advantageously in combination with cathodic protection. Should this be the case, the most promising methods will be considered in selecting the techniques to be evaluated in the field validation studies in sub-task 4-2.2,e. Task 4-3.4 has essentially the same goal as Task 4-3.3 but the scope of the task is limited to those techniques which can be used without prior concrete removal. This task will also be used to develop the methods needed in sub-task 4-2.1,c of protecting components against further ingress of chlorides following electrochemical treatment. The post-treatment, as opposed to concurrent treatment, methods are included in Task 4-3.4 because they are essential to the success of Project 4-3 and would be unfunded if Task 4-2.1 were to end after sub-task 4-2.1,a. Using the worst case scenario that Task 4-3.2 were to be unsuccessful, Tasks 4-3.3 and 4-3.4 would concentrate on the incremental rather than the major advances in technology. In any event, the two tasks will develop procedures to the stage where the most promising are

ready for field trials in Task 4-3.5. This task will establish the practicality, costs and service life of the various methods evaluated.

A separate task (4-3.6) has been defined to develop solutions where the prime requirement is for a rapid method of rehabilitation and protection. There are many bridge sites, especially in high traffic-volume locations where alternative routes do not exist and where the costs of traffic control and user delays are extremely high. In such cases, the owner may choose to apply a protective treatment which has a shorter service life than the maximum attainable if the construction time can be reduced significantly. It is anticipated that some of the techniques developed in Tasks 4-3.3 and 4-3.4 will also facilitate rapid construction, in which case they will be further developed in Task 4-3.6.

Much of the corrosion-induced distress in substructure components is the result of surface run-off containing deicing chemicals contacting the concrete because of leaking joints. Post-construction protection applies constraints which are not present in new designs. Task 4-3.7 will identify standard details which can be used with a greater assurance of achieving watertight expansion joints in rehabilitation contracts. Phase I of this task is largely a paper study supplemented by field observations. Phase II will only be possible if funding becomes available from Task 4-2.1 and involves field validation of the results of Phase I.

An important task in Project 4-3 which must be undertaken concurrently with the development of new technology is the determination of the costs and service life of existing techniques. These data are required so that the better methods of protection already in use can be included with the new methods in the decision model to be developed in Project 4-4. The task will be facilitated by the development of improved methods of inspection and assessment in Project 4-1.

The remaining task (4-3.9) involves documenting the results of the earlier tasks in a usable form. It is envisaged that the product of this task will be a manual which includes specifications and a description of construction and quality assurance procedures.

Task Statements

4-3.1 Concrete Removal and Surface Preparation

Objective: To evaluate concrete removal and surface preparation techniques and prepare specifications.

Scope: The study includes removal of both unsound concrete and sound, chloride-contaminated concrete on decks, beams and substructure components. It does not include component (e.g. deck) removal. Define requirements for preparing a surface to receive a protective treatment. Parameters specifically included are the speed of removal, control of depth, no damage to concrete left in place, ability to clean bars and concrete from around the bars and the procedures must be environmentally acceptable. Where a two stage approach is required to prepare a surface adequately (e.g. corroded bars) this should be defined. Evaluate equipment available (mainly scarifiers, shot-blasters and water jets). Also examine the possibility of using new approaches such as vibration or lasers. If such approaches prove promising it

is intended that equipment development would be done in the private sector. Determine if methods need to be used in conjunction with saw cutting to outline areas of removal. Prepare non-proprietary specifications to encourage further development and increase competition. The task includes small scale field tests.

Product: Non-proprietary specifications for rapid and economical methods of concrete removal and surface preparation which offer control of process.

4-3.2 Background Studies

Objective: To determine the feasibility of using new approaches to protecting salt-contaminated components against future corrosion.

Scope: This task will examine new approaches to protection and rehabilitation. The task will concentrate on techniques which allow chloride-contaminated concrete to remain in place. In addition, it will also examine techniques such as the use of inhibitors which could be used to prevent corrosion in a component where unsound concrete is removed (but some salt-contaminated concrete is left in place) prior to the application of a more conventional treatment such as patching or overlay. The first phase of the task is basic research at the microscopic level into the factors affecting pitting corrosion rates. This is necessary to determine the viability of the several approaches to preventing or reducing corrosion activity. Knowledge of the conditions at the anode which determine the rate of corrosion would afford the opportunity to ascertain how the conditions can be improved without adversely affecting conditions elsewhere in the structure. This could produce a major breakthrough in corrosion protection. Techniques to be evaluated include oxygen scavengers, chloride scavengers, corrosion inhibitors, chemical dewatering, and impregnation without drying. The main phase of the study comprises laboratory screening tests followed by exposure plot studies in various parts of the U.S. to determine the influence of different weather conditions. Year 3 is mainly for confirmation of results. The more promising approaches which can be used in conjunction with the partial removal of salt-contaminated concrete will be further developed in Task 4-3.3. Those which are used without prior concrete removal will be included in Task 4-3.4. The latter is especially important for the protection and rehabilitation of beams and vertical surfaces where concrete removal is very difficult.

Products:

i) Documentation.

ii) Identification of promising options for stopping or slowing corrosion without removing salt-contaminated concrete.

4-3.3 Post-Removal Protection

Objective: To develop methods of protecting existing concrete members against corrosion after partial or complete removal of salt-contaminated concrete.

Scope: The task must address the needs of decks, beams and substructure components constructed from both reinforced and prestressed concrete. The precise content of the study will be influenced by the early success of Task 4-3.2. If successful, the promising approaches will be developed to the stage where full scale field trials are possible. If Task 4-3.2 is not successful, Task 4-3.3 will concentrate on improvements in existing approaches. In either

case, the task will address two distinct conditions:

i) where all the salt-contaminated concrete is removed,

ii) where only unsound concrete is removed and sound, salt-contaminated concrete is left in place.

In case i), the emphasis should be on developing low permeability, or other corrosion resistant materials compatible with typical concrete substrates. The study includes consideration of the method of application. Candidates include polymer concretes, modified portland cement concretes, inhibitors, field-applied coatings to the exposed reinforcing steel, and surface treatments of plain or modified concretes, or combinations of the above.

Case ii) need only be considered if the cost of the corrosion-prevention treatment plus partial concrete removal is less than removing all the salt-contaminated concrete using the methods identified in Task 4-3.1. Candidate treatments include corrosion inhibitors and any promising developments identified in Task 4-3.2.

The task includes small scale field trials and shakedown testing prior to full-scale field validation tests of the most promising techniques in Task 4-3.5. These techniques should be examined to determine if any can be used advantageously in combination with any of the methods of cathodic protection developed in Project 4-2. If so, they should be included in sub-task 4-2.2,e

Products: i) Documentation.

ii) Potentially long life, economical options.

4-3.4 Protection and Rehabilitation Without Concrete Removal

Objective: To develop methods of preventing corrosion damage in salt-contaminated concrete components without concrete removal.

Scope: This task is also concerned with the protection of reinforced and prestressed concrete beams, decks. and substructure components. It consists of devising economical equipment and procedures for future full scale trials through small scale testing. The task includes consideration of the most promising techniques identified in Task 4-3.2 and other possible approaches (e.g. the deep impregnation of columns using sealants, inhibitors or polymers). The task is an essential intermediate stage between the laboratory and exposure plot testing in Task 4-3.2 and the full scale testing in Task 4-3.5. The findings have direct application to the post-treatment protection of components after electrochemical removal and will be used in the field validation studies in sub-task 4-2.1,d.

Products: i) Documentation.

ii) Potentially long life, economical options.

4-3.5 Field Validation Studies

Objective: To develop field-proven methods of protecting reinforced and prestressed concrete bridge components.

Scope: The task includes installations on decks, beams, piers, and abutments. No less than twelve test sites should be constructed using the following guidelines:

i) The combinations of treatments should maximize the information available. Duplicates of each combination should be installed.

ii) Marine and deicing salt exposures should be represented.

iii) The following components should be represented: reinforced concrete decks, beams and either piers or abutments; prestressed concrete decks and beams.

The budget assumes that the test sites will be included in other construction contracts and only the additional costs associated with the experimental nature of the installations will be assumed. The task includes the preparation of costs and estimate of service life. Monitoring for ten years beyond the 5 year period of this program will be required. The cost of this monitoring is not included in the budget for this task.

Product: Costs, service life and specifications for field-proven, economical options.

4-3.6 Rapid Rehabilitation and Protection of Bridge Decks

Objective: To develop and evaluate rapid techniques for deck protection, rehabilitation and replacement.

Scope: The task will develop methods of deck protection, rehabilitation and replacement which can be used where construction must be rapid. Such cases may arise due to an emergency or where the contract time must be kept to a minimum because of weather constraints or where traffic control costs and user delays are significant. The penalty for rapid construction may be a shorter service life though this may be acceptable to some agencies. Possible approaches are improved patching techniques, polymer concrete overlays and any rapid techniques identified in Tasks 4-3.3 and 4-3.4. The task includes the investigation of the corrosion protection and installation details of precast deck replacement methods, but not the structural design of the precast panels. Duplicate installations of at least three options for protection or rehabilitation are included. The replacement option is an engineering study and field trials are not required. Monitoring beyond the five year period of the program will be required to provide long-term data on service life. The task includes the development of specifications for the successful procedures, a determination of costs and an estimate of service life.

Product: Specifications, costs and service life of rapid techniques offering improved corrosion protection.

4-3.7 Improvements in Deck Joints

Objectives: Phase I, To develop design parameters, specifications and acceptance procedures for improved, sealed joint systems compatible with rehabilitation projects.

Phase II, To validate the findings of Phase I under field conditions.

Scope: The task is necessary because a significant proportion of beam and substructure deterioration is the result of leaking expansion joints. Phase I is largely a paper study, supplemented by field observations. It includes consideration of requirements for the joint seal (material properties, methods of attachment and replacement) as well as factors such as skew angle, end dam treatment and anchorage. The product of Phase I will be specifications and recommended acceptance procedures.

Phase II will only be undertaken if funding becomes available from Task 4-2.1. It consists of the installation and evaluation of joints using the specifications and acceptance procedures developed in Phase I. The documents will be modified as necessary in view of the field experiences.

Product: Specifications and acceptance procedures for long-life watertight expansion joints.

4-3.8 Service Life of Existing Methods of Protection

Objective: To evaluate the cost and the extension of service life which results from the use of existing protective treatments applied to salt-contaminated decks, beams, and substructure components.

Scope: The task will obtain data on the service life and cost of existing rehabilitation treatments (e.g. patches, sealants, membranes, overlays) when applied to salt-contaminated decks and substructure components. New construction is specifically excluded. Funds are limited for this activity which must therefore focus on a limited number of well-documented cases (condition before repair, construction procedures, quality of construction, performance history since rehabilitation) representing the range of repair techniques and widely varying geographical locations. The investigation includes both the service life of the repair and the effect on the service life of the overall structure, i.e. what effect did the method of repair have on corrosion elsewhere in the structure? Although the task begins in the first year of the program, year 1 will be spent identifying suitable sites to be monitored. As the products of Project 4-1 become available, these will be used to improve the estimates of service life. In order to obtain the maximum amount of information from this task, it should be continued beyond the time of the five-year program. The information is essential to ensure that the options for protection and rehabilitation include the best of the existing techniques and the most successful products of Projects 4-2 and 4-3.

Product: Cost and service life of existing methods.

4-3.9 Manual

Objective: To document the results of Project 4-3 for use by operating agencies.

Scope: A manual will be prepared which contains specifications and a description of the procedures recommended for future use and included in the decision model in Project 4-4. It will include a combination of those existing methods and the products of Project 4-3 shown to be cost-effective.

The manual must be suitable for use by personnel in operating agencies. Separate sections may be required for decks, beams, substructure elements, and prestressed concrete components.

Product: Specifications, procedures, and a first estimate of service life for field-proven, cost-effective methods of protection and rehabilitation.

PROJECT 4-4: METHODOLOGY FOR THE PROTECTION AND REHABILITATION OF EXISTING BRIDGE COMPONENTS

Concept of the Project

Project 4-4 will develop a decision model which will ensure a rational, cost-effective approach to the protection and rehabilitation of concrete bridge components.

The concept of Project 4-4 is that it will be the unifying element of TRA 4 and will combine the products of Projects 4-1, 4-2 and 4-3 into a single usable form. The final goal is to develop a decision model which is applicable at the project level and will select the most cost-effective treatment for any specific bridge. In order to do this, two items must be known:

i) the condition of the bridge and,
ii) the cost, service life and technical viability of the range of protective treatments from which the selection can be made.

The products of Project 4-1 will permit a reliable determination of the condition of the bridge. Projects 4-2 and 4-3 will develop a number of options for protecting bridge components for which the cost, service life and operational constraints are known. The model will then determine, on the basis of the existing condition and the service life of each treatment which is technically viable, the predicted future condition of the bridge for each of the options considered. This, in turn, leads to the identification of the option which has the minimum life-cycle cost.

Project 4-4 has been designed as a relatively small project which does not involve data collection except from literature studies. Rather, all the data needed to develop the decision model will become available from the other projects. The requirement for input from the other projects also means that Project 4-4 will not begin until Year 3 of the five year program. Except for calibration studies, which will be undertaken in cooperation with selected highway agencies, the project can be completed in an office environment.

While all bridge owners are faced with the question of when and how to protect existing bridges against corrosion for the minimum life-cycle costs, it is unrealistic to try and develop a decision model which will be applicable in all parts of the country. It is therefore essential that the model can be modified by the user to reflect local conditions and practices.

Description

Project 4-4 has been designed to develop a decision model for the protection of existing bridges within the constraints imposed by the range of climatic conditions in the United States and the different practices of operating agencies. The individual tasks which comprise Project 4-4 are

listed below and are illustrated, with the input required from other projects, in Figure 8 in Section 7.

4-4.1 Time-Deterioration Model

4-4.2 Methodology for the Decision Model

4-4.3 Other Constraints

4-4.4 Develop the Decision Model

4-4.5 Test the Decision Model

4-4.6 User's Handbook

The methods of determining the existing condition and predicting the future condition of bridge components identified in Project 4-1 and the information on service life of protective treatments from Projects 4-2 and 4-3 will be used to develop a Time-Deterioration model. This will enable a prediction to be made of the service life which would result from the application of a given technique to a component of a structure in known condition. Because of the limitations imposed by the five year time frame for the program, Task 4-4.1 must begin before all the required input will be available from Projects 4-1, 4-2 and 4-3. It will therefore be necessary to use an iterative approach beginning with the best information available at the inception of the task and modifying the product as additional information becomes available.

The methodology for the decision model will be developed in Task 4-4.2. Since this task does not require input from the other projects, theoretically it could begin in Year 1 of the program. However, it would be illogical to do so because it would be more effective to have the same researchers working on Tasks 4-4.1, 4-4.2 and 4-4.3 simultaneously to ensure compatibility between the products and a complete treatment of the subject matter.

Task 4-4.3 will identify and quantify the constraints which are not corrosion related but which influence the selection of the corrosion protection treatment. This includes such items as temperature limitations, duration of construction and expertise required. It also includes determining the effect of deterioration on the structural adequacy of a component. While this topic is outside the scope of TRA 4, the subject cannot be ignored because the decision model must ensure that the method of corrosion protection is compatible with the condition and remaining life of the structure. For example, it would not be acceptable to apply corrosion protection to members which are deficient for other reasons (e.g. cracks due to temperatures, shear or settlement) unless the deficiency is also corrected. The information for this aspect of Task 4-4.3 is expected to be developed in NCHRP Projects 10-15, 12-28(1), and 12-28(8).

Task 4-4.4 will take the products of Tasks 4-4.1, 4-4.2 and 4-4.3 and consolidate them in a comprehensive decision model. The range of options which will be included will be determined by the success of Project 4-2 and 4-3 in developing new techniques and in identifying treatments already in use which can be shown to be cost-effective. Although the text refers to a single

decision model, it is recognized that there may be two separate elements, one of which applies to decks, and the second to other components, because the options for treatment will be different. It is also possible that a third model, which is applicable to prestressed concrete components, will be required though this will depend on the progress of the research.

Task 4-4.5 involves calibration and testing of the model. This will be done by using data supplied by operating agencies representing a wide range of geographical locations and practices. As already noted, the model must be sufficiently flexible to permit user modification. Tasks 4-4.4 and 4-4.5 are viewed as a series of iterations until the research contractor and the participating agencies are satisfied with the model and its calibration. This is also seen as an important step in exposing the model and building user confidence and acceptance. The final step in Project 4-4 involves the development of a user's handbook for the decision model.

Task Statements

4-4.1 Time-Deterioration Model

Objective: To develop a model which can be used to predict the future condition of a component from a knowledge of its present condition and the life expectancy of the options for protection and rehabilitation.

Scope: The task will develop a time-deterioration model which satisfies the objective which has been defined. Separate elements may be needed to deal with bridge decks and with substructure components. The model will be developed using the data from Project 4-1 on assessing existing condition and predicting future condition. Information on rates of deterioration will be developed from the data collected in Task 4-3.8 and data available from operating agencies. It is anticipated that a probabalistic model will be required to account for the variances in the data. The options for protection and rehabilitation will be the cost-effective treatments identified in Projects 4-2 and 4-3. An iterative approach will be necessary because the task must begin before all the relevant tasks in Projects 4-1, 4-2 and 4-3 are complete. However, this could be an advantage because the work to develop the model will clearly identify the inputs which are required before the data collection phase is over.

Product: A time-deterioration model applicable to individual components.

4-4.2 Methodology for the Decision Model

Objective: To develop the theoretical framework for the decision model.

Scope: The task will build upon existing models for bridge rehabilitation (which are mainly applicable to decks) to develop the theoretical framework for the decision model to be assembled in Task 4-4.4. The methodology must be applicable to decks and substructures though separate elements may be required. The research contractor will need to determine whether the methodology should be based on decision tables or a computer program (or a combination of both). However, the final model must be sufficiently flexible to permit user modifications and the inclusion of optional parameters.

Product: A methodology for the decision model.

4-4.3 Other Constraints

Objective: To identify and make provision for user input of other parameters to be included in the decision model.

Scope: The task will identify constraints which influence the selection of the method of protection and rehabilitation. These include but are not limited to maintenance of traffic, future functional requirements (life and capacity), contractor skill required, specialized equipment, agency expertise, environmental limitations (temperature, precipitation), and duration of construction. A further important consideration is the effect of deterioration on the structural capacity of the component. This must be considered to ensure that the corrosion protection is not applied to components which are deficient for reasons other than corrosion-induced distress. It is assumed that the necessary information can be abstracted from the results of NCHRP Projects 10-15, 12-28(1), and 12-28(8). Should this not be the case, it is the intention that the model make provision for consideration of structural effects so that the findings could be incorporated at a later date.

Product: Identification of constraints to be included in the decision model.

4-4.4 Develop the Decision Model

Objective: To develop a decision model suitable for user agencies.

Scope: The task will take the products of Tasks 4-4.1, 4-4.2 and 4-4.3 together with the options for protection identified in Projects 4-2 and 4-3 to develop life-cycle cost decision model. Information on the costs and service life of the options for protection will also be provided from Projects 4-2 and 4-3. The decision model must ensure that protective treatments are not selected for application to components for which they are unsuitable. For example, some cathodic protection systems should not be applied to non-air entrained concrete components and some overlays are not suitable for application to components with moving cracks. A separate model, or models, may be required for decks and other components. Prestressed concrete components may also require separate treatment. The models must allow user modification to permit inclusion of local conditions and practices. It is the intention that the research contractor use values for costs and other parameters established from the other projects in TRA 4, from the literature, and from contact with operating agencies. These figures can then be changed by the user to reflect local conditions and can be updated as necessary.

Product: A decision model.

4-4.5 Test the Decision Model

Objective: To calibrate and validate the decision model under operating conditions.

Scope: The decision model will be tested and calibrated by working with a minimum of six agencies at the state and local level which are widely separated geographically and use a diverse range of protection and rehabilitation procedures. Modifications to the decision model will be made followed by further testing to ensure that the model is properly calibrated.

Product: A user-validated decision model.

4-4.6 User's Handbook

Objective: To prepare a user's handbook for the decision model.

Scope: The task will develop a user's handbook to support the decision model. It will include a full explanation of how modifications can be made by the user and how the model should be calibrated following modification.

Product: A user's handbook.

SECTION 5
RESULTS TO BE ACHIEVED

The specific products of each task and sub-task have been defined in Section 4. The research plan for TRA 4 was conceived to produce the single result of a decision model which agencies can use to determine when and how to protect existing bridge components against corrosion for the minimum life-cycle costs. The model will be applicable at the project rather than the network level, i.e. it will apply to individual bridges and will lead to the most appropriate protection strategy for the bridge under consideration. The model will be applicable to bridge decks, beams, and substructure components constructed from reinforced or prestressed concrete. It will determine, on the basis of the existing condition of the component and the service life of each candidate treatment, the condition of the bridge in future years if each treatment were to be applied. This, in turn, permits the selection of the option which leads to the minimum life-cycle costs for components. The model will permit user modifications to incorporate the range of options which an agency wishes to consider, and the service life and costs of those options under local conditions.

For the model to be usable, the bridge owner must have available:

i) reliable and economical means of determining the condition of bridge components,

ii) a range of options for protecting (and rehabilitating where necessary) the components.

Item (i) will be satisfied by the results of Project 4-1 which will provide a reliable and economical field method of assessing the condition of bridge components which form an integral part of the decision-making process for bridge protection. The specific results of Project 4-1 will be:

- A rate of corrosion device
- A method of detecting delamination in beams and substructure components
- A method of detecting deterioration in asphalt-covered deck slabs
- A procedure to determine the integrity of membranes
- A procedure to determine the presence and effectiveness of sealers

- A test method for the permeability of concrete
- A field test method for the chloride ion content of concrete
- A procedural manual detailing the test procedures and the significance and interpretation of the results

In all cases, the test procedures will be field proven and their cost will be known. Provision has also been made to include in the procedural manual, the results of research projects outside TRA 4, particularly with respect to the condition of prestressed components and automated methods of investigating the condition of exposed concrete bridge decks.

Item (ii), the range of options for protection, will be satisfied by the results of Projects 4-2 and 4-3. As previously noted in Sections 2 and 4, bridge owners require a range of options because of the range of components, location, climate and local conditions which may be encountered. For example, methods of protecting bridge decks may not be applicable to substructure components and vice versa; coatings suitable for marine pilings may be unsuitable for bridge piers in locations having a severe winter climate; temperatures may limit some forms of construction such as modified concrete to certain periods of the year; high traffic volumes may dictate that construction times be kept to a minimum; some forms of protection require specialized expertise that may not be available at some locations. Furthermore, agencies have developed preferences for certain approaches (exposed decks vs membranes and bituminous surfacings for example) which must be accommodated to ensure that the results of TRA 4 are applicable in all jurisdictions.

The results of Project 4-2 will be:

- Methods of removing chlorides from salt-contaminated components and protecting them against future corrosion
- Methods of cathodically protecting bridge components

In both cases, the research plan has been structured to ensure that new technology will be developed, validated under field conditions and the cost and service life determined. The presentation of the results is, however, as important as the development of the technology. Electrochemical techniques have not traditionally been used in the highway industry and are generally viewed as alien technology. Care has therefore been taken to ensure that user handbooks are prepared which are simple and explicit and assume no prior knowledge of the technology.

The results of Project 4-3, while also representing new technology, will have a greater similarity to more conventional approaches to bridge protection. The products will be:

- Methods which will offer a range of options for protecting:
  - decks
  - beams, piers and abutments
  - reinforced concrete components
  - prestressed concrete components
  - components in a marine environment

components in a deicing salt environment
components in high traffic volume locations
components in different climatic zones

- Deck joints which are compatible with post-construction protection

The results of Project 4-3 will also be field proven and of known cost and service life. Although there are not the same organizational barriers to the implementation of the results of Project 4-3 as apply to Project 4-2, the results will be carefully packaged in a format which meets the needs of user agencies.

The full economic benefits of the results of this research are difficult to establish because of the assumptions which must be made on the costs of corrosion. Fortunately, it does not require a very sophisticated analysis to demonstrate the cost-effectiveness of the research plan. As noted in Section 1, approximately $20 billion is required to correct corrosion-induced distress and the figure is increasing at almost $500 million annually. The $10 million research plan for TRA 4 represents 0.005% of the outstanding liability. The annual cost of $2 million per year for 5 years represents 0.4% of the annual costs of correcting corrosion damage in concrete components. The benefits can be expressed in another equally simple way. The replacement cost of a typical small to medium size bridge is approximately $500,000. Large bridges may cost a hundred times as much and more. If TRA 4 were to result in saving only one small to medium sized bridge in each state and the cost of protection and rehabilitation were as high as 50% of the replacement cost, the research would more than have paid for itself. Multiply these savings by the number of deficient bridges and the benefits are truly staggering.

TRA 4 will generate products which are immediately useful to operating agencies and its successful completion will result in the following benefits:

- Lower life-cycle costs for existing bridges
- Reduced operating costs
- Improved cost allocations
- Better information on the condition of bridges
- More timely protection and rehabilitation
- Fewer construction delays
- Fewer change orders and simpler construction administration
- New technology
- Improved bridge management methods.

SECTION 6
IMPLEMENTATION OF RESULTS

TRA 4 is unusual in that it deals only with the subject of the protection of existing bridges and this is an ongoing activity in all states. This is important because the implementation of results requires only that existing practices be modified rather than the introduction of entirely new activities. In other words, within each jurisdiction there already exists a group of individuals familiar with the problems of bridge protection, acutely aware of the limitations of current practices and eager to use improved technology. It is for these reasons that the implementing of results of TRA 4 should not be difficult.

An important concept in the development of the research plan which needs to be re-iterated is the involvement of the private sector in developing new materials and equipment. Tasks have been designed to evaluate materials and equipment and develop the acceptance criteria. In addition to maximizing what can be accomplished with the available budget, this approach has two distinct advantages:

i) It ensures that the needed products are available in the private sector

ii) Developments will continue beyond the five years of this program and this will encourage competition in the marketplace

The involvement of the private sector in the research program means that products will be available when needed and it will not be necessary to await the construction of new manufacturing plant before the results of the research can be implemented.

TRA 4 will, however, develop products for which the implementation will require special attention. These fall into two categories: those products which will be adopted by national standards-writing organizations and those for which training programs must be established.

The major source of standard documents will be the methods of test developed in Project 4-1. These will be written in a form suitable for adoption by ASTM and AASHTO, but the responsibility for guiding the documents through the committee processes will have to be assigned. As a minimum, standard test procedures for rate of corrosion, chloride ion content and concrete permeability will be developed and there may be others. The other "document" which will require special attention with respect to implementation is the decision model. One of the dangers in developing a new manual, decision table or computer program is that it soon becomes obsolete unless it is the subject of periodic review and updating. In the case of the decision

model, this problem has been kept to a minimum by making provision for user modification as local practices change and better information on costs and service life becomes available. However, the model will require a custodian and it is suggested that this be handled through the auspices of AASHTO.

Although the production of "user friendly" documents has been emphasized throughout the research plan, it is recognized that the implementation of research results does not begin until the findings and their impact is communicated to the appropriate personnel in each potential user agency. It will therefore be necessary to conduct seminars and training sessions to introduce the user handbooks and familiarize personnel with the technology developed in Projects 4-1, 4-2 and 4-3. It is likely that this can best be done through the development of audio-visual training aids. The development of the training aids and the conduct of the seminars and training sessions has not been included in the budget for TRA 4.

SECTION 7
SCHEDULE OF PROJECTS, TASKS AND SUB-TASKS

The titles, objectives and interaction of the four projects which comprise TRA 4 are illustrated in Figure 1. The schedule for each project, task and sub-task is contained in Figures 2 and 3. The flow charts for Project 4-1, the two tasks within Project 4-2, Project 4-3 and Project 4-4 are illustrated in Figures 4 to 8 respectively, and are self-explanatory. The budgets shown in Figures 4 to 8 are in thousands of dollars.

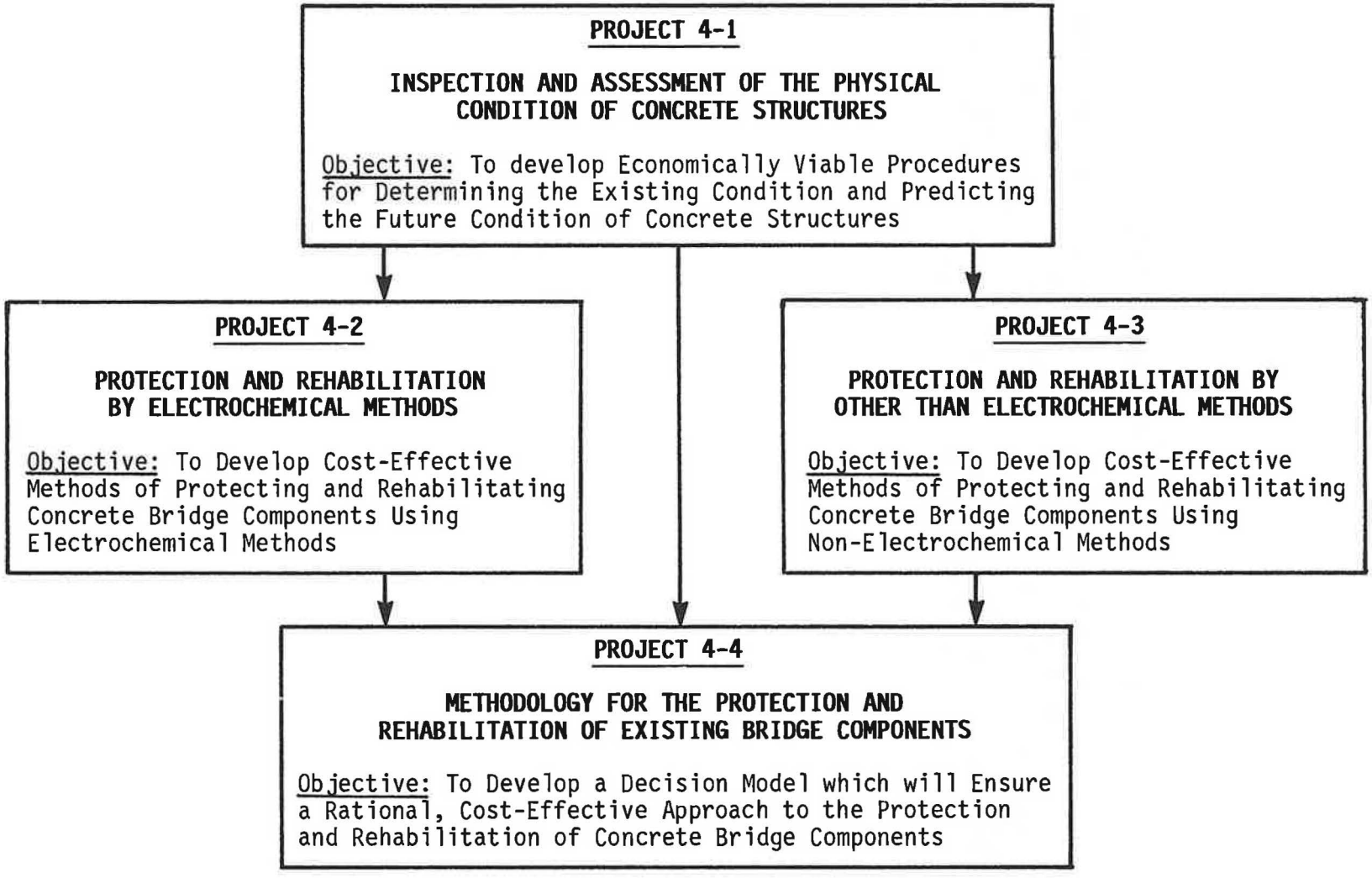
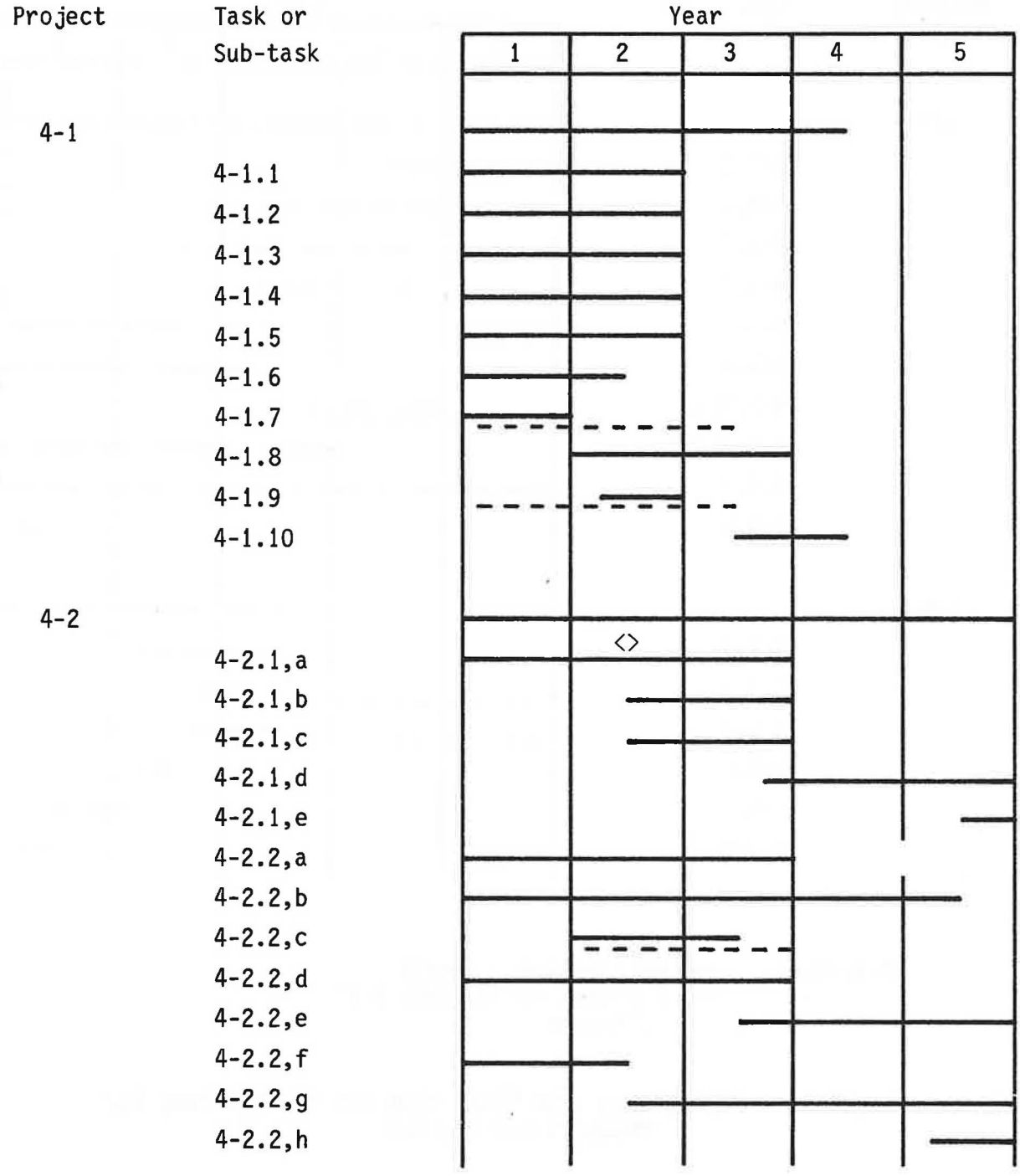
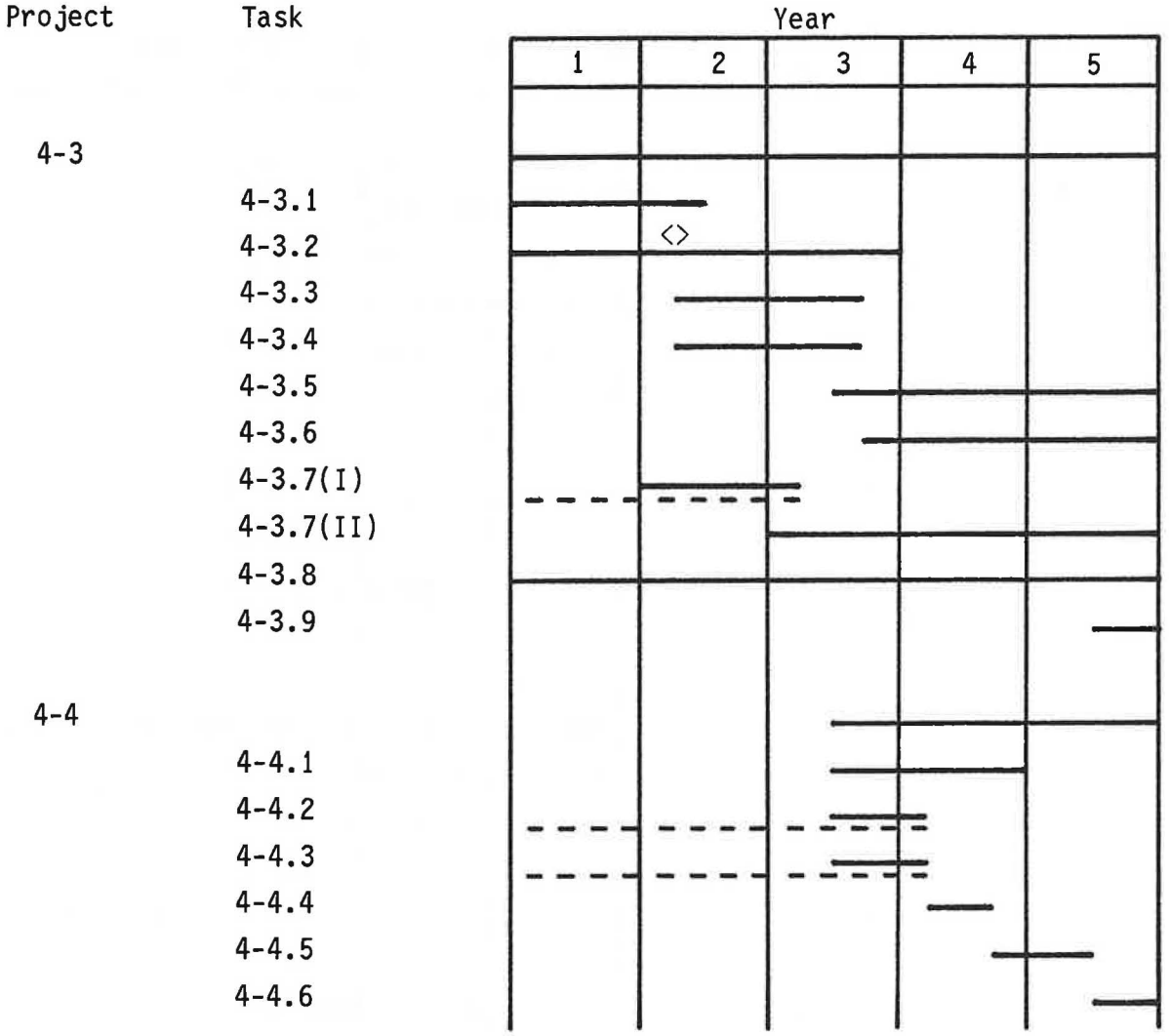


FIGURE 1: RESEARCH PROJECTS FOR TRA 4, BRIDGE COMPONENT PROTECTION



Footnotes: —— Recommended schedule
--- Earliest start, latest finish
<> Milestone

FIGURE 2: PROJECT AND TASK START YEAR AND ELAPSED TIME FOR PROJECTS 4-1 AND 4-2



Footnotes: ——— Recommended schedule
--- Earliest start, latest finish
<> Milestone

FIGURE 3: PROJECT AND TASK START YEAR AND ELAPSED TIME FOR PROJECTS 4-3 AND 4-4

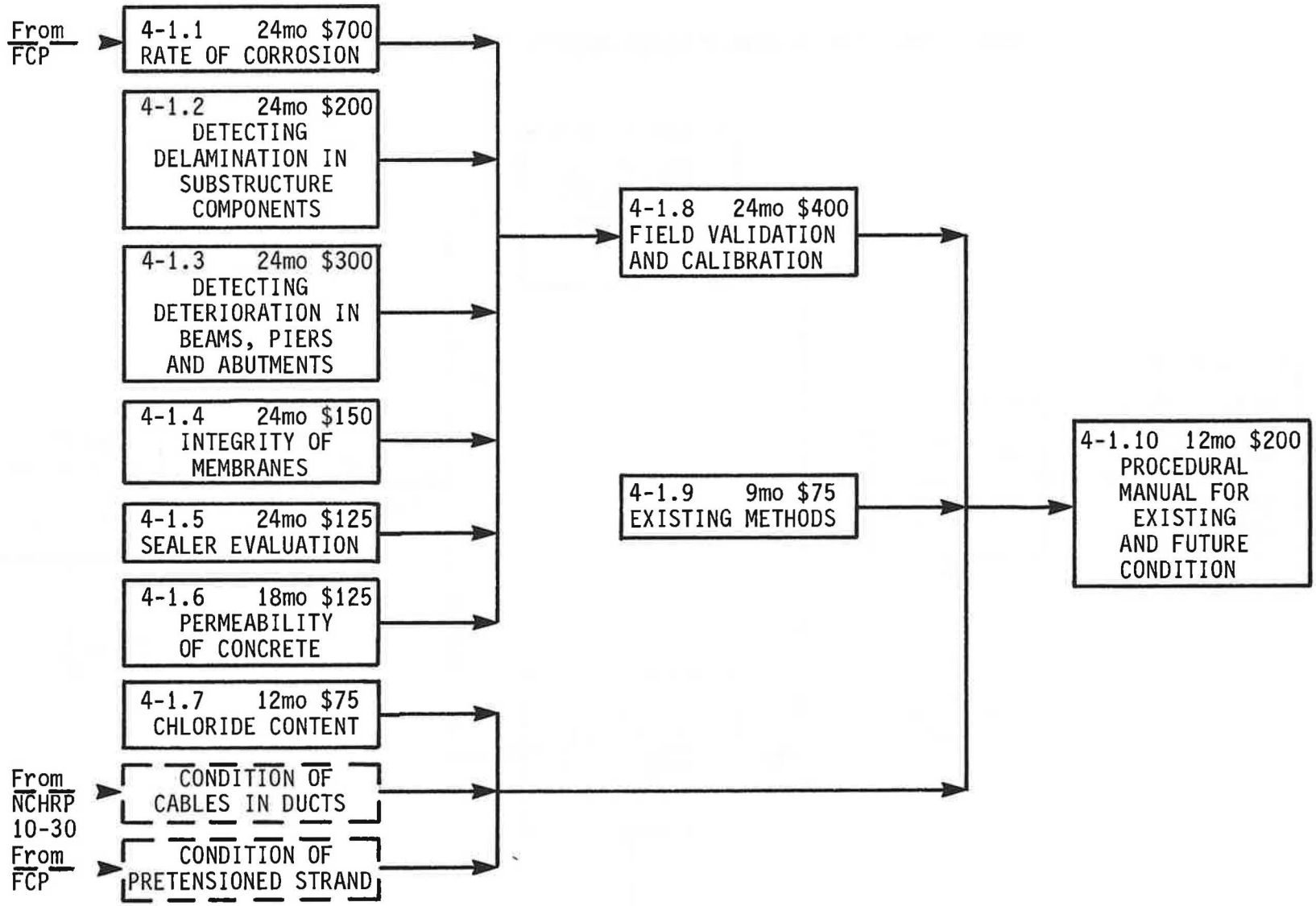


FIGURE 4: PROJECT 4-1, INSPECTION AND ASSESSMENT OF THE PHYSICAL CONDITION OF CONCRETE STRUCTURES

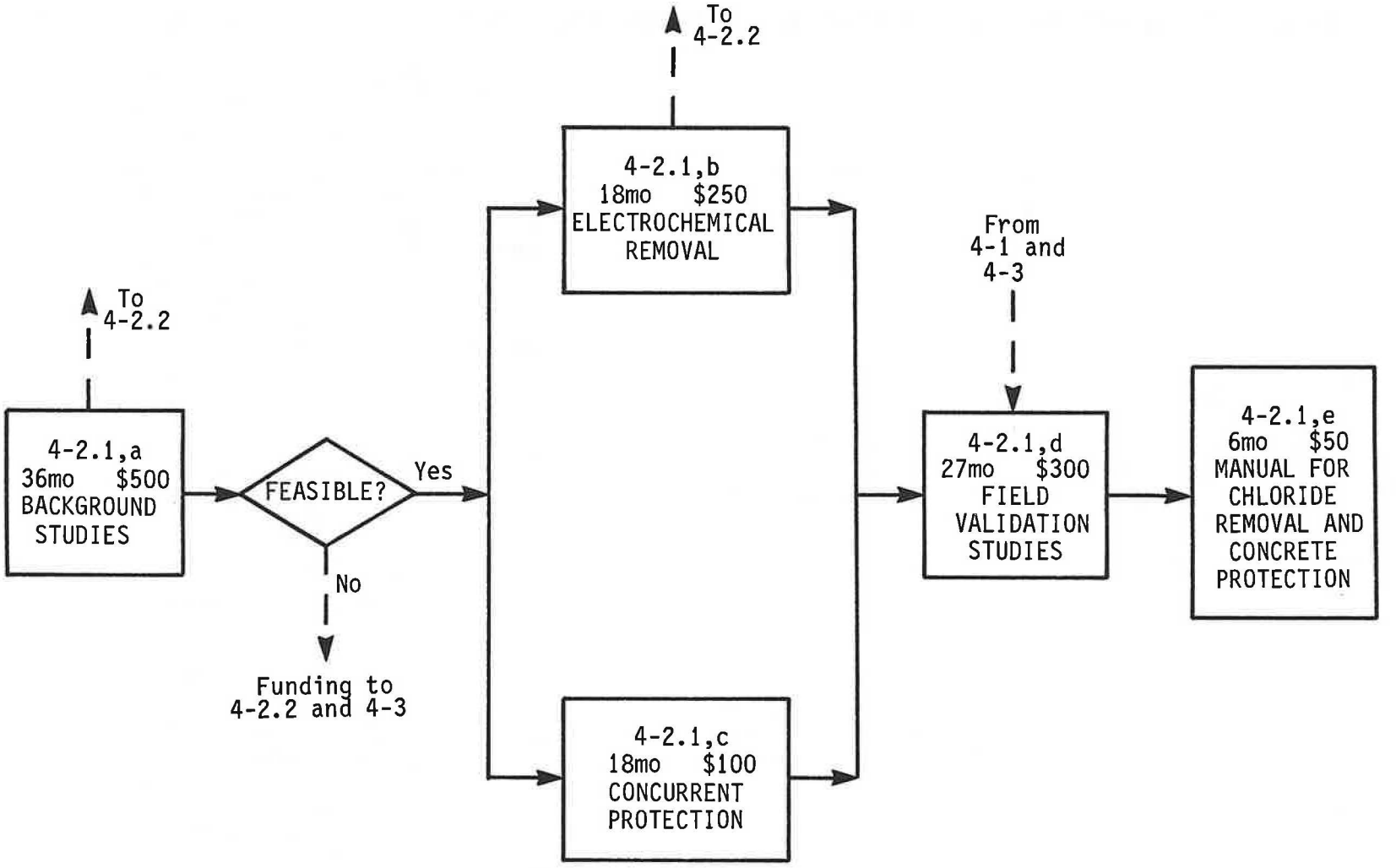


FIGURE 5: TASK 4-2.1, ELECTROCHEMICAL REMOVAL AND PROTECTION

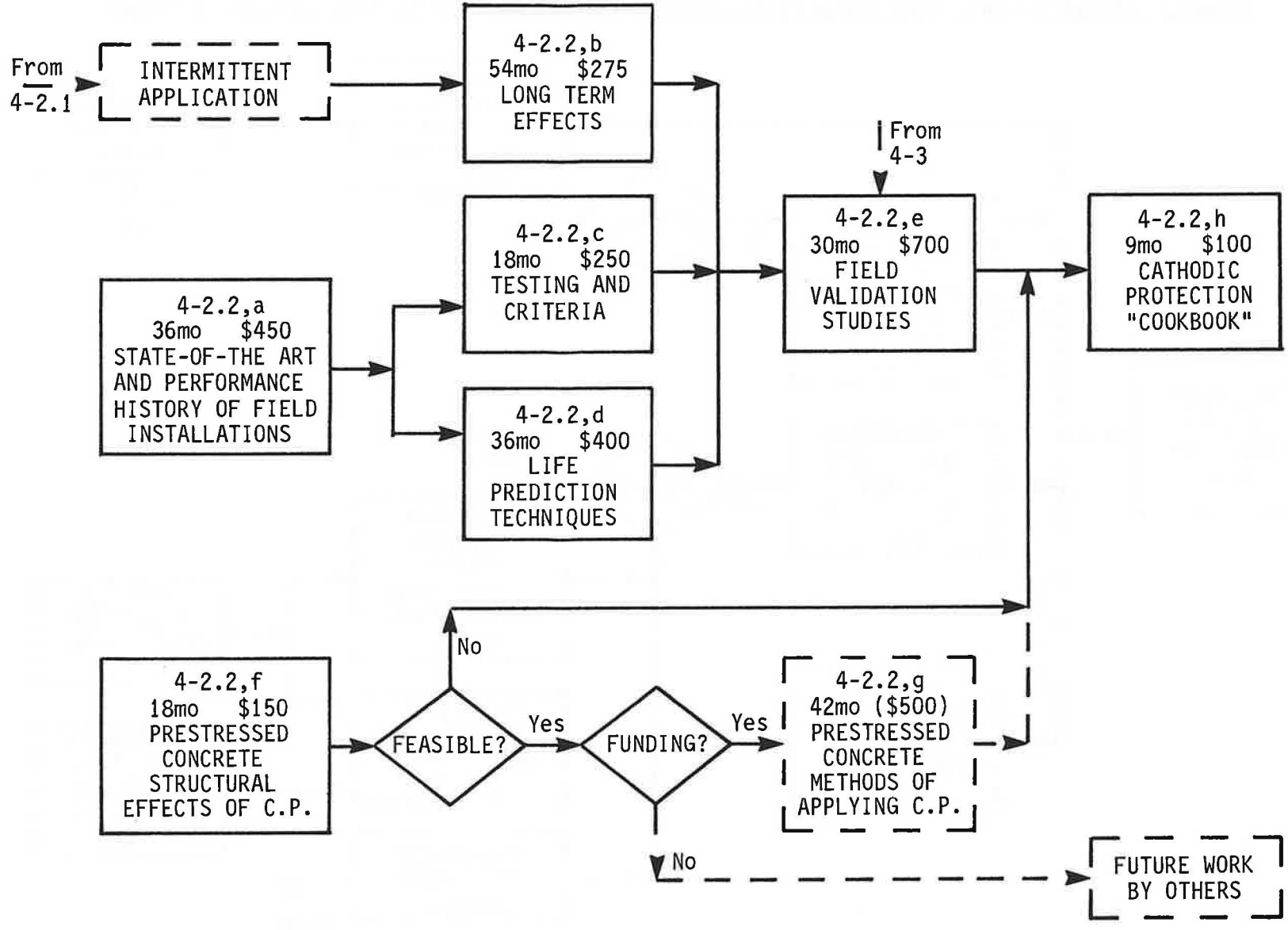


FIGURE 6: TASK 4-2.2, CATHODIC PROTECTION

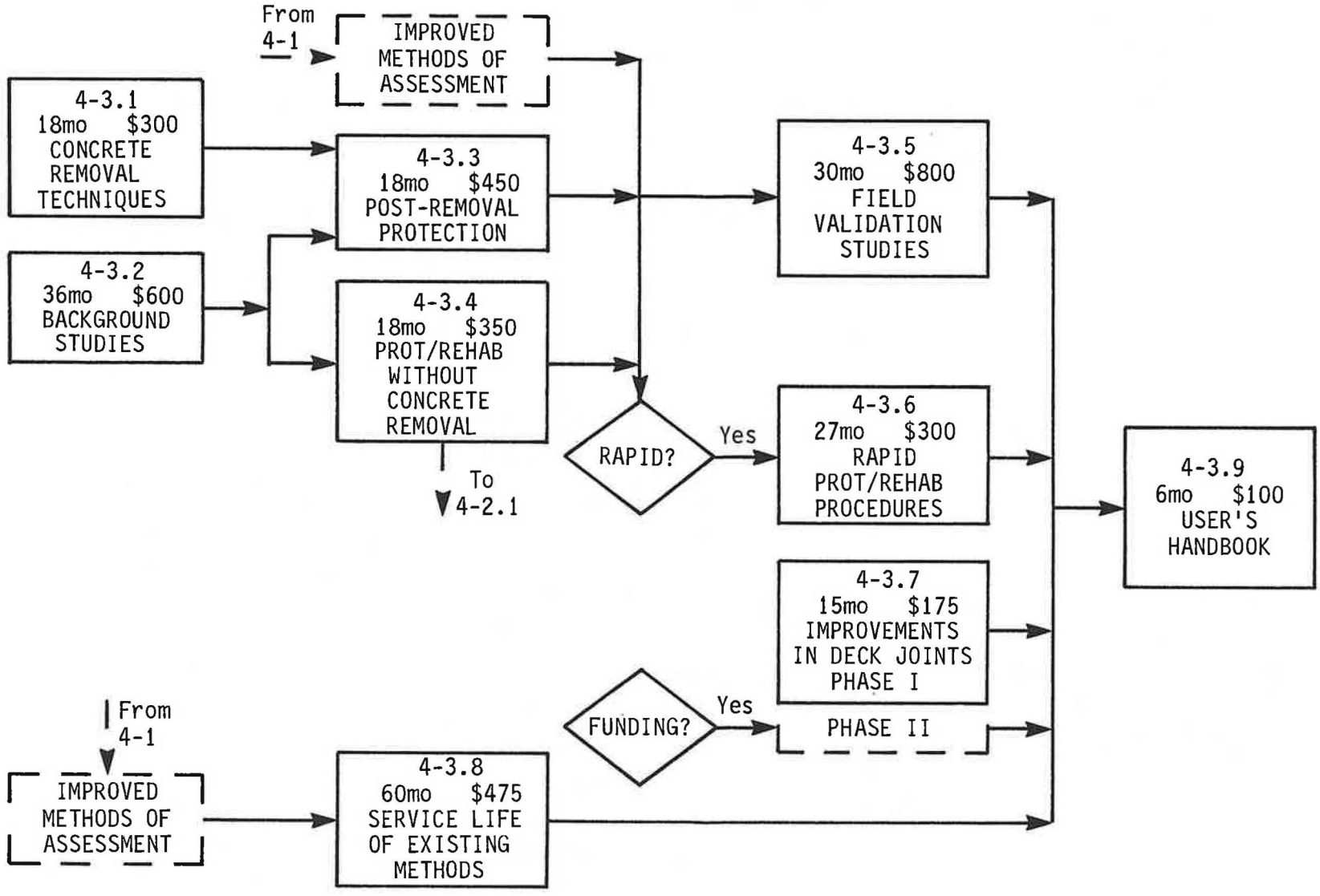


FIGURE 7: PROJECT 4-3, PROTECTION AND REHABILITATION BY OTHER THAN ELECTROCHEMICAL METHODS

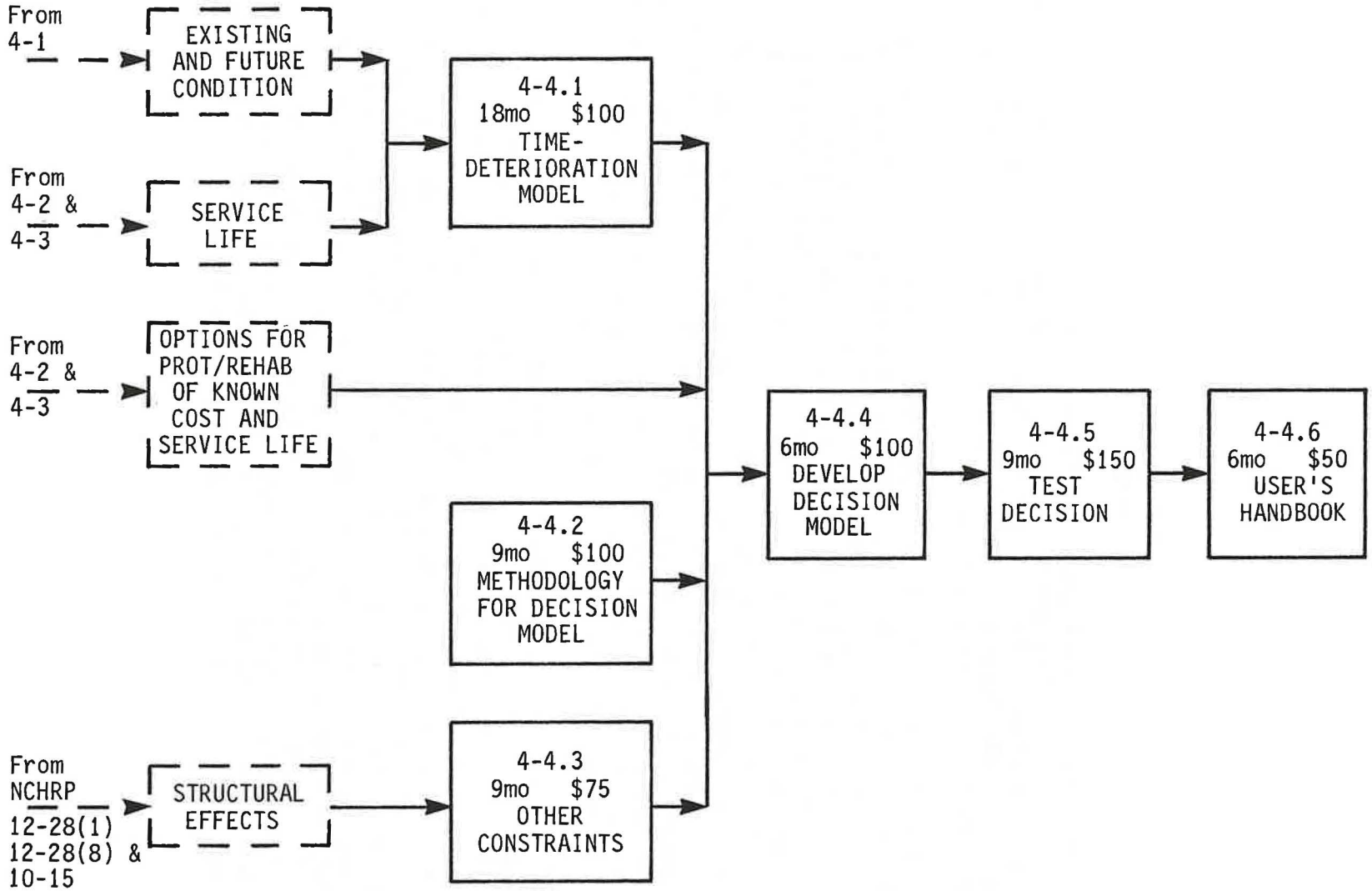


FIGURE 8: PROJECT 4-4, METHODOLOGY FOR PROTECTION AND REHABILITATION OF CONCRETE BRIDGE COMPONENTS

SECTION 8
BUDGET

The budget for each project, task and sub-task is given in Tables 1 and 2. The level of effort and the facilities necessary to complete each task and sub-task are shown in Tables 3 and 4. Four categories of personnel have been used in the development of Tables 3 and 4: Senior Professional, Research Associate, Technician, and Support Staff.

Facilities have also been divided into four categories: office, laboratory, exposure plot and field. Office studies require no special equipment or facilities beyond those normally found in an engineering office. Laboratory studies involve the physical testing of model specimens in simulated environments. Exposure plot studies, which are an intermediate stage between the laboratory and the field, involve testing large scale specimens (which may be custom fabricated or removed from service) under outdoor exposure conditions. Exposure plot studies may also include accelerated testing. Except for fundamental studies and initial screening tests, exposure plot studies are preferred to laboratory studies for corrosion research because of the difficulty of simulating the service environment in the laboratory. Field studies involve observing or monitoring the performance of full scale structures in the service environment.

The expertise required varies from task to task but includes civil engineering design and construction, corrosion engineering, materials, science, chemistry, electronics and electrical engineering and mathematical modelling. However, none of the tasks requires such specialized expertise or facilities that the ability to undertake the work could be jeopardized by the lack of a suitable contractor. There are several independent research organizations, universities and private sector consultants with the capability to undertake the work. The number of potential contractors is increased considerably if teams of smaller, specialized groups are formed. This position will not be significantly changed by the size of the contracts awarded. Consequently, specific recommendations for potential contractors have not been made because of the danger of alienating, or even discouraging, capable organizations or team members who may be overlooked.

TABLE I: TRA 4 - BUDGET, PROJECTS 4-1 AND 4-2

Project	Task or Sub-task	Year 1	2	3	4	5	Cost $,000
4-1							2,350
	4-1.1	350	350				700
	4-1.2	100	100				200
	4-1.3	125	175				300
	4-1.4	75	75				150
	4-1.5	75	50				125
	4-1.6	75	50				125
	4-1.7	75					75
	4-1.8		150	250			400
	4-1.9		75				75
	4-1.10			125	75		200
4-2							3,525
	4-2.1,a	200	200	100			500
	4-2.1,b		100	150			250
	4-2.1,c		50	50			100
	4-2.1,d			50	175	75	300
	4-2.1,e					50	50
	4-2.2,a	150	150	150			450
	4-2.2,b	75	75	50	50	25	275
	4-2.2,c		150	100			250
	4-2.2,d	150	150	100			400
	4-2.2,e			100	400	200	700
	4-2.2,f	100	50				150
	4-2.2,g		(75)	(125)	(175)	(175)	(500)
	4-2.2,h					100	100

Footnote: Sub-task 4-2.2,g will only be undertaken if Task 4-2.1 terminates after sub-task 4-2.1,a. The budget for this task is not included in the total

TABLE 2: TRA 4 - BUDGET, PROJECTS 4-3 AND 4-4

Project	Task	Year					Cost
		1	2	3	4	5	$,000
4-3							3,550
	4-3.1	150	150			300	
	4-3.2	300	200	100		600	
	4-3.3		225	225		450	
	4-3.4		175	175		350	
	4-3.5			175	450	175	800
	4-3.6			100	150	50	300
	4-3.7(I)		125	50			175
	4-3.7(II)			(50)	(100)	(50)	(200)
	4-3.8	75	100	100	100	100	475
	4-3.9					100	100
4-4							575
	4-4.1			25	75		100
	4-4.2			75	25		100
	4-4.3			50	25		75
	4-4.4				100		100
	4-4.5				50	100	150
	4-4.6					50	50
TRA 4							10,000

Footnote: Task 4-3.7 (Phase II) will only be undertaken if Task 4-2.1 terminates after sub-task 4-2.1,a. The budget for this task is not included in the total.

TABLE 3: TRA 4 - STAFFING & FACILITIES, PROJECTS 4-1 and 4-2

Project, Task or Sub-task	Man-Months[1] SP	RA	T	S	Other* $,000	Total $,000	Facilities[11]
4-1.1	12	33	48	4	60	700	O,L,E,F
4-1.2	2	12	12	1	20	200	O,L,F
4-1.3	4	12	18	2	70	300	O,L,F
4-1.4	1	10	9	1	15	150	L,F
4-1.5		9	8	1	15	125	L,E
4-1.6		9	8	1	15	125	L,E
4-1.7		5	4	1	10	75	L,F
4-1.8	6	12	27	3	100	400	F
4-1.9	1	7		1		75	O
4-1.10	9	6		3	25	200	O
4-1	35	115	134	18	330	2,350	
4-2.1,a	10	15	45	3	50	500	O,L,E
4-2.1,b	2	7	27	1	50	250	L,E
4-2.1,c	1	3	9	1	20	100	L,E
4-2.1,d	2	5	30	2	100	300	F
4-2.1,e	1	2			20	50	O
4-2.2,a	6	12	40	5	90	450	O,F
4-2.2,b	4	8	28	2	35	275	L,E,F
4-2.2,c	3	8	24	1	40	250	L,E
4-2.2,d	4	16	32	2	75	400	O,L,E
4-2.2,e	8	15	24	4	360	700	F
4-2.2,f	2	5	16	1	15	150	O,L
4-2.2,g	(4)	(12)	(32)	(4)	(200)	(500)	E,F
4-2.2,h	2	4		8	30	100	O
4-2	45	100	275	30	885	3,525	

Footnotes: * includes materials, equipment, construction and travel

(1) SP - Senior Professional
RA - Research Associate
T - Technician
S - Support Staff

(11) O - Office
L - Laboratory
E - Exposure Plot
F - Field

See also the footnote on Table 1

TABLE 4: TRA 4 - STAFFING & FACILITIES, PROJECTS 4-3 and 4-4

Project or Task	Man-Months[1] SP	RA	T	S	Other* $,000	Total $,000	Facilities[11]
4-3.1	2	16	20	2	50	300	L,E,F
4-3.2	18	18	36	4	60	600	O,L,E
4-3.3	6	17	36	2	75	450	L,E,F
4-3.4	4	12	32	2	60	350	L,E,F
4-3.5	3	16	32	4	480	800	F
4-3.6	3	12	18	2	80	300	L,E,F
4-3.7(I)	2	14		5	15	175	O,F
4-3.7(II)	(2)	(7)	(7)	(2)	(80)	(200)	F
4-3.8	5	20	30	5	100	475	O,F
4-3.9	2	4		3	30	100	O
4-3	45	129	204	29	950	3,550	
4-4.1	2	8		2		100	O
4-4.2	2	8		2		100	O
4-4.3	2	6				75	O
4-4.4	2	8		2		100	O
4-4.5	4	9		3	15	150	O,F
4-4.6	1	1		4	15	50	O
4-4	13	40		13	30	575	

Footnotes: * includes materials, equipment, construction and travel

(1) SP - Senior Professional
RA - Research Associate
T - Technician
S - Support Staff

(11) O - Office
L - Laboratory
E - Exposure Plot
F - Field

See also the footnote on Table 2

APPENDIX A
RELATED RESEARCH NOT FUNDED

The recommended research plan for TRA 4 addresses the problems associated with the corrosion protection of existing concrete bridge components. While it will have a significant impact within the defined scope, it would be a mistake to assume that TRA 4 will take care of all research needs concerning the performance of highway bridges. It would be an even greater mistake to reduce funding for bridge research because of the creation of this program. Consequently, it is useful to summarize those subject areas relating to the durability of highway bridges which are not included in TRA 4 so that these might be included in other research programs.

TRA 4 does not include work on:

i) steel or timber bridge components

ii) the design or analysis of concrete components

iii) the corrosion protection of new concrete components

iv) investigating the condition of prestressed concrete components

Unless funding becomes available from Task 4-2.1 (because the electrochemical removal of chlorides is found not to be feasible), the following two tasks cannot be accommodated within TRA 4:

4-2.2,g Prestressed Concrete - Methods of Applying Cathodic Protection

4-3.7, Phase II, Improvements in Deck Joints

The scope of these two studies is given in the text.

As noted in the report, TRA 4 does not include the development of entirely new materials or equipment. The philosophy which has been adopted is to develop applications, procedures and the acceptance criteria for new products. This approach deliberately encourages the development of materials and equipment in the private sector and in other research programs. Where the results of other research studies (especially NCHRP projects and other studies in the FCP) will be useful to accomplishing the goals of TRA 4, these have been identified in the text. However, other complementary studies are encouraged, even where there may appear to be some duplication, because of the inherent value in having different investigators pursue different approaches.

The subject of the corrosion protection of new concrete construction was included in the technical amplification phase of STRS. The following is a summary of the projects relating to new construction which were identified in the AASHTO Select Committee on Research Report "Strategic Transportation Research Study Technical Design" to the AASHTO Executive Committee.

i) Title: Long Term Effectiveness of Additives to Portland Cement Concrete in Corrosion Protection

Objective: To determine the long term effectiveness of additives such as corrosion inhibitors, silica fume, pozzolans and supplementary cementing materials in providing protection against corrosion.

ii) Title: Service Life of Deck Protective Systems

Objective: To quantify the benefits of single and multiple protection systems in common use (coated bars, overlays, membranes and penetrants) for corrosion protection under service conditions.

iii) Title: Effectiveness and Life of Coatings and Penetrants

Objective: To develop test methods and field data which quantify the effectiveness and life of coatings and penetrants in non-trafficked areas and under different service environments.

iv) Title: Concrete Cover Requirements for Large Bar Sizes

Objectives: To determine the relationships between the corrosion performance of black steel and concrete cover, bar size, spacing, laps, and steel stress in concrete columns.

v) Title: Corrosion Protection Requirements for Other Than Deck Elements

Objective: To develop guidelines for determining the exposure conditions under which different levels of corrosion protection of embedded steel should be provided.

vi) Title: Effect of Cracks on Protective Systems

Objective: To determine the effect of cracking of the concrete on the effectiveness of protective systems including one and two mats of coated reinforcement, corrosion inhibitors and specialty concretes.

vii) Title: Influence of Design on Rehabilitation

Objective: To develop design details which will permit economical rehabilitation of structures under traffic and to identify details which preclude or increase the cost of rehabilitation.

viii) Title: Effect of Deck Design on Service Life of Structures

Objective: To quantify the consequences of design parameters such as reinforcement percentage, deck thickness and flexibility on corrosion protection, overload capacity, load distribution, rate of deterioration and the fatigue life of girders.

ix) Title: Effect of Fatigue on Epoxy Coated Reinforcement

Objective: To determine the effect of fatigue under simulated service conditions of stress and environment on the corrosion and structural performance of epoxy coated reinforcing steel.

x) Title: Non-Corrosive Reinforcing Steel

Objective: To predict the corrosion performance of non-corrosive reinforcing steel and metallic coatings.

xi) Title: Alternative Approaches to Accommodating Surface Run-off

Objective: To examine and develop design concepts for drainage and joints (other than sealed joints) for preventing corrosion damage to bridge structures.

xii) Title: Fundamental Studies of Corrosion in Prestressed Concrete Members

Objective: To carry out fundamental studies of the corrosion of prestressing steel used in the U.S. and to study the interaction (with respect to corrosion) between the various metallic components in a typical member.

xiii) Title: Performance and Corrosion Protection of Pretensioned Concrete Girders

Objective: To document the condition of pretensioned beams in adverse service environments and to develop protective treatments for the ends of such beams in both new construction and rehabilitation.

xiv) Title: Corrosion Protection Systems for Prestressed Concrete Construction

Objective: To evaluate design considerations, non-metallically coated strand, non-metallic and coated ducts, specialty concretes and grouts for their effectiveness in preventing corrosion of pretensioned and post-tensioned members including segmental construction.

BIBLIOGRAPHY

The following is not intended to be an exhaustive list of references on the subject matter pertaining to TRA 4. The intention has been to select a few key references, concentrating on those which have been published recently and those which themselves contain an extensive bibliography or reference list.

General

"America's Highways, Accelerating the Search for Innovation", Special Report 202, Transportation Research Board, 1984.

"Strategic Transportation Research Study Technical Design", AASHTO Select Committee on Research Report to the AASHTO Executive Committee, May 7, 1984.

"Durability of Concrete Bridge Decks", NCHRP Synthesis of Highway Practice 57, 1979, 60pp.

"ACI Committee 222 "Corrosion of Metals in Concrete", J. American Concrete Institute, Vol. 82, No. 1, 1985, pp3-32.

Project 4-1

"Detecting Defects and Deterioration in Highway Structures" NCHRP Synthesis of Highway Practice 118, 1985, 52pp.

"Bridge Inspection", Organization for Economic Cooperation and Development, Paris, 1976, 132pp.

Hansson, C.M., "Comments on Electrochemical Measurements of the Rate of Corrosion of Steel in Concrete", Cement and Concrete Ressearch, Vol. 14, 1984, pp574-584.

Escalante, E., Cohen, M. and Kahn, A.H., "Measuring the Corrosion Rate of Reinforcing Steel in Concrete", Report No. FHWA-RD-84-077, FHWA, 1984, 86pp.

Joyce, R.P., "Rapid Non-Destructive Delamination Detection", Report No. FHWA-RD-85-051, 1985.

Malhotra, V.M., "Testing Hardened Concrete: Nondestructive Methods", ACI Monograph No. 9, American Concrete Institute, 1976, 188pp.

Manning, D.G. and Holt, F.B., "Detecting Deterioration in Asphalt-Covered Bridge Decks," Transp. Res. Record No. 899, 1983, pp10-20.

Morrison, G.L. et al., "Rapid In-Situ Determination of Chloride Ion in Portland Cement Concrete Bridge Decks" Report No. FHWA-KS-RD-75-2, 1976, 39pp.

Price, W.I.J., "Highway Bridge Inspection: Principles and Practices in Europe", IABSE Reports, Vol. 38, 1982, pp15-29.

Stowe, R.L. and Thornton, H.T. Jr., "Engineering Condition Survey of Concrete in Service", Tech. Rep. REMR-CS-1, U.S. Army Engineer Waterways Experiment Station, U.S. Army Corps of Engineers, 1984, 109pp.

Vassie, P.R., "A Survey of Site Tests for the Assessment of Corrosion in Reinforced Concrete", LR 953, Transport and Road Res. Lab., England, 1980, 33pp.

Whiting, D., "In-Situ Measurement of the Permeability of Concrete to Chloride Ions", In-Situ/Nondestructive Testing of Concrete, American Concrete Institute SP-82, 1984, pp501-524.

Project 4-2

Proceedings of the Conference on Cathodic Protection of Reinforced Concrete Bridge Decks, San Antonio, Texas, February 12-13, 1985, National Association of Corrosion Engineers.

Fontana, J.J., Reams, W. and Elling, B.,"Sprayable Electrically Conductive Polymer Concrete Overlays" Report No. FHWA-RD-85-102, 27pp.

Morrison, G.L. et al., "Chloride Removal and Monomer Impregnation of Bridge Deck Concrete by Electro-Osmosis", Rep. No. FHWA-KS-RD-74-1, FHWA, 1976, 41pp.

Perenchio, W.F., Langren, J.R., West, R.E. and Clear, K.C. "Cathodic Protection of Concrete Bridge Substructure" NCHRP Report 278, 1985, 60pp.

Schell, H.C. and Manning, D.G., "Evaluating the Performance of Cathodic Protection Systems on Reinforced Concrete Bridge Substructures", Materials Performance, Vol. 24, No. 7, 1985, pp18-25.

Slater, J.E., Lankard, D.R. and Moreland, P.J., "Electrochemical Removal of Chlorides from Concrete Bridge Decks", Transp. Res. Record No. 604, 1976, pp6-15.

Stratfull, R.F., "Criteria for the Cathodic Protection of Bridge Decks" Corrosion of Reinforcement in Concrete Construction, Ellis Horwood, Chichester, England, 1983, pp287-332.

Stratfull, R.F., Noel, E.C. and Seyoum K., "Evaluation of Cathodic Protection (CP) Criteria for the Rehabilitation of Bridge Decks" Report No. FHWA-RD-80-04, 1983, 75pp.

Vrable, J.B., Cathodic Protection for Reinforced Concrete Bridge Decks - Laboratory Phase", NCHRP Report 180, 1977, 135pp.

Webster, R., Fontana, J.J. and Reams, W., "Electrically Conductive Polymer Concrete Overlays" Report No. FHWA-RD-84-033, 96pp.

Whiting, D. and Stark, D., "Galvanic Cathodic Protection for Reinforced Concrete Bridge Decks - Field Evaluation, NCHRP Report 234, 1981, 63pp.

Project 4-3

Chamberlin, W.P., "Long Term Evaluation of Unprotected Concrete Bridge Decks", Res. Rep. No 128, New York State DOT, 1985, 45pp.

Chamberlin, W.P., Irwin, R.J. and Amsler, D.E., "Waterproofing Membranes for Bridge Deck Rehabilitation", Rep. No. FHWA-NY-77-59-1, 1977, 43pp.

Clear, K.C. and Forster, S.W., "Internally Sealed Concrete - Material Characterization and Heat Treating Studies", Rep. No. FHWA-RD-77-16, 1977, 73pp.

Fincher, H.E., "Final Report on Bridge Deck Protection Systems Category II, Experimental Features", Indiana Dept. of Highways, 1983, 218pp.

Griffin, D.F., "Corrosion Inhibitors for Reinforced Concrete", Corrosion of Metals in Concrete, SP-49, American Concrete Institute, 1975, pp95-102.

Hay, R.E., "The Bridge Deck Problem - An Analysis of Potential Solutions", Public Roads, Vol. 39, No. 4, 1976, pp142-147.

Kuhlmann, L.A., "Performance History of Latex-Modified Concrete Overlays," American Concrete Institute SP69, 1983, pp123-144.

Kukacka, L.E., Fontana, J. and Steinberg, M., "Polymer Concrete for Repairing Deteriorated Bridge Decks", Transp. Res. Record No. 542, 1975, pp20-28.

Linfante, A., "Performance Specification for Bridge Deck Joint-Sealing Systems" Transp. Res. Record No. 899, 1983, pp61-64.

Manning, D.G. and Witecki, A.A., "Requirements for Deck Joints in Highway Structures", Joint Sealing and Bearing Systems for Concrete Structures, American Concrete Institute SP-70, Vol. 1, 1981, pp291-309.

Manson, J.A. et al., "Long-Term Rehabilitation of Salt-Contaminated Bridge Decks", NCHRP Report 257, 1983, 32pp.

O'Connor, E.J., "Iowa Method of Partial-Depth Portland Cement Resurfacing of Bridge Decks", ASTM STP 629, 1977, pp116-123.

Pasko, T.J. Jr., Virmani, Y.P. and Jones, W.R., "Polymer Concrete Used in Redecking a Major Bridge Deck", Report No. FHWA-RD-85-079, 1985, 55pp.

Sprinkel, M.M., "Overview of Latex Modified Concrete Overlays", Report No. VHTRC 85-R1, Virginia Highway and Transportation Research Council, 1984, 39pp.

Virmani, Y.P., Clear, K.C. and Pasko, T.J., Jr., "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, Vol 5: Calcium Nitrite Admixture or Epoxy-Coated Reinforcing Bars as Corrosion Protection Systems", Rep. No. FHWA-RD-83-012, 1983, 71pp.

Project 4-4

"Bridge Deck Repairs", NCHRP Digest 85, 1976, 22pp.

Cady, P.D., "Bridge Deck Rehabilitation Decision Making", Transp. Res. Record No. 1035, 1985.

Clear, K.C., "Evaluation of Portland Cement Concrete for Permanent Bridge Deck Repair" Rep. No. FHWA-RD-74-5, 1974, 44pp.

Manning, D.G. and Ryell, J., "Decision Criteria for the Rehabilitation of Concrete Bridge Decks", Transp. Res. Record No. 762, 1980, pp1-9.

Shirole, A.M. and Hill, J.J., "Systems Approach to Bridge Structure Rehabilitation or Replacement Decision Making", Transp. Res. Record No. 664, 1978, pp22-31.

Tracy, R.G., "Priority Assignment for Bridge Deck Repairs", Transp. Res. Record No. 727, 1979, pp50-55.

TECHNICAL RESEARCH AREA 5
CEMENT AND CONCRETE

Prepared for:
NCHRP Project Number 20-20(7)
Pre-Implementation Activities for the
Strategic Highway Research Program (SHRP)

January 1986

Prepared by

CONSTRUCTION TECHNOLOGY LABORATORIES
A Division of the Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077

TABLE OF CONTENTS

		Page
	LIST OF FIGURES	TRA 5-ii
	LIST OF TABLES	TRA 5-iii
	ABSTRACT	TRA 5-iv
	SUMMARY	TRA 5-v
	ACKNOWLEDGEMENTS	TRA 5-vi
SECTION 1	STATEMENT OF THE PROBLEM	TRA 5-1
SECTION 2	GOALS AND OBJECTIVES OF THE PLAN	TRA 5-3
SECTION 3	FORMULATION OF THE PLAN	TRA 5-9
SECTION 4	RECOMMENDED RESEARCH PLAN	TRA 5-13
SECTION 5	RESULTS TO BE ACHIEVED	TRA 5-49
SECTION 6	IMPLEMENTATION OF RESULTS	TRA 5-54
SECTION 7	SCHEDULE OF PROJECTS AND TASKS	TRA 5-56
SECTION 8	BUDGET	TRA 5-59
APPENDIX A	OTHER RESEARCH PROJECTS CONSIDERED	TRA 5-61
BIBLIOGRAPHY		TRA 5-64

LIST OF FIGURES

Figure 1 - TRA 5 Flow Chart

Figure 2 - Project 5-1 Flow Chart

Figure 3 - Project 5-2 Flow Chart

Figure 4 - Project 5-3 Flow Chart

Figure 5 - Project 5-4 Flow Chart

Figure 6 - Schedule of Projects and Tasks

LIST OF TABLES

Table 1 - Budgets

ABSTRACT

Presents a research plan for Technical Research Area 5, Cement and Concrete Study, one of six study areas of the Strategic Highway Research Plan. This plan for cement and concrete research includes projects in four major areas: (1) chemistry and physics of cement and concrete, (2) durability of concrete, (3) quality control and condition analysis through nondestructive testing, and (4) mechanical behavior of concrete. The plan covers a five-year period, at an estimated cost of $12,000,000, including some provision for monitoring performance of test sections beyond the five-year period.

SUMMARY

TRA 5, Cement and Concrete Study, is a research plan directed to two basic objectives: (1) develop a better understanding of the mechanisms of setting and strength development and the chemical processes during hydration of the cementitious component, and (2) improve the production, placement, quality control, nondestructive testing, and durability of concrete. Four major projects, subdivided into 16 tasks, have been developed as follows:

- Chemistry and Physics of Cement and Concrete
- Durability of Concrete
- Quality Control and Condition Analysis Through Non-destructive Testing
- Mechanical Behavior of Concrete

The plan provides a detailed description of the objectives set for each task. Primary emphasis is given to:

- Prediction and control of microstructure of hydrated paste to produce significant decreases in permeability, thus enhancing durability
- Better understanding of alkali-aggregate reaction to extend life of existing afflicted pavements and new pavements
- Treating existing pavements suffering from D-cracking and alkali-aggregate reaction to extend service life
- More reliable tests for aggregate durability
- Developing an expert system for diagnosis and prediction of performance
- Developing a Q/A system for acceptability
- Developing non-destructive tests for in-place permeability of hardened concrete and air void parameters of freshly-mixed concrete
- Developing a means for measuring the residual functional capability of existing pavements

- Providing data on fatigue and strain capacity of high strength concretes, effect of additional cementing materials on performance, and possible use of combinations of fiber types in concrete

The report includes recommendations for the implementation of the results achieved in the conduct of the program.

ACKNOWLEDGEMENTS

The Construction Technology Laboratories, a Division of the Portland Cement Association, acknowledges the work of the following staff members in the development and preparation of the research plan for SHRP TRA-5, Cement and Concrete Study:

Principal Investigator
Paul Klieger, Consultant, R&D/CTL

Co-Investigators
Dr. Richard Helmuth, Principal Research Consultant,
Chemical/Physical Research Department
David Stark, Manager, Concrete Materials Research Section
Dr. David Whiting, Senior Research Engineer,
Concrete Materials Research Section
Steven Gebler, Senior Research Engineer,
Concrete Materials Research Section

SECTION 1
TRA 5 - STATEMENT OF THE PROBLEM

GENERAL OVERVIEW OF PROBLEM

TRB Special Report 202, "America's Highways - Accelerating the Search for Innovation," contained concise statements with respect to the need for the development of a research plan designed to improve and extend the service life of concrete pavement systems. The following quote from Special Report 202 typifies the concerns:

> "Deterioration of concrete is a problem in highway bridge decks, pier caps, and other exposed structural components. Research is needed to improve the flexural strength, volume stability, resistance to sulfate, and thermal expansion of concrete pavements. Research that leads to increased durability of concrete in the highway environment can provide savings to local, state, and federal agencies that fund street and highway programs. The Federal Highway Administration (FHWA) estimates an annual accruing bridge deficiency (in 1980 dollars) of $2.3 billion and a total expenditure for bridge repair and replacement from 1981 through 2000 of $102.6 billion as shown in Table 15 (3). Reducing the cost of the highway bridge program by 1 percent as a result of cement and concrete research would amount to a saving of more than $1 billion during the next 20 years."

Although there was a recognition of the need for research to resolve the problems, the report recognized that private research efforts were inadequate for a number of reasons. The following statement from Special Report 202 characterizes this situation:

> "Because cement and concrete are commodities, there is little incentive for private companies to invest in long-range research to improve them. When compared with other nations, the U.S. investment in cement and concrete research is low and declining. The concrete construction industry is not on the Securities and Exchange Commission list of firms that spend 1 percent or more of revenues on R&D. Cement industry records show that expenditures for research are less than 0.03 percent of gross sales, which is even less than the 0.15 percent spent for R&D by the total highway industry. A recent comparison of published papers and presentations at the International Congress on the Chemistry of Cement shows that those for Japan and the Soviet Union outnumbered those for the United States. These trends show not only neglect of needed research in the United States but strong indications that the position of leadership in cement and

concrete technology is being usurped by other nations. The loss of technological leadership is generally followed by a loss of market position as the steel, electronic, and automotive industries well understand.... This important industry needs a significant national research program."

THE BASIC PROBLEM

The basic problem, in short, is the deterioration of concrete exposed to the severe environments in our concrete pavement system at a rate which results in an unanticipated shortening of service life.

Means must be found to enhance the durability of concrete and thus extend its service life. It appears that research efforts by the cement and concrete industry of a magnitude sufficient to resolve these problems is unlikely to be undertaken in the near future. Special Report 202 recognizes this barrier in the following statement:

> "Although the needed research program is not large in the context of the industry it serves, it represents a requirement greater than any previously met by the cement and concrete industry. The industry is unlikely to make a commitment for a large, integrated research effort specifically addressing the improvement of quality, testing, and durability of cement and concrete. It faces major needs for plant modernization that challenge available resources; it realizes a low rate of return on investment compared with other industries; it has no tax or market incentives to invest in product improvements when existing products meet market-place specifications and when low-bid procurement characterizes the major public works buyer.
>
> If cement and concrete technology is to advance in the United States in keeping with the increasing challenges in the highway industry, a large commitment of public funds to a national research program will be required."

THE NEED

There is a need, therefore, to develop a program of research in cement and concrete which will resolve, within the constraints of time and funds available, the major performance problems currently being faced. The program needs to have as its primary goal the development of an increased understanding of the chemistry of cement hydration, of the properties of concrete, and of the performance of concrete in the highway environment. Such an understanding should lead to significant increases in service life.

SECTION 2
TRA 5 - GOALS AND OBJECTIVES OF THE PLAN

PRIMARY GOAL

The primary goal of the research plan for cement and concrete is to develop a sufficient increase in the understanding of the chemistry of cement hydration, of the properties of concrete, and of the performance of concrete in the highway environment which will result in the means necessary to increase service life.

Basic Objectives of Plan

To achieve the primary goal, the plan includes the following basic objectives:

1. Develop a better understanding of the mechanisms of setting and strength development and the chemical processes during hydration of the cementitious component of the concrete.

2. Improve the production, placement, quality control, nondestructive testing, and durability of concrete.

Achieving the first basic objective should provide a basis for predicting, controlling, and changing the performance of the cementitious system in a manner required by the anticipated environment, i.e., the total pavement system and its location. The end results of such an effort should provide the ability to reduce the permeability of the paste to the point where water and other potentially aggressive liquids have difficulty in entering and enhance the bond between paste and aggregate thus enhancing strength and other physical properties.

The second objective deals with the general effort to ensure increased durability of concrete, with emphasis on the development of techniques to enhance durability in aggressive environmental exposures, both in new and existing pavement systems, and to develop quality assurance - quality control techniques, accompanied by new and innovative nondestructive tests, that will ensure quality construction for new facilities.

Within the constraints of time and funds proposed, this research plan, which is described in the following pages, will provide the tools in terms of new knowledge, new techniques, new test equipment, and new materials to achieve the specific objectives noted above. The task statements developed are grouped into four major project areas. Much of the work will be

directed toward the chemistry and physics of cement and concrete. The four major projects are:

- 5-1: Chemistry and Physics of Cement and Concrete
- 5-2: Durability of Concrete
- 5-3: Quality Control and Condition Analysis Through Non-destructive Testing
- 5-4: Mechanical Behavior of Concrete

The flow chart showing the interrelationships between these projects is shown in Figure 1.

Objectives and Goals of Project Areas and Tasks

Project 5-1: Chemistry and Physics of Cement and Concrete

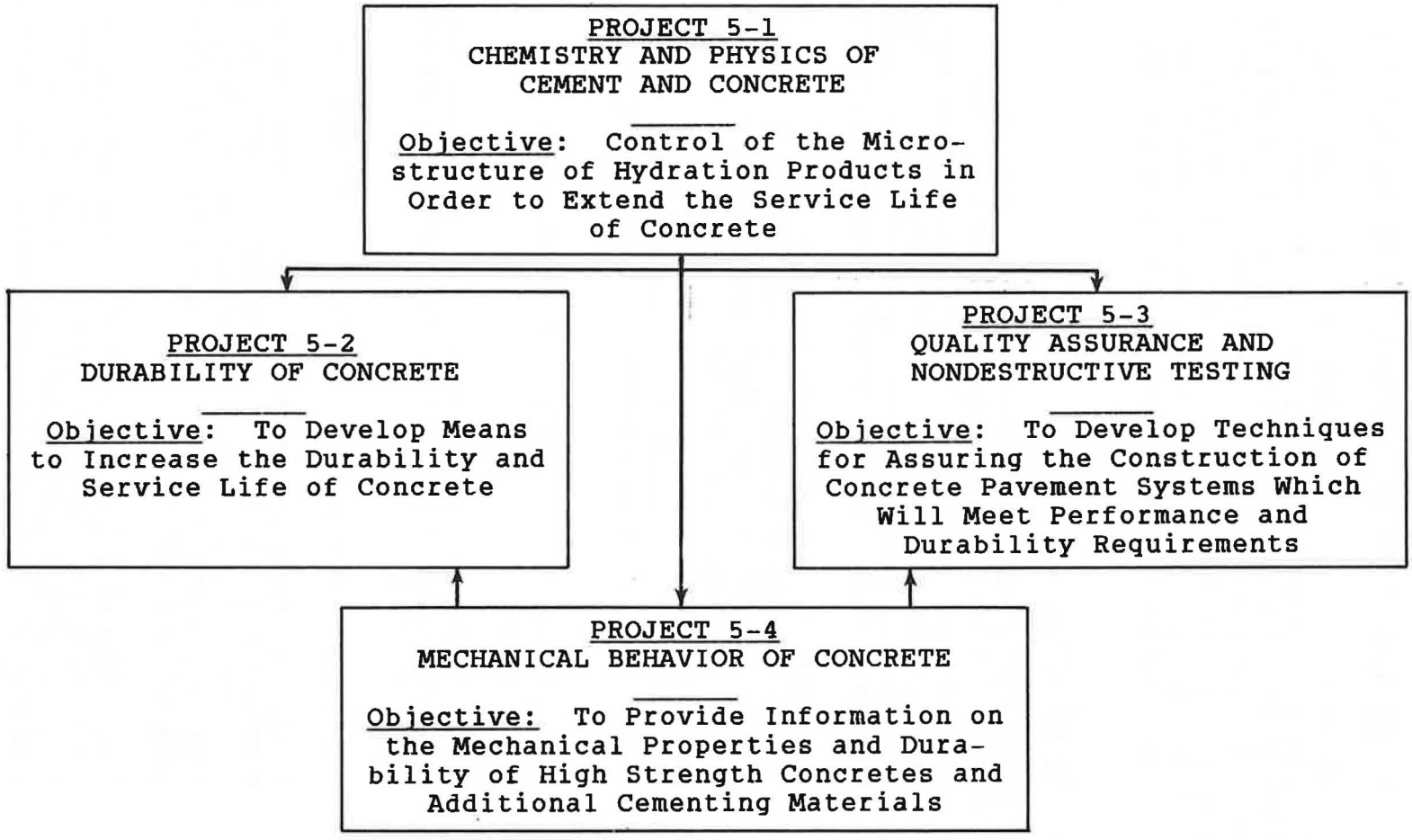
The ultimate goal of this project is to improve the basis for prediction and control of concrete properties, and to improve the performance of cements and concretes. The approach used is to conduct research to improve understanding of how the properties of concretes depend on the characteristics of cements, admixtures, and aggregates. The project focuses on how the microstructure of fresh cement pastes, the chemistry of hydration of cements and pozzolanic reactions, and the chemistry of deterioration processes, each affect the microstructure and properties of hardened cements and concretes.

The rationale used to design this project and the tasks selected are a mixture of a purely scientific approach and the empirical methods usually used to develop test methods and establish specifications for cements and concretes. It is an attempt to provide a basis for improved test methods and specifications by replacing empirical relationships by much more soundly based mathematical relationships derived from a correct understanding of the physical and chemical processes involved. For this reason each problem is attacked by formulating mechanistic mathematical representations, or models, of these processes. These models provide testable hypotheses for experimental work, identify the most important characteristics of materials that are required to control concrete properties, and permits irrelevant complexities to be set aside. The latter is an important consideration when dealing with materials as heterogeneous, complex, and diverse as concretes. Because of this complexity, attention is focussed, in most tasks, on the effects of hydration on the pore structure and the distribution of the hydration reaction products, rather than on the individual hydrated phases. However, in cases where the exact nature of the reaction products is critical to the problem, phase compositions become a major part of the study.

This project consists of three major tasks, in the following order of priority:

- 5-1.1: Development of the microstructure of concrete for improved performance.

FIGURE 1
TRA 5 FLOW CHART



- 5-1.2: Mechanisms of chemical deterioration processes and their control.

- 5-1.3: Development of superior concretes for highways.

With the exception of the last task, each task deals with specific problems of concretes in practice, and is designed to develop significantly improved understanding of specific aspects of the microstructure and properties. There is a logical progression in the way each task or sub-task contributes to work in the following tasks. The last task is a higher risk endeavor aimed at a big pay-off: a quantum jump in concrete performance. That risk will be minimized by the improved understanding achieved in the preceding tasks.

Project 5-2: Durability of Concrete

The primary objective of research in this project is to develop means to significantly increase the durability and service life of concrete. Accordingly, consideration must be given to existing concretes potentially vulnerable to premature failure as well as to new construction. Results of work proposed in Project 5-1, Chemistry and Physics of Cement and Concrete, will serve in a sense as "basic building blocks" to meet this objective.

The tasks included in this project are generally directed to specific durability problems in concrete pavements and associated structures. One task deemed to be of high priority, and which has application to all aspects of long-time pavement performance, is covered in the task on moisture condition of field concrete. Included also is a task directed to the development of an expert system adaptable to computer use which will enable concrete technicians to select the latest recommendations to resolve specific durability problems.

The tasks included in this project, in the following order of priority, thus are directed to:

- 5-2.1: Minimizing deterioration in existing pavements due to freezing and thawing, particularly D-cracking, and alkali-silica reactivity.

- 5-2.2: Determining moisture gradients in field concrete.

- 5-2.3: Clarifying the mechanism of freeze-thaw damage and developing more definitive information on aggregates and entrained air void criteria for enhancing durability when using high range water reducers and supplementary cementitious materials and admixtures.

- 5-2.4: Resolving the problem of guarding against alkali-aggregate reactivity which leads to deleterious expansion and cracking, with a clearer understanding of the role of moisture condition of the concrete as influenced by environmental conditions.

- 5-2.5: Developing a computerized system to provide diagnostic capability and solutions to durability problems.

Project 5-3: Quality Control and Condition Analysis Through Non-Destructive Testing

Quality control during construction is an absolute necessity to ensure the requirements of function and durability. The knowledge that is gained in the tasks involved in Project 5-1, Chemistry and Physics of Cement and Concrete and Project 5-2, Durability of Concrete, in addition to existing technology, all come to naught in the absence of adequate quality control during construction. Non-destructive testing can play a significant role in achieving the needed level of control. Such techniques can also be useful in evaluating the condition of existing structures, thus enabling the necessary remedial measures to be taken to extend service life.

The tasks in this project are directed to these ends, in a relatively specific form addressing specific needs of the present regarding pavement system function and durability. They include tasks, in the following order of priority, which will:

- 5-3.1: Develop a quality-assurance system for acceptance, form stripping, and placing in service based on existing and newly developed nondestructive tests.

- 5-3.2:Develop an in-place permeability test for hardened concrete.

- 5-3.3: Develop a test method and apparatus to determine the characteristics of the entrained air void system in freshly mixed concrete to facilitate acceptance or rejection before placement.

- 5-3.4: Develop a means for determining the residual functional capability of a pavement.

Project 5-4: Mechanical Behavior of Concrete

The mechanical behavior of concrete during its exposure to traffic loads plays an important role in the performance of the pavement system. While much is known about the mechanical behavior of most present-day concretes, relatively new developments in concrete technology may be of significance in improving the function and durability of pavement systems. The use of finely divided materials such as fly ash, ground granulated blast-furnace slag, silica fume and other cementing materials plays an increasingly important role in enhancing durability. Fiber reinforcement may assist in mitigating cracking problems. High strength concrete could provide the capability for longer span bridges. To utilize these materials properly more information on the mechanical properties of such concretes is required.

The tasks in this project therefore include, in the following order of priority, an evaluation of:

- 5-4.1: The fatigue resistance and strain capacity of high strength concrete subjected to repetitive loading.

- 5-4.2: The properties of early high strength concrete.

- 5-4.3: The influence of fly ash, ground granulated blast-furnace slag, silica fume and other cementing materials on the structural properties of concrete, including an evaluation of various combinations.

- 5-4.4: The effect of random fiber reinforcement, including combinations of different fibers, on structural properties.

SECTION 3
TRA 5 - FORMULATION OF THE PLAN

GENERAL APPROACH

For the guidance of the contractor (Construction Technology Laboratories), a copy of a preliminary report was made available which suggested a study plan relating to Chapter 8, Cement and Concrete in Highway Pavements and Structures, of TRB Special Report 202. The study was performed by a panel including the following:

R. E. Philleo, Consultant to the Panel
L. Gary Byrd, TRB, Panel Member
Wm. G. Gundermann, TRB, Panel Member
Thomas J. Pasko, FHWA, Panel Member
Crawford F. Jencks, TRB, Panel Member

The development of this research plan built on the above study plan. As the plan developed by CTL, under contract to TRB's National Cooperative Highway Research Program, advice and counsel were sought from an Advisory Committee appointed by SHRP. The chairman of the Advisory Committee was Robert Philleo, Consultant.

In addition to the input provided by the Advisory Committees and the SHRP staff, a National Workshop held in Dallas in September, 1985, provided an opportunity for additional input from invited representatives of other research organizations, highway departments, university researchers, and government agencies interested in the performance of cement and concrete. This national workshop provided a broad spectrum of capabilities with regard to concrete performance and its constituent materials.

Details of the Formulation Process

Advisory Committee Deliberations. Between the time of the inception of the contract to develop the plan, March 15, 1985, and the first meeting of the Advisory Committee, May 2 and 3, 1985, CTL prepared the outline of a plan covering four project areas, which were generally similar to those suggested in the initial study plan referred to above. A total of 28 tasks were selected for these four project areas. For both the four projects and the 28 tasks, detailed write-ups were prepared which included statements describing the selected area and the objectives. In addition, each task was divided into the necessary sub-tasks which would be required to achieve the task objectives, thus leading to achievement of the objectives within each project area. Each task statement contained a preliminary estimate of time

for completion, manpower requirements, estimated costs, and equipment requirements. Copies of this initial plan were made available to the members of the Advisory Committee well in advance of the meeting.

Following an initial review of the objectives of the Strategic Highway Research Program by SHRP staff and the chairman of the Advisory Committee at this first meeting, the committee was divided into three groups, each to consider portions of the initial program, as follows, in a workshop format:

Group 1: Project 5-1, Chemistry and Physics of Cement and Concrete.

Group 2: Project 5-2, Durability of Concrete

Group 3: Project 5-3, Quality Assurance and Nondestructive Testing, and Project 5-4, Mechanical Behavior of Concrete

Although the division into these groups was somewhat voluntary, the chairman of the Advisory Committee made some assignments to assure a proper balance of interests. The leader of each workshop group was a member of the Advisory Committee, assisted by the representative of the contractor (CTL) who developed the project or projects assigned to the group.

The participants in each group thoroughly discussed this initial program, both as to the selection of project areas, the tasks selected within each project, and the sub-tasks listed to accomplish each task. Factors which were considered included: (1) the importance of the need, i. e., priority, (2) the adequacy of the project and task statements, (3) the clarity of the objectives, (4) the selection and description of sub-tasks, (5) the potential for producing a usable end product which would assist in enhancing service life, and (6) the adequacy of the estimated budget.

In addition to considering the initial plan, suggestions were made for the consideration of the inclusion of new tasks which merited discussion. The discussion followed the same guidelines as noted above.

In all of these deliberations, a prime consideration, as recommended in TRB Special Report 202, was the call for "....the development of an innovative approach to highway research that will result in new techniques, new technologies, and new processes." In some instances, this plan responds to this call in a positive manner.

Subsequent meetings of the Advisory Committee, the second of which took place on August 15 and 16, 1985, followed the same pattern of operation.

Contractor Deliberations. Although the Advisory Committee's views were not binding on the contractor, as the name of the committee implies, the suggestions and recommendations for deletion or inclusion of tasks were given great weight in the refinement of the plan by the contractor between meetings. For example, in addition to consideration of the tasks put before them, at the second Advisory Committee meeting a fundamental shift in outlook developed. Whereas the initial plan was directed primarily toward achieving greater service life for newly constructed concrete pavements and other concrete elements of the pavement system, it became apparent during the discussions that enhancing the service life of the existing system, which represents a tremendous investment, would respond to the SHRP call for innovative

approaches. In response to this shift in emphasis, the plan developed by the contractor after this second meeting of the Advisory Committee reflected this new awareness of the significant benefits to be attained.

The Impact of the National Workshop. The National Workshop was held in Dallas Texas, during the period September 18-20, 1985, shortly after the second meeting of the Cement and Concrete Advisory Committee. In addition to the members of this Advisory Committee, there were approximately 75 individuals in attendance who responded to the SHRP invitation. Included were a number of people from overseas.

Following the plenary sessions, which all participants for the six Technical Research Areas attended, the Cement and Concrete Advisory Committee and the invited participants for TRA 5 met in separate sessions to consider the plan developed by the contractor after the second meeting of the Advisory Committee. After an initial session at which the plan was presented by the contractor, the group broke up into the now familiar small workshop plan to consider the projects and tasks in detail. The group then reconvened to report the results of their deliberations.

The input at this National Workshop by the invited participants, who generally endorsed the plan, was considered by the contractor in the further refinement of the research plan. The plan reflecting the National Workshop input was sent to the Advisory Committee in advance of its third meeting with the contractor.

Further Advisory Committee Deliberations. The third and last meeting of the Cement and Concrete Advisory Committee on November 4, 1985, was a meeting of the committee as a whole to consider the research plan which reflected the input at the two previous meetings and the National Workshop. The major considerations were the priorities assigned to the various tasks and the $12,000,000 total limit assigned to the technical research area on cement and concrete by SHRP.

The research plan presented at this third meeting of the Advisory Committee was approximately 25% over this maximum budget. In considering the means to conform to this limit, the committee agreed with SHRP that the tasks selected should be budgeted in the amounts necessary to achieve the objectives, i. e. the higher priority tasks within each of the four project areas should be adequately funded. The discussion therefore concentrated on priorities and resulted in recommendations for the deletion of lower priority tasks, and sub-tasks in some instances, to effect a major reduction in cost. In a few cases, however, it was agreed to effect some reduction in certain task budgets which could be made without reducing the chances of achieving the stated objectives and goals.

With this guidance, the contractor finalized the research plan presented in this report.

Interaction with Other Technical Research Areas

During all of these deliberations, the contractor and various members of the Advisory Committee interacted with other contractors in at least three other technical research areas and with certain over-all activities

requested by SHRP. These included TRA 2 on Long-Term Pavement Performance, TRA 4 on Protection of Bridge Components, and TRA 6 on Chemical Control of Snow and Ice on Highways.

With respect to TRA 2 on Long-Term Pavement Performance, the TRA 2 contractor was advised as to which of the tasks included sub-tasks which necessitated field evaluations of the procedures or techniques recommended to achieve the task objectives. In the case of TRA 4 on Protection of Bridge Components, possible cooperative tasks relative to corrosion of steel reinforcement were discussed. With respect to TRA 6 on Chemical Control of Snow and Ice on Highways, similar possible cooperative efforts were considered. Firm commitments were made only with respect to TRA 2 on Long-Term Pavement Performance.

Other Activities

Members of the Advisory Committee were assigned as liaison and to provide assistance to the following efforts:

TRA 2: Long-Term Pavement Performance
TRA 3: Maintenance
TRA 4: Concrete Bridge Components
TRA 6: Snow and Ice Control
Data Management Subcommittee of the
SHRP Overview Committee

SECTION 4
TRA 5 - RECOMMENDED RESEARCH PLAN

The detailed description of the recommended research plan is set forth in this Section, presenting the Projects, Tasks, and Sub-Tasks which flowed from the deliberations of the Advisory Committee and the Contractor for Technical Research Area 5 - Cement and Concrete. Figure 1 showed the interrelationships between these projects.

In the budget section for each Task, the following abbreviations are used: SP-Senior Professional, RA-Research Associate, T-Technician, and S-Support.

PROJECT 5-1: CHEMISTRY AND PHYSICS OF CEMENT AND CONCRETE

Project 5-1 Statement: The ultimate goal of this project is to improve the basis for prediction and control of concrete properties, and to improve the performance of cements and concretes. The approach used is to conduct research to improve understanding of how the properties of concretes depend on the characteristics of cements, admixtures, and aggregates. The research tasks focus on how the microstructure of fresh cement pastes, the chemistry of hydration of cements and pozzolanic reactions, and the chemistry of deterioration processes, each affect the microstructure and properties of hardened cements and concretes.

The rationale used to design this project is a mixture of a purely scientific approach and the empirical methods usually used to develop test methods and establish specifications for cements and concretes. It is an attempt to provide a basis for improved test methods and specifications by supplementing or replacing empirical relationships with much more soundly based mathematical relationships derived from a correct understanding of the physical and chemical processes involved. For this reason each problem is attacked by formulating mechanistic mathematical representations, or models, of these processes. Such models have long been used to explain specific phenomena. Recent and current work at the NBS, the Cement and Concrete Association in the U.K., and elsewhere has shown that effective use can be made of more general multivariant models. These models reveal gaps in our knowledge, provide testable hypotheses for experimental work, identify the most important characteristics of materials that are required to control concrete properties, and permit irrelevant complexities to be set aside. The latter is an important consideration when dealing with materials as heterogeneous, complex, and diverse as concretes. Because of this complexity, attention is focussed, in most tasks, on the effects of hydration on the pore structure and the distribution of the hydration reaction products, rather than on the individual hydrated phases. However, in cases where the exact nature of the reaction products is critical to the problem, phase compositions become a major part of the study.

The diversity of materials used in concrete-making presents problems for any research program, and especially so for one dealing with the chemistry of cement and concrete. For the results of the program to be most useful, it will be desirable to be able to relate results in any project or task to those from other tasks. Uncertainties in such comparisons are greatly reduced if the same cements and other materials are used for all of the work. Within this project, this concept is carried further by use of samples of the same hardened cements and mortars in several tasks and sub-tasks. This also avoids unnecessary duplication of work in characterization of cements in the different projects and tasks, which reduces costs in each task. It would also be desirable to coordinate acquisition of cements and other materials in TRA 5 with other technical research areas, especially the placement of test sections in TRA 2, and patching materials used in TRA 3. If adequate quantities of each cement, fly ash, and other admixtures were acquired and stored they could be tested for suitability in TRA 5. If used, data procured would be directly applicable to work in TRA 2 and 3. Such coordination should be developed.

Project 5-1 consists of the following three major tasks, in order of priority:

5-1.1 Development of the microstructure of concrete for improved performance.

5-1.2 Mechanisms of chemical deterioration processes and their control.

5-1.3 Development of superior concretes for highways.

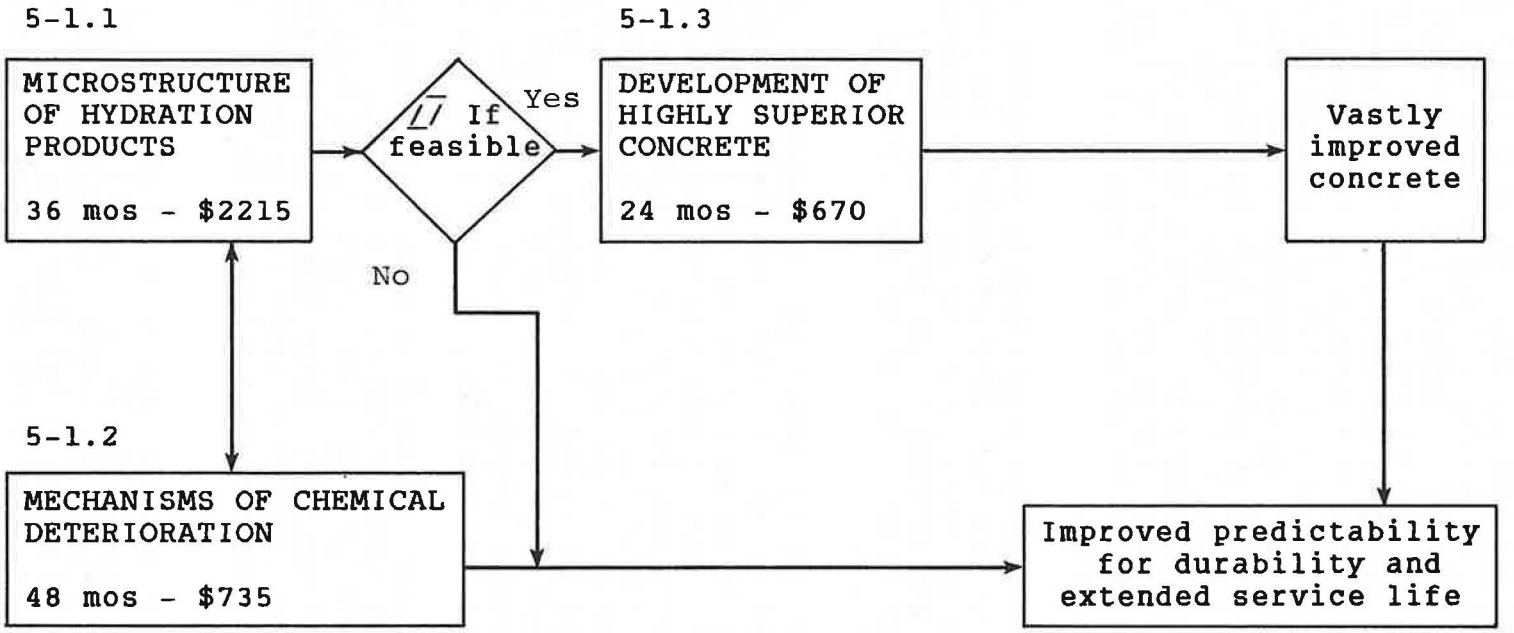
Each task deals with specific problems of concretes in practice, and is designed to develop significantly improved understanding of specific aspects of the microstructure and properties. The interrelationship of these tasks is shown in Figure 2. The output from the first two tasks will be input data for tasks dealing with concrete problems in the other three projects (5-2 on Durability, 5-3 on Quality Control and Non-destructive Testing, and 5-4 on Mechanical Properties). This output will include recommendations for development of improved test methods and specifications as well as life test analyses and mathematical models for proper understanding of mechanisms of maturation and deterioration processes. The latter provide input for service life prediction and life cycle cost estimates in other projects.

The first two tasks also provide the basis for the decision whether or not to proceed with Task 5-1.3: Development of Superior Concrete for Highways. This is a higher risk endeavor aimed at a big pay-off: a quantum jump in concrete performance. That risk will be minimized by the improved understanding achieved in the preceding tasks.

The sub-task descriptions are given in some detail to indicate possible approaches that may be used. They are not intended to discourage consideration of other possibly more cost effective or fruitful approaches to achieve the project objectives.

Task 5-1.1 Title: Development of the Microstructure of Concrete for Improved Performance.

FIGURE 2
PROJECT 5-1 FLOW CHART



Footnote: $ in Thousand

Task 5-1.1 Statement: One of the most important properties of fresh concrete is its ability to flow and remain plastic during placement. The initial floc structure of the fresh cement paste not only controls the flow properties but is also the framework for development of the microstructure of the hardened cement paste matrix and its interconnected system of capillaries (large pores). Changes in the pore structure directly affect all mechanical and physical properties, permeability, transport of moisture and aggressive solutions, and durability. In mortars and concretes, there is an interfacial or transition zone on the aggregate surfaces which is different from the structure of the paste matrix more than about 50 μm from these surfaces. The performance of concrete is a direct result of the development of the microstructure during mixing, setting, and hardening of concrete. Practical problems such as early stiffening or retarded setting, excessive bleeding or drying shrinkage, and failure to develop adequate strength, impermeability, or frost resistance also originate in processes occurring on a microscopic or submicroscopic scale in the matrix of the concrete. Solving these problems depends upon a good understanding of the development of the microstructure during setting and hardening.

Variations of the water requirement of the cement, admixture effects, temperature, or aggregate moisture contents may result in changes in the workability of the concrete. Water contents are sometimes increased if the required slump is not obtained at the job site. Such concrete may still be accepted if strength is adequate but its durability will be less than without the additional water.

The number of factors controlling the workability of concrete increases when chemical and mineral admixtures are used. Chemical admixtures are formulated for use in concrete under various field conditions and may contain chemical accelerators or retarders and water reducing components (dispersants). Specifications for chemical admixtures are given in ASTM C 494, which requires performance testing for relative water content, time of setting, strength development and other properties. However, C 494 requires that an admixture be tested at only one temperature with only one cement, or one blend of two or more cements in equal parts. Some combinations of chemical admixtures and portland cements are incompatible under some conditions; when used together premature stiffening or rapid slump loss may occur.

Fine powders used as mineral admixtures and fines generated by abrasion of some aggregates during mixing can also increase stiffening. Certain constituents in some fly ashes may also affect the chemistry of early reactions and stiffening of concrete. These interactions are not well understood, create additional problems in control of the consistency of fresh concretes, and have as yet unpredictable effects on the microstructure of fresh and hardening concretes.

Among the most important aspects of the microstructure of hardened concrete is the pore structure and changes in pore structure of the matrix that occur during hydration of the cement and subsequent drying. The effects of water-cement ratio and degree of hydration after moist curing on the porosity and permeability, on strength, drying shrinkage, frost damage, and chemical attack have long been recognized. Moist curing promotes cement hydration, which reduces permeability; self-desiccation, or even slight drying may tend to improve densification, but results in slower hydration and

different distributions of hydrates in the originally water-filled spaces. Water-reducing admixtures disperse the normal floc structure of fresh cement pastes, but little is known about how they may change the continuity of capillary pores in the hardened cement paste microstructure, its permeability, or rates of leaching or resaturation after partial drying. Mineral admixtures also affect the microstructure of the fresh paste and some have very large effects on the permeabilities of hardened cements and concretes, but how changes in their microstructures and properties are brought about are not well understood.

The mechanisms by which cement hydration and partial drying cause shrinkage of concretes are also not fully understood. Early age shrinkage of concretes can cause uncontrolled cracking of pavements. Some of the effects of cement fineness, alkali and sulfate contents (optimum gypsum) are known, but little is known about how chlorides may increase drying shrinkage. Factors influencing volume changes of concrete, especially at early ages, and the use of controlled small expansions to prevent shrinkage cracking need to be more fully understood.

In mortars and concretes, the microstructure is strongly affected by the development of interfacial zones on the aggregate surfaces. The reduced concentration of cement particles on these surfaces in the fresh concrete results in increased porosity in the transition zone. Very thin (1μm) duplex films of calcium hydroxide and calcium silicate hydrate formed on the aggregate tend to increase the bond, but the higher porosity and the large size and preferred orientation of calcium hydroxide crystals formed in the pores in the transition zone prevent it from developing water tightness, resistance to crack propagation, and strength equal to those of the unaltered cement paste. Not only are these zones weaker, but because the elastic moduli of the aggregates in normal concretes are higher than the cement paste, deformations are concentrated at the aggregate surfaces; these larger deformations lead to tensile and shear failures.

Even essentially unreactive aggregates undergo superficial reactions with cement reaction products. Siliceous aggregate surfaces may react with the calcium and hydroxyl ions to produce pozzolanic reaction products. Carbonate surfaces react with aluminates to form calcium carboaluminate hydrates, and have been shown to have thinner transition zones.

Little is known about the effects of chemical and mineral admixtures on the microstructure and properties of these transition zones. Very recent research has shown that additions of silica fumes have a very much larger effect on the pore structure and durability of mortars than on cement pastes. There is evidently a large and important effect of silica fumes on the microstructure of the transition zone. Similar effects may be expected with some fly ashes.

A research program is needed to improve understanding of the development of the microstructure of the matrix phase in concretes and how the physical properties, performance, and microstructure depend on the characteristics of concrete making materials, processes, and exposure history. This program should provide a basis for selection of combinations of materials that produce less porous and permeable microstructures for strong, volume stable, and more durable concretes.

Objectives: The objectives of Task 5-1.1 are to develop an improved understanding of

(1) the factors controlling cement hydration and the development of the microstructures.

(2) how the microstructure controls the properties, and

(3) how the microstructure and properties can be optimized to improve the performance of concretes in various environments and applications.

The improved understanding and the data generated will be synthesized into predictive models for use in other tasks and projects, along with recommendations for development of improved test methods, specifications, and performance criteria for a superior concrete.

A final objective of this task is to evaluate the results obtained, along with those of Task 5-1.2, to decide whether Task 5-1.3 appears feasible and should be undertaken to develop superior concretes for highways.

Sub-Task Descriptions:

Sub-Task 5-1.1,a: Review the literature on the rheology and hydration of portland cement and blended cement pastes, mortars, and concretes with special attention to factors that influence the initial floc structure, pore structure, and permeability. Critically evaluate published data for possible use of inadequately characterized materials, test methods, and controls. Solicit recent and current unpublished work on mechanistic mathematical models used to synthesize such data. Identify characteristics of cements and admixtures, and aspects of mixing and hydration processes, that influence the distribution of cement particles, the crystalline hydrates, and the calcium silicate hydrate gel during setting and hardening. Synthesize the data and existing models to identify the largest gaps in our knowledge. Formulate testable hypotheses for the effects of cement characteristics on rheological properties and specific mechanisms by which the originally water-filled spaces are progressively filled with hydrates, reduce the continuity of capillary pores, encapsulate leachable hydrates, and affect physical properties.

Sub-Task 5-1.1,b: Generate sufficient data to test hypotheses and models synthesized in Sub-Task 5-1.1, a. Characterize a variety of portland cements by chemical and phase compositions (including states and rates of solubility of calcium sulfates), finenesses, particle size distributions and standard performance tests (such as ASTM C 150, C 187, C 191, C 359, C 451 and C 109). If some cements used in TRA 2 and 3 are suitable they should be used, as well as others as required for composition and fineness variation. Prepare cement pastes at water-cement ratios representative of the range in highway concretes and determine their flow properties as functions of temperature, and time after mixing up to time of set. Follow the early hydration reactions, heat evolution and volume changes by appropriate means. Establish the most significant correlations between water requirements for specified flow, fresh paste structure, hydration kinetics and cement characteristics, temperature, and time after mixing.

Cure specimens under moist curing and self-desiccation conditions, then partially dry some specimens. Examine the microstructure by appropriate means and perform leaching tests, permeability measurements, and measurements of drying shrinkage, elastic moduli, compressive and flexural strength, and deformation capacities at various stages of hydration. Provide replicate specimens for Task 5-2.3, Durability for freeze-thaw testing. Reexamine microstructures and physical properties of specimens after these tests.

Sub-Task 5-1.1,c: Test hypotheses formulated in Sub-Task 5-1.1,a for the rheological properties of fresh pastes and the dependence of the microstructure and properties of hardened cements on the physical and chemical characteristics of the cements.

Modify the mechanistic mathematical model synthesized in Sub-Task 5-1.1,a for water requirements of portland cements in terms of the most significant parameters examined in Sub-Task 5-1.1,b. Extend this model to include the effects of hydration on the microstructure of the paste in the dormant state after casting and the further development of structure and physical properties during hardening. Relate hydration kinetics to a quantitative description of the rate of filling pore spaces and distribution of hydrates, and to their effects on physical properties. Modify hypotheses as required by experimental data in Sub-Tasks 5.1.1,a and 5.1.1,b to develop a predictive model that permits identification of favorable characteristics of portland cements and curing conditions, and has predictability adequate for engineering design.

Sub-Task 5-1.1,d: Generate sufficient data to test hypotheses from Sub-Task 5-1.1,a pertaining to the effects of chemical and mineral admixtures, and to develop modifications of the predictive model of Sub-Task 5-1.1,c. Select several water reducing admixtures of different types and of varied compositions suitable for the U.S. highway market. Characterize the admixtures by infrared spectroscopy and other appropriate means.

Select a number of fly ashes, ground granulated blast-furnace slags, silica fumes, natural pozzolans, and aggregates which generate fines by abrasion during mixing in concrete for use as mineral admixtures. Characterize these by chemical and phase compositions, particle size distributions and other means. Select some of the portland cements used in Sub-Tasks 5-1.1,b and 5-1.1,c, and repeat Sub-Tasks 5-1.1,b and 5-1.1,c with combinations of portland cements and chemical and mineral admixtures.

Sub-Task 5-1.1,e: Review the literature on the microstructure and properties of the cement paste-aggregate transition zone and bond, with special attention to factors that influence the pore structure and durability of concrete. Extend the review of Sub-Task 5-1.1,a to include the effects of aggregate surfaces in considering the effects of cement composition, and chemical and mineral admixtures, on the initial structure of fresh mixtures, and the changes of that structure during hydration. Formulate testable hypotheses for the influence of compositional and other variables on the initial structure after mixing, the growth of hydrates during setting and hardening, and the effects on physical properties of hardened mortars and concretes.

Sub-Task 5-1.1,f: Test hypotheses formulated in Sub-Task 5-1.1,e by direct microscopic examinations of the microstructure, pore size distribution analyses, leaching tests, permeability measurements, strength tests, and any other appropriate means. Using some of the same set of portland cements, chemical and mineral admixtures from Sub-Task 5-1.1,d, and a set of aggregates of different mineralogical compositions, prepare cement mortars at several water-cement ratios. Using variations of the methods which are appropriate for mortars, repeat the tests made on cement pastes in Sub-Tasks 5-1.1,b and 5-1.1,d.

Modify hypotheses as required by experimental data and develop a predictive model that permits identification of characteristics of portland cements, chemical and mineral admixtures, aggregates, and curing conditions that reduce the depth, porosity, and crystal sizes in the transition zones, and favorably influence the development of strong, highly impermeable microstructures that remain resistant to leaching and microcracking. Refine the predictive model to achieve accuracy adequate for engineering design.

Sub-Task 5-1.1,g: Summarize the above results and evaluate standard test methods and specifications for portland cements, blended cements, and chemical and mineral admixtures with respect to their ability to predict performance and identify characteristics that impair or enhance performance with respect to placement of concrete, physical properties, and resistance to deterioration. Prepare recommendations for development of improved test methods and specifications. Evaluate data in Tasks 5-1.1 and 5-1.2 and recommend whether or not to proceed with Task 5-1.3.

Estimated Cost of 5-1.1: $2,215,000 (includes $250,000 for equipment)

Task Time (months): 36

Man-Months:	SP	RA	T	S	Total
Sub-Task 5-1.1,a Literature Review	3	7	0	3	13
Sub-Task 5-1.1,b Cement Paste Properties	5	17	4	3	29
Sub-Task 5-1.1,c Predictive Model for Cement Pastes	5	10	0	2	17
Sub-Task 5-1.1,d Effects of Chemical and Mineral Admixtures and Model for Admixture Effects	11	62	15	8	96
Sub-Task 5-1.1,e Review of Paste-Aggregate Interface	2	4	0	2	8
Sub-Task 5-1.1,f Cement Mortar Properties and Model	10	52	20	8	90
Sub-Task 5-1.1,g Summary and Evaluation; Is Highly Superior Concrete Feasible?	15	33	0	7	55
Totals	51	185	39	33	308

Task 5-1.2 Title: Mechanisms of Chemical Deterioration Processes and Their Control.

Task 5-1.2 Statement: Alkali-aggregate reactions continue to be a significant cause of deterioration of concrete pavements and structures. This may be partly a result of an improved ability to recognize such cases involving different types of aggregates, and partly because of generally increasing alkali contents of cements resulting from modern energy saving technologies. Some concrete aggregates containing reactive andesites and rhyolites have also been shown to release alkalies during reaction, thereby making the use of low alkali cement an ineffective control measure in such cases.

Recent research indicates that some silica fumes may be very effective in preventing deleterious alkali-aggregate reactions. Pozzolans such as ASTM C 618 Class F fly ashes have been used successfully for control of alkali-silica reactions to a degree that depends on their alkali contents, but they are not effective with reactive carbonate rocks. The increasingly used ASTM C 618 Class C fly ashes are less effective in control of alkali-silica reactions. In addition to the usual alkali-silica and alkali-carbonate rock reactions, slowly-developing expansive reactions have been found to occur with argillites and graywackes.

Much research has been directed towards understanding the mechanisms involved and the development of appropriate test methods to determine potentially unsafe combinations of cements and aggregates. However, even with relatively simple reactive aggregates there is considerable controversy over the validity of test procedures and the significance of results. The mortar bar test for cement-aggregate combinations (ASTM C 227) has been criticized because reactions with aggregates which have been crushed to sand sizes are recognized to proceed differently from those in concrete, where larger particles may show reaction rims.

For test methods to be used with confidence to predict service life of concrete, the mechanisms of the reactions and deleterious processes must be well understood. A research program is needed to improve our understanding of the mechanisms of the several types of alkali-aggregate reactions and provide a basis for improved test methods and specifications for concrete-making materials. This latter effort will be a task (5-2.4) pursued in the project on Durability (5-2).

Objectives: The objectives of Task 5-1.2 are to develop an improved understanding of the mechanisms of alkali-aggregate reactions and means of their control, to obtain reliable data on phase compositions and chemical equilibria between the hydration products of cements and their reaction products with various aggregates and admixtures, and to prepare recommendations for improved practices.

Sub-Task Descriptions:

Sub-Task 5-1.2,a: Review the literature on the mechanisms of various alkali-aggregate reactions. Identify aggregate characteristics which influence the progress of the reaction for specific mechanisms, ranges of conditions for which reactions may be safe or unsafe, and gaps in our knowledge. Formulate alternative postulated mechanisms as mathematical models for each type of alkali-aggregate reaction, and for possible preventive measures. Design experiments to directly test the alternative mechanisms.

Sub-Task 5-1.2,b: Collect samples of a variety of reactive aggregates with well-documented histories of deleterious reaction in concrete, and available chemical and petrographic data on the same materials. Perform additional analyses as required for characterization, and prepare samples with controlled particle size ranges.

Sub-Task 5-1.2,c: Generate sufficient data to test hypotheses and models formulated in Sub-Task 5-1.2,a on the reactive aggregates of Sub-Task 5-1.2,b. Conduct tests in mortar or concretes made with cements of several alkali contents using portland cements from Task 5-1.1 in addition to any tests of aggregates in artificial environments, (such as osmotic cells or rock prism tests). Follow the progress of the reaction by microscopic examinations, analytical methods, and expansion measurements. Determine the compositions of pore solutions and reaction products and their distribution. Compare microstructures with those made with nonreactive aggregates in Task 5-1.1 and the same cement paste matrix materials. Determine the relationships between aggregate characteristics, alkali contents, and the progress of the reaction in different environments. Use these data to revise the predictive model for the progress of the reaction for each class of reactive aggregate in terms of aggregate characteristics, cement and concrete compositions, and environmental conditions.

Sub-Task 5-1.2,d: Using materials from Task 5-1.1, determine the effects of various pozzolans (and any other useful material) on the progress of the reaction, the composition and distribution of reaction products, and the expansion and cracking of mortars and concretes made with cements of several alkali contents. Extend the predictive model to include the effects of pozzolans and any other preventive measures.

Sub-Task 5-1.2,e: Summarize the above results and evaluate standard test methods and specifications with respect to their ability to identify materials which cause deleterious expansive reactions of aggregates in concrete, or which may be used to ameliorate such reactions. Prepare recommendations for improved test methods and specifications.

Estimated Cost of 5-1.2: $735,000 (includes $100,000 for equipment)

Task Time (months): 48

Man-Months:	SP	RA	T	S	Total
Sub-Task 5-1.2,a Review of A.A.R. Mechanisms	2	4	--	2	8
Sub-Task 5-1.2,b Aggregate Samples and Analysis	2	5	2	1	10
Sub-Task 5-1.2,c Experimental Tests of Mechanisms	2	15	7	2	26
Sub-Task 5-1.2,d Effects of Pozzolans	2	10	4	3	19
Sub-Task 5-1.2,e Evaluation of Specifications	4	9	--	5	18
Totals	12	43	13	13	81

Task 5-1.3 Title: Development of Superior Concretes for Highways.

Task 5-1.3 Statement: The majority of concrete durability problems are associated with high moisture contents and excessive capillary (or large pore) porosity of the hardened cement paste. Continuous capillaries provide the most rapid flow passages for aggressive solutions and for diffusion of ions. When concrete is damaged by freezing and thawing, it is by stresses caused by ice formation in these capillaries. These same large pores at aggregate surfaces and voids caused by bleeding are also the sites of initiation of cracks and the cause of low tensile and flexural strengths in hardened concretes. Strength and durability are progressively increased as the capillary porosity is reduced by hydration of cement or by reduction of the initial water-cement ratio. However, reduction of water-cement ratio by itself does not entirely eliminate large pores because of the tendency of particles in the fresh cement paste to flocculate and create large pores. Recent research on "macro defect free" cement pastes has shown that extreme measures can be used to produce hardened cements with essentially no large pores. In that case, polymeric additions are used and water-cement ratios are so low that very little of the cement actually hydrates. It does not appear that practical concretes for highways could be constructed of such material because of both fabrication and economic considerations. If some means could be found to make concretes of adequate workability that are also free of sedimentation deposits and large pores (or to mitigate their adverse effects) and also utilize the cement more completely than in macro defect free cement pastes, much less permeable and more durable concretes may become practical for highway construction.

Among the most important problems in highway rehabilitation are the time required for concrete hardening and the need to reopen pavements to traffic with minimum delay. Cements that produce concretes that achieve required strengths very rapidly and still have long service lives would solve this problem.

Such improved concretes may require cements of optimum composition and particle size distributions, water-reducing and accelerating admixtures, carefully selected mineral admixtures, and perhaps other additions to control the microstructure. The cementitious mixtures should be designed not only to control the pore structure in the paste and the transition zones on aggregate surfaces before hydration stops, the voids caused by sedimentation under coarse aggregates, and tendencies to early shrinkage cracking of concretes, but also to rapidly attain sufficient self-desiccation to be safe from frost action and deleterious reactions with aggregates. Results of the projects on the development of microstructure, and on the mechanisms of chemical deterioration processes should provide excellent background for the systematic development of concretes of superior performance that could greatly extend service life. A research program is needed to fully exploit the results of the previous tasks to develop a new generation of concretes that harden rapidly and have virtually no large flaws, permeability, or freezable water, and to develop criteria for such concretes.

Objectives: The objective of this project is to develop a new basis and criteria for practical concretes of designed microstructures for highways which develop design properties rapidly and have greatly extended service life, and will reduce life-cycle costs.

Sub-Task Descriptions:

Sub-Task 5-1.3,a: Review the literature and work on the microstructure of concrete with respect to ways of eliminating flaws and improving the pore and void structures. Using the predictive models, select the most promising combinations of materials used in the above investigations based on alternative processes for improving the microstructure. Design test programs based on these alternatives.

Sub-Task 5-1.3,b: Prepare or acquire any additional materials required for the test programs. Perform experiments to test the feasibility of several alternative processes to modify the microstructure. Prepare both cement pastes and mortars with several aggregate types to separate effects of flaws in the paste from paste-aggregate interfacial zones. Examine the microstructure by direct microscopic observation and pore size distribution analysis. Determine the effects on microstructure and properties of variations of curing, leaching, drying and wetting, temperature cycling, and freezing and thawing tests.

Sub-Task 5-1.3,c: If the results of Sub-Task 5-1.3,b yield at least one highly superior system, select the most promising process and material combinations for optimization with several aggregate types. Allow adequate tolerance for reasonable variation in materials properties in this selection. Prepare concretes from combinations of materials indicated to produce the best long-term properties in the shortest curing times. Conduct extensive tests of physical properties of concretes before and after leaching, wetting and drying, temperature cycling, and freezing and thawing tests. Compare the results with those from the predictive models, and those for ordinary concretes. Coordinate with TRA 2 and 3.

Sub-Task 5-1.3,d: Evaluate standard test methods, specifications for portland cements, aggregates, admixtures, and concrete production and placement methods. Prepare recommendations and criteria for changes required to introduce the new concrete technology, with an emphasis on pavement applications, for economical concrete with the high durability associated with improved microstructures.

Estimated Cost of 5-1.3: $670,000 (includes $50,000 for equipment)

Project Time (months): 24

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-1.3,a	Review	2	4	--	2	8
Sub-Task 5-1.3,b	Feasibility Testing	2	6	20	2	30
Sub-Task 5-1.3,c	Concrete Testing	4	10	36	4	54
Sub-Task 5-1.3,d	Evaluation	3	6	--	1	10
	Totals	11	26	56	9	102

PROJECT 5-2: DURABILITY OF CONCRETE

Project 5-2 Statement: The primary objective of research in this project is to develop means to significantly increase durability and service life of

concrete. Accordingly, consideration must be given to existing concretes potentially vulnerable to premature failure as well as to new construction. Results of work proposed in Project 5-1 on Chemistry and Physics of Cement and Concrete will serve, in a sense, as "basic building blocks" to meet this objective.

The tasks included in Project 5-2 are directed most specifically to freezing and thawing and alkali-silica reactivity. Greatest priority is given to preserving existing pavements where these two processes are expected to initiate premature failure of concrete. In addition, high priority is given to characterizing moisture conditions, which relate to nearly all aspects of pavement durability in addition to freezing and thawing and deleterious aggregate reactivity. Mechanisms of failure, and evaluation of materials combinations vulnerable to failure, are directed more specifically to preventing durability problems in future pavement construction. An expert system is included to serve primarily as a diagnostic tool to determine causes, remedial measures, and preventive measures of such premature failure.

The tasks in this project, shown in Fig. 3 in order of priority, are:

5-2.1 Minimize deterioration due to D-cracking and alkali-silica reactivity in existing concrete pavements

5-2.2 Develop techniques to characterize moisture and relative humidity gradients in field concrete

5-2.3 Improve assessment of the freeze-thaw durability of concrete and aggregate and air void criteria

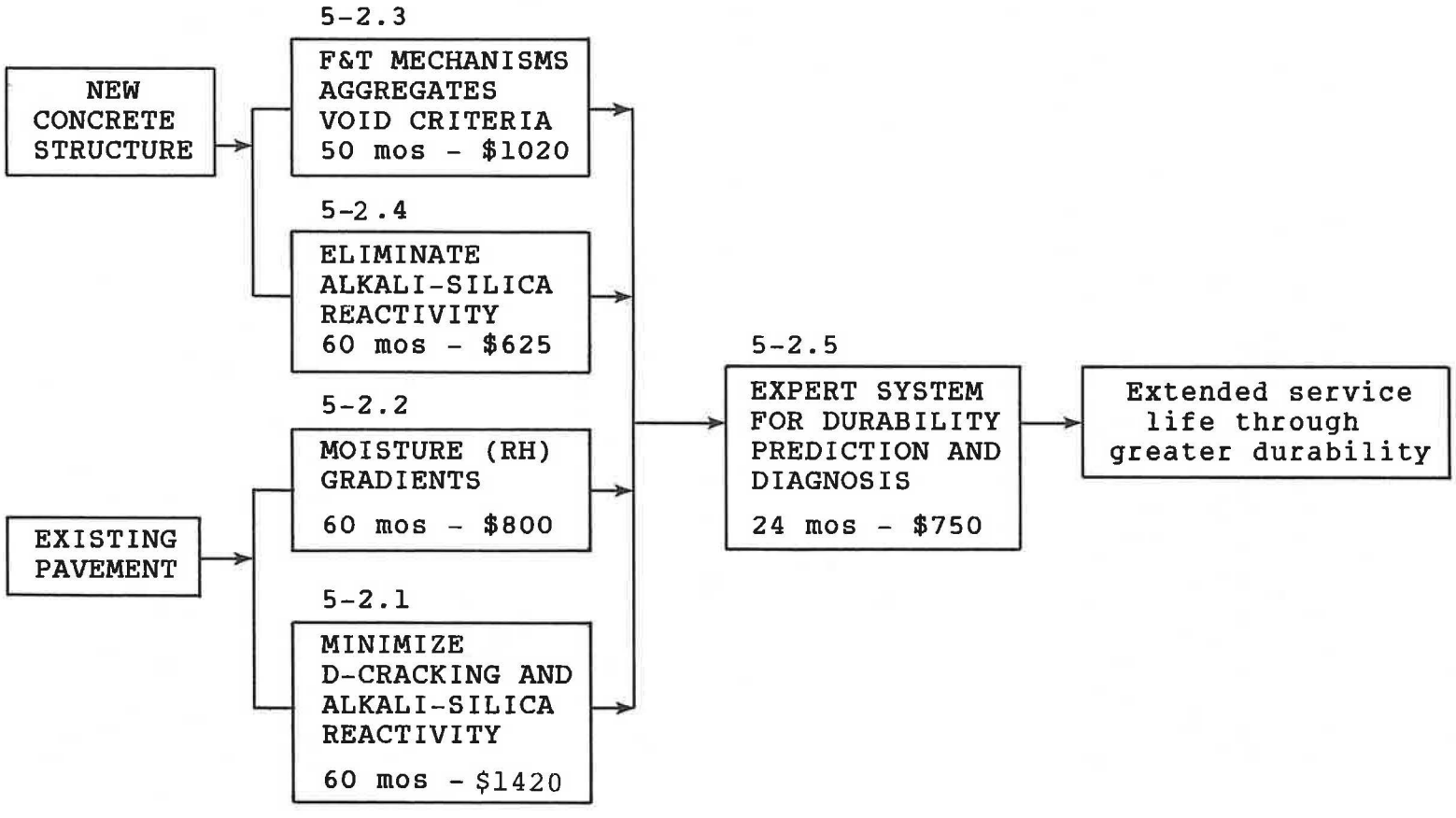
5-2.4 Develop requirements for aggregates, pozzolans, and alkali levels to avoid expansions due to alkali-aggregate reactivity (new pavements)

5-2.5 Develop computerized expert system for durability and service life of concrete

Task 5-2.1 Title: Minimizing Deterioration Due to D-Cracking and Alkali-Silica Reactivity in Existing Concrete Pavements

Task 5-2.1 Statement: Numerous highway structures are in service in which D-cracking due to freeze-thaw failure of the aggregate and deterioration due to alkali-silica reactivity are known to pose serious rehabilitation problems in the future. The potential for these problems has resulted from the use of coarse aggregate or cement-aggregate combinations which have been found, from tests subsequent to construction, to be susceptible to failure but which have not yet caused deterioration. Extending the service life of such highway structures by reducing early rehabilitation needs can save millions of dollars over the long-term. A method to minimize progressive development of D-cracking and alkali-silica reactivity in highway structures would be highly cost-effective.

FIGURE 3
PROJECT 5-2 FLOW CHART



Footnote: $ in Thousands

Objectives: Major objectives of Task 5-2.1 are:

1. To develop an effective method of dealing with highway structures to minimize development of deterioration due to D-cracking and alkali-silica reaction.

2. To demonstrate the practicability of the method in field concrete.

3. To show that the method can be cost-effective in field application.

Sub-Task Descriptions:

Sub-Task 5-2.1,a: Develop in the laboratory methods to control deterioration due to D-cracking and alkali-silica reactivity in concrete pavement and other highway structures. The methods must be effective in presently sound concrete as well as in concretes that already show incipient or progressive deterioration.

Sub-Task 5-2.1,b: If the work in Sub-Task 5-2.1,a shows promise, conduct trial tests to demonstrate the practicability of the method in field applications.

Sub-Task 5-2.1c: Justify from an economic standpoint the applicability of the methods to concrete pavement and other highway structures.

Sub-Task 5-2.1,d: Prepare a final report describing the development work and the effectiveness and applicability of the methods to concrete pavement and other highway structures.

Estimated Cost of 5-2.1: $1,420,000 (includes $200,000 for equipment)

Project Time (months): 60

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-2.1,a	Laboratory Methods	42	12	36	--	90
Sub-Task 5-2.1,b	Field Trials	24	18	24	--	66
Sub-Task 5-2.1,c	Economic Analysis	3	2	--	1	6
Sub-Task 5-2.1,d	Report	4	1.5	--	1.5	7
	Totals	73	33.5	60	2.5	169

Task 5-2.2 Title: Develop Technique to Characterize Moisture and Relative Humidity Gradients in Field Concrete.

Task 5-2.2 Statement: One of the major obstacles in properly applying laboratory test results and research findings to field performance of concrete is the lack of an understanding of the micro-climate in concrete. Many phenomena affecting durability and performance of highway structures, such as freezing and thawing, alkali-aggregate reactivity, curling and warping, creep, drying shrinkage, and corrosion of steel, are contingent on moisture availability and moisture gradients in concrete. There is virtually no

information available on moisture contents and relative humidities of field concretes, thus a serious need exists to develop information in this area.

Objectives: The major objectives of Task 5-2.2 are:

1. To establish a method that can be used to quickly measure moisture content and/or relative humidity in concrete.

2. To characterize the moisture conditions of highway structures.

3. To demonstrate the applicability of moisture and/or relative humidity data obtained to phenomena that affect field performance.

Sub-Task Descriptions:

Sub-Task 5-2.2,a: Develop a procedure to measure moisture content and/or relative humidity in field concrete. The procedure must be rapid and be non-destructive to the concrete. It must also have the capability of characterizing moisture and relative humidity gradients in concrete.

Sub-Task 5-2.2,b: Demonstrate the efficacy of using the test procedure for field concretes. Include highway pavements, bridge structures, retaining walls, etc. located in a range of climates. Also include structures exhibiting various types of durability problems, including alkali-aggregate reactivity, D-cracking, and corrosion-induced cracking. Obtain sufficient data to confirm the repeatability and sensitivity of the procedure.

Sub-Task 5-2.2,c: Prepare a final report that describes the development, application, and limitations of the procedure. Include needs for future research.

Estimated Cost of 5-2.2: $800,000

Project Time (months): 60

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-2.2,a	Test Procedure	18	12	--	4	34
Sub-Task 5-2.2,b	Test Demonstration	18	18	8	--	44
Sub-Task 5-2.2,c	Report	4	1	1	--	6
	Totals	40	31	9	4	84

Task 5-2.3 Title: Improved Assessment of the Freeze-Thaw Durability of Concrete and Aggregates and Air Void Criteria.

Task 5-2.3 Statement: One of the most important causes of deterioration of concrete in the U.S. is freezing and thawing. Previous research has provided a good understanding of the mechanisms of frost action on hardened cements and the protective effect of entrained air. For many years these findings provided a sound basis for the void spacing factor concept, which has been the basis for assessment of the adequacy of air void systems. However, even good quality concrete may suffer damage from cyclic freezing under certain

conditions, such as when critical saturation is reached or where nondurable aggregates are used. The use of deicing salts contributes to this condition and can accelerate surface disintegration. Admixtures such as high-range water reducers (HRWR), fly ash, slag, and silica fume may also affect entrained air void systems. Air void spacing factors below 0.008 in. seem to correlate with expected satisfactory laboratory freeze-thaw resistance. However, higher spacing factors often found in the concrete containing these admixtures may or may not result in poor durability based on laboratory tests.

Insofar as aggregate durability is concerned, D-cracking and popouts are known to be caused by freeze-thaw failures in aggregate particles. Various tests have been developed through the years to identify and screen aggregates that cause these problems. The most reliable and informative method, that of testing the aggregate in concrete, unfortunately is very time-consuming and requires purchase of expensive testing equipment. A more rapid and inexpensive method is needed for these evaluations. The procedure must identify not only whether an aggregate is durable or nondurable, but also aggregate gradations and other mix design parameters required for durability.

Recurrent problems with concrete deterioration suggest that our understanding of the mechanisms may not be sufficiently complete. It is suspected that chemical admixtures and pozzolans affect the paste microstructure and hence affect spacing factor requirements for durability. Loss of entrained air during transport and placement may also be accelerated. Partial drying and rewetting may also have important effects on the microstructure and these requirements, as well as the time required to reach critical saturation levels. A research program is needed in which the mechanisms of frost action, and the protective effect of entrained air are reexamined with special emphasis on the effects of changes in the microstructure caused by use of chemical and mineral admixtures and partial drying and rewetting.

Objectives: The first objective of Task 5-2.3 is to develop an improved understanding of the mechanisms of frost action and the protective effect of entrained air, and to determine how these are modified by the use of chemical and mineral admixtures, the characteristics of aggregates, and environmental effects such as partial drying and rewetting. The second objective is to develop criteria and improved test procedures which can be used to assess the potential freeze-thaw durability of concretes and aggregates.

Sub-Task Descriptions:

Sub-Task 5-2.3,a: Review the literature on the factors influencing air void systems and frost action in cement pastes, mortars, and concretes. A review of test procedures for concrete and aggregates should also be included. Synthesize available information concerning the durability of concrete containing HRWR, fly ash, silica fume, blast furnace slag, and other admixtures. Emphasis should be on the relationships between air-void parameters (air content, specific surface, spacing factor) and durability. Data on field performance will be very valuable in this regard.

Formulate testable hypotheses for the variation of air contents, air void parameters, and other characteristics of the pore structure with

characteristics of cements and admixtures. Design experiments to separate the effects of changes of air void system parameters from the effects of changes in microstructure.

Sub-Task 5-2.3,b: Prepare air-entrained paste and mortar mixes using cements, admixtures, aggregates, and several representative air-entraining admixtures. Measure air void parameters of hardened specimens. Test hypotheses formulated in Sub-Task 5-2.3,a for variation of air contents, void system parameters, and pore structure with characteristics of cements and admixtures. Identify characteristics that have the greatest effects on air void system parameters and develop a predictive model for air entrainment in pastes and mortars.

Investigate the air void systems of concretes prepared with selected cements, admixtures, and aggregates. In addition to standard (ASTM C 457) analyses, parameters such as Philleo Factor, modal chord length, and chord length distribution functions should also be evaluated. Qualitative and quantitative studies of so-called "entrapped" air voids should also be undertaken.

Results of these investigations should be used to establish correlation between the various air void system parameters and durability as determined in subsequent tasks.

Sub-Task 5-2.3,c: Develop a procedure which can be used to accurately assess the durability of aggregates for concrete. Use field performance records of aggregate as a basis for establishing acceptance criteria. Consider both aggregate gradations and other mix design parameters of the concrete in establishing these criteria.

The validity of the test procedure developed should be statistically validated. Also, determine time and cost advantages of the test, compared with procedures previously used.

Sub-Task 5-2.3,d: Using some of the same cement pastes and mortars prepared for Sub-Task 5-2.3,b, test hypotheses formulated in Sub-Task 5-2.1,a. Perform freezing tests and compare performance and microstructures of specimens after cycles of freezing and thawing with virgin specimens by direct microscopic examinations, and other appropriate means. The degree of saturation of test specimens immediately prior to and during the course of freezing should be included in the measurements. Identify characteristics of materials that have the greatest effects on spacing factor requirements, and develop a model that can be used to predict spacing factor requirements in specific freezing tests.

Perform controlled laboratory durability tests on concretes containing selected admixtures and aggregates with mix designs typical of those used for bridge decks and highway pavements. Commonly used admixture types (such as HRWR, mineral admixtures) should be included. Testing may include standard (ASTM C 666) freeze-thaw tests, freeze-thaw tests utilizing slower rates of freezing and lower temperatures, critical dilation (ASTM C 671 and C 682) and freeze-thaw tests carried out in salt-water solution. Also included should be a study of effects of drying and saturation prior to exposure on durability.

Sub-Task 5-2.3,e: Based on the literature review on the mechanisms of salt scaling, formulate testable hypotheses in mathematical terms for the effects of chloride salts on the freeze-thaw processes. Design and perform experiments to discriminate between alternative hypotheses. Examine the effects of salt scaling on paste microstructure. Verify predicted effects of freezing and thawing during exposure to chloride solutions of hardened cement pastes of various compositions. Examine possible protective measures such as changes in the air void parameters required for durability, and the effect of cement composition on salt scaling under severe conditions. Concretes prepared with various admixtures are to be included in tests of deicer scaling resistance.

Sub-Task 5-2.3,f: In cooperation with state highway agencies, carry out field trials on at least two highway bridge decks and two pavements using admixtures and aggregates similar to those employed in the laboratory studies. Air contents should be measured at various times during placement and prior to and subsequent to consolidation and finishing. If possible, the freshly-mixed concrete air void analysis device (Task 5-3.3) should be integrated into these field studies. For the pavement sections, long-term monitoring of performance may be performed under TRA 2, Long Term Pavement Performance.

Sub-Task 5-2.3,g: Based on results of laboratory studies, develop criteria for required air contents and air void system parameters consistent with concrete durable to freezing and thawing in the presence of deicing agents. Evaluate standard test methods and specifications for materials with respect to their ability to identify characteristics that favorably influence durability. Prepare recommendations for development of improved test methods.

Estimated Cost: $1,020,000

Task Time (months): 50 months

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-2.3,a	Literature Synthesis	4	4	--	4	12
Sub-Task 5-2.3,b	Air-Void Investigation	5	10	24	2	41
Sub-Task 5-2.3,c	Aggregate Test Development	4	8	14	1	27
Sub-Task 5-2.3,d	Laboratory Durability Studies	4	13	20	2	39
Sub-Task 5-2.3,e	Salt Scaling	2	10	5	2	19
Sub-Task 5-2.3,f	Field Trials	11	4	2	1	8
Sub-Task 5-2.3,g	Criteria Development	2	2	--	1	5
	Total	22	51	65	13	151

Task 5-2.4 Title: Requirements for Aggregates, Pozzolans, and Alkali Levels to Avoid Expansions Due to Alkali-Aggregate Reactivity.

Task 5-2.4 Statement: It has become evident that earlier concepts for avoiding alkali-silica and silicate reactivity often are not effective in field structures. In some cases, low alkali cement does not eliminate the

problem. In others, test procedures do not adequately identify potentially reactive aggregates. In addition, pozzolanic requirements to avoid harmful reactivity are not fully understood and environmental conditions favorable to reactivity have not been adequately defined. Comprehensive research is needed to clarify requirements in the above areas of alkali-aggregate reactivity, so that more responsive specifications and rapid and reliable test methods can be developed to effectively avoid deleterious reactivity.

Objectives: Major objectives of Task 5-2.4 are as follows:

1. To develop a procedure to identify within one month slowly reactive aggregates.

2. To characterize quantitatively relationships among alkalies, aggregate characteristics, and pozzolans that sustain or prevent deleterious reactivity.

3. Define the internal relative humidity and temperature relationship under which expansions occur.

4. From the foregoing, identify practical measures that control expansive reactivity.

Sub-Task Descriptions:

Sub-Task 5-2.4,a: Conduct an investigation to determine aggregate types and quantities, alkali levels, concrete mix designs, service record, and type of structure where deleterious alkali-aggregate reactivity has or has not occurred in field concrete. Field environmental determinations should not be included since this information will be developed in a separate task (5-2.2) to identify moisture gradients and relative humidities in concrete.

Sub-Task 5-2.4,b: Based on information developed in Sub-Task 5-2.4,a, test in the laboratory combinations of materials that will fully identify interrelationships that permit or prevent expansions due to reactivity. Develop test methods to assure such performance.

Sub-Task 5-2.4,c: Conduct laboratory studies to characterize environmental limits favorable to expansion due to alkalia-aggregate reactivity. Include alkali from external sources such as deicer salts, and conditions under which concentration gradients of alkali may develop in the concrete.

Sub-Task 5-2.4,d: Prepare a report which describes the work carried on in this project, and includes guidelines on permissible or required cement alkali-aggregate-environmental combinations to avoid distress due to alkali-aggregate reactivity.

Estimated Cost of 5-2.4: $625,000

Task Time (months): 60 months

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-2.4,a	Lab Study	6	--	--	3	9
Sub-Task 5-2.4,b	Test Methods	9	6	16	--	31
Sub-Task 5-2.4,c	Environmental Effects	12	6	9	--	27
Sub-Task 5-2.4,d	Report	3	3	--	0.5	6.5
	Total	30	15	25	3.5	73.5

Task 5-2.5 Title: Computerized Expert System for Durability and Service Life of Concrete.

Task 5-2.5 Statement: Among the most active research areas in artificial intelligence during the past 20 years has been the development of expert systems, which also are known as knowledge-based systems. The usefulness of expert systems in solving difficult practical problems has become recognized and their development is being pursued in many fields. For example, expert systems have been developed to give recommendations in such areas as medical diagnosis, mineral exploration, and structural analysis. An expert system should be able to give recommendations at a level comparable to, or above, an expert. Expert systems are most useful when the knowledge is based on heuristics and when mathematical relationships are not available, which is often the case in the construction field.

The knowledge required to solve difficult problems encountered in the construction industry is not often readily available to the field engineer or designer. Until now the construction industry had to depend on a relatively few well-qualified experts to give recommendations on problem resolution. Expert systems appear to be an effective tool for preserving and maintaining the knowledge of experts and for using it in solving difficult problems. The area of concrete durability is one in which such expert knowledge is often employed, and one which is ripe for development of expert systems. Major problems encountered in durability of concrete structures often can be expeditiously solved if experience and expert assistance can be judiciously applied. It is also an accepted fact that major problems encountered in the durability of concrete can be significantly reduced by improved selection of concrete constituents and concrete design. Development of expert systems in this area, augmented by field and laboratory testing of materials, can improve performance of concretes subject to severe environments.

Objective: The objective of Task 5-2.5 is to develop a computer-based expert system covering the area of concrete durability. Such an expert system will allow the user to diagnose concrete materials problems, select repair strategies, select concrete materials and mix designs so that structures may be successfully rehabilitated or, in the case of new construction, be designed to perform adequately in the environment of interest. Emphasis should be placed on collecting data, rather than on the development of more sophistication in the computer system.

Sub-Task Descriptions:

Sub-Task 5-2.5,a: The general programming techniques, knowledge base, and central system to be used will be developed for the diagnosis of concrete

durability problems. This will include the fields of freezing and thawing resistance, sulfate resistance, and cement/aggregate reactions. If feasible, resistance of the concrete to chemical attack should also be included. Identification should be made of all sources of information in the system.

Sub-Task 5-2.5,b: The freezing and thawing knowledge base will be developed and integrated into the computer program. Sources to be used should include, but not be limited to, ACI documents, reviews of pertinent literature, and interviews with acknowledged experts. At least three experts shall be interviewed in depth for this task.

Sub-Task 5-2.5,c: The area of sulfate resistance will be addressed using the same techniques as outlined in Sub-Task 5-2.5,b.

Sub-Task 5-2.5,d: The area of cement/aggregate interaction will be addressed using the same techniques as outlined in Sub-Task 5-2.5,b.

Sub-Task 5-2.5,e: If sufficient, well documented information exists, the area of chemical attack on concrete shall be addressed.

Sub-Task 5-2.5,f: All areas will be integrated and the complete expert system will be thoroughly documented and made available in format suitable for use on an IBM personal computer (or equivalent). Copies of the user's manual and disc should be sent to at least 5 users in state highway agencies. The users should be selected so as to represent geographical regions where different durability problems are encountered. The users should be encouraged to use the system for a few typical problems, and report their findings, impressions, and suggestions to the contractor.

Estimated Cost of 5-2.5: $750,000

Task Time (months): 24

Man-Months:	SP	RA	T	S	Total
Sub-Task 5-2.5,a General Programming	4	6	6	12	28
Sub-Task 5-2.5,b Knowledge Base Freeze-Thaw	6	9	4	2	21
Sub-Task 5-2.5,c Knowledge Base Sulfate Resistance	4	6	4	2	16
Sub-Task 5-2.5,d Knowledge Base Cement/ Aggregate Interaction	4	6	4	1	15
Sub-Task 5-2.5,e Knowledge Base Chemical Attack	2	3	1	1	7
Sub-Task 5-2.5,f Documentation and Trials	4	6	5	6	21
Total	24	36	24	24	108

PROJECT 5-3 Title: Quality Control and Condition Analysis Through Non-Destructive Testing

Project 5-3 Statement: Quality control during construction is an absolute necessity to ensure the requirements of function and durability. The knowledge that is gained in the tasks involved in Project 5-1, Chemistry and Physics of Cement and Concrete and Project 5-2, Durability of Concrete, in addition to existing technology, all come to naught in the absence of adequate quality control during construction. Non-destructive testing can play a significant role in achieving the needed level of control. Such techniques can also be useful in evaluating the condition of existing structures, thus enabling the necessary remedial measures to be taken to extend service life.

The tasks in Project 5-3 are directed to these ends, in a relatively specific form directed to specific needs of the present regarding pavement system function and durability. The interrelationship of these tasks is shown in Figure 4. They are, in order of priority, as follows:

5-3.1 Develop a quality-assurance system for acceptance, form stripping, and placing in service based on existing non-destructive tests.

5-3.2 Develop an in-place test for permeability of hardened concrete as a criterion for durability.

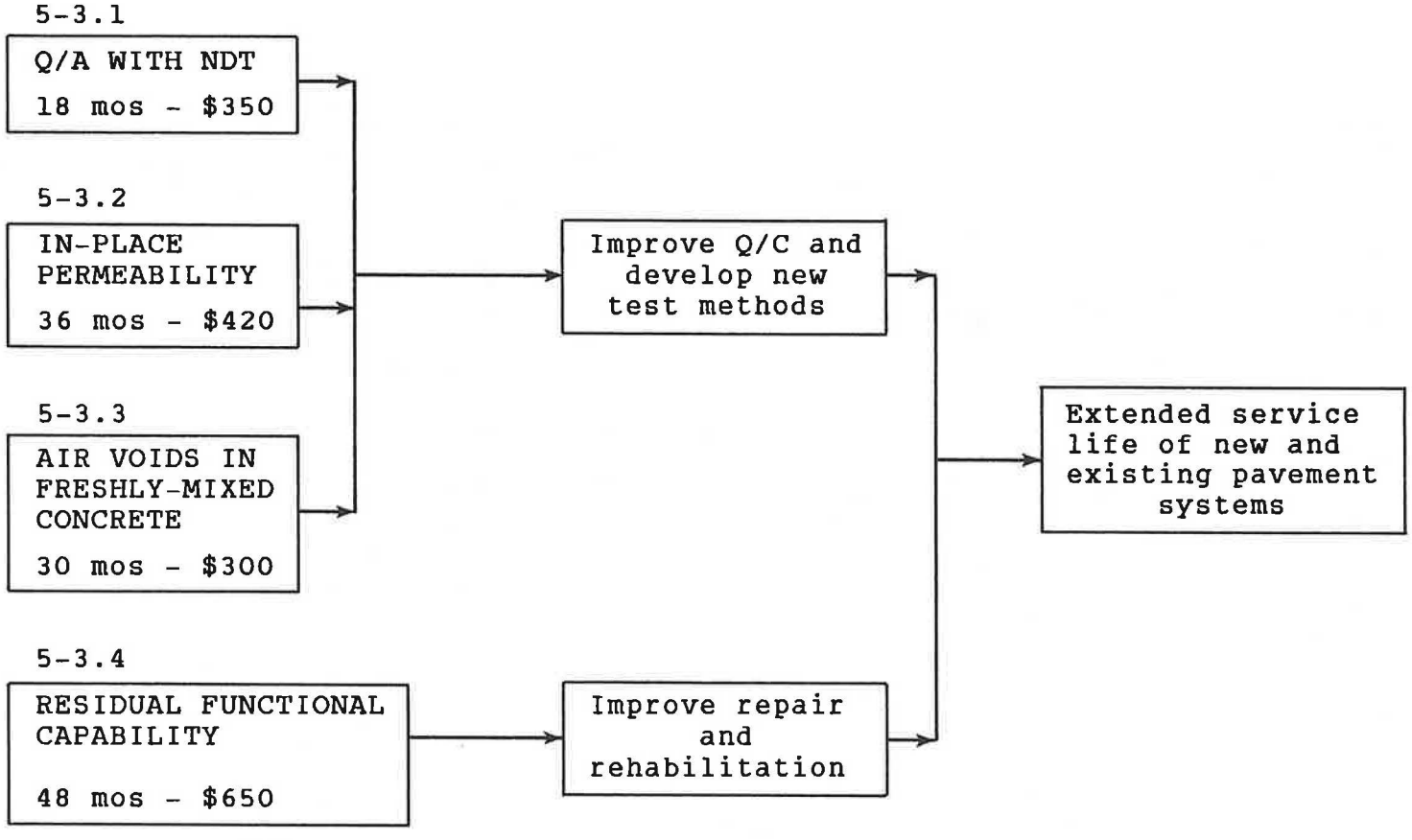
5-3.3 Develop a test method and apparatus to determine the characteristics of the entrained air void system in freshly mixed concrete to facilitate acceptance or rejection before placement.

5-3.4 Develop equipment and techniques to determine the residual functional capability of existing elements in a pavement system.

Task 5-3.1 Title: Adapting Non-Destructive Tests to a Quality Assurance System for Acceptance, Form Stripping, and Placing in Service.

Task 5-3.1 Statement: In an over-all quality assurance program, it must be assured that a finished concrete element is structurally adequate for the purposes for which it has been designed. If the 28-day compressive strength of test cylinders or cubes, or flexural strengths of beams, indicates compliance with specified strength, it is assumed that the concrete represented by the test specimens satisfies the design criteria. The main disadvantages of this approach are: the delay in obtaining test results, the fact that the test specimens may not be truly representative of concrete in a structure because of different placing, consolidation and curing conditions, the necessity of testing the specimens to failure, and the fact that other properties of concrete, such as w/c ratios, air void characteristics, extent of curing, consolidation, and permeability may have a greater influence on ultimate durability of a concrete structure than compressive strength. These, combined with the fact that structural concrete elements are considerably larger and more massive in size than test specimens, cast doubt whether test cylinders, beams, or other types of specimens tested in the laboratory do really represent the in-place properties of concrete in a structure. As a result, there have been a large number of attempts over the last 40 years to develop methods for in-situ and non-destructive testing of concrete.

FIGURE 4
PROJECT 5-3 FLOW CHART



Footnote: $ in Thousands

Most of this work has focussed on alternatives to strength test cylinders, and has included techniques such as pulse velocity, rebound, penetration resistance, pull-out, break-off, and maturity methods. Combinations of these techniques have also been utilized with some degree of success. Further work is needed to develop a quality assurance system which integrates these techniques with others being developed under the SHRP program. As has been done with concrete compressive and flexural strength, statistically-based acceptance procedures are needed which would allow the implementation of these non-destructive, rapid techniques into current specifications.

Objectives: The objectives of Task 5-3.1 are to evaluate the precision, accuracy, and reliability of a variety of non-destructive techniques (using those already developed for prediction of strength, as well as those NDT techniques being developed in other phases of the SHRP program). These statistical data will be used to develop model quality assurance programs into which these techniques can be integrated. Field trials of these programs, in cooperation with state highway agencies, would be desirable.

Sub-Task Descriptions:

Sub-Task 5-3.1,a: Review published information with regard to non-destructive techniques which can be used to assess quality of in-place concrete. Emphasis should be on precision, accuracy, and reliability of the techniques. Special consideration should be given to those studies utilizing combinations of techniques for improved precision and accuracy. Techniques developed under other SHRP tasks will also be reviewed.

Sub-Task 5-3.1,b: On the basis of results obtained in Sub-Task 5-3.1,a, select those techniques which show the most promise in application to an integrated quality assurance program for highway construction. Emphasis should be on those techniques most applicable to use by both contractor and inspector agency personnel. Carry out limited laboratory evaluation in order to verify performance of the system selected. Concrete materials and mixtures typical of those used for pavement and structural applications should be included.

Sub-Task 5-3.1,c: Develop statistically based quality assurance systems utilizing the package of techniques. Model programs should be developed for full-scale paving operations and for bridge deck placements. Consideration should be given to inclusion of adjusted pay schedules in the model programs. Acceptance based on overall quality level (as determined by the non-destructive techniques) as well as schemes for use of non-destructive methods to determine optimum times for form stripping should be included.

Sub-Task 5-3.1,d: Conduct field trials of the model quality assurance programs at two construction sites in cooperation with appropriate state highway agencies. These trials should include demonstration of the feasibility of use of these programs by contractor personnel.

Estimated Cost of 5-3.1: $350,000

Task Time (months): 18 months

Man-Months:	SP	RA	T	S	Total
Sub-Task 5-3.1,a Information Review	2	2	--	1	5
Sub-Task 5-3.1,b Technique Section	4	6	6	2	18
Sub-Task 5-3.1,c Quality Assurance System Development	6	4	--	4	14
Sub-Task 5-3.1,d Field Trials	1	2	4	1	8
Totals	13	14	10	8	45

Task 5-3.2 Title: Measurement of In-Place Permeability of Hardened Concrete

Task 5-3.2 Statement: The majority of highway components are subjected to ingress of water from various sources, including direct rainfall on flatwork, splash from vehicles onto support elements, drainage through joints, or hydraulic pressure from subgrade. This moisture is known to be a key component in such deteriorative processes as freeze-thaw, scaling, alkali-aggregate reactivity, chemical attack, D-cracking, and corrosion of reinforcing steel. Reduction in permeability of concrete to liquids is one method for avoiding such problems. A need exists for a rapid, reliable field test which can measure the permeability of concrete so as to ensure that the low permeability needed to resist ingress of fluids has been achieved.

Objective: The objective of Task 5-3.2 is to develop a rapid, reliable technique for field measurement of in-situ concrete permeability. A non-invasive approach is preferable. However, techniques which would involve only limited disturbance of concrete (e.g using a small drill hole) would be acceptable. The technique should be capable of measurement of permeabilities of a variety of concretes, ranging from very dense mixtures to porous low quality concretes. While a technique capable of measurement of absolute permeability in conventional units (i.e. Darcys) would be preferable, techniques which measure relative permeability would also be acceptable, provided calibration was relatively easy and results reproducible. If feasible, the technique should have the capability of "profiling" permeability from the top layer of concrete (within 0.5-in. of the surface) to the interior of the concrete member.

Sub-Task Descriptions:

Sub-Task 5-3.2,a: Conduct a review of current technology to identify whether any techniques are currently available which could be adapted to the current problem. Consideration should be given to air permeability measurements, electrical resistance measurements, high pressure, and applied voltage techniques, among others.

Sub-Task 5-3.2,b: Construct equipment for preliminary laboratory experiments and verify the accuracy of the approach using carefully prepared concretes exhibiting a wide range of permeabilities. Concretes should be prepared over a wide range of compositions, so that the effects of such variables as cement type, aggregate type, cement content, and presence of admixtures (including calcium chloride) may be studied. If possible, the method under development should be compared with standardized laboratory permeability tests to establish correlation.

Sub-Task 5-3.2,c: Construct a field prototype device incorporating desirable features of the equipment developed in Sub-Task 5-3.2,b. Test the prototype on laboratory-scale specimens representing such highway components as pavements, CRCP, bridge decks, and substructure elements. Determine the effects of temperature, steel location, depth of clear cover, concrete thickness, and moisture content on instrument response.

Sub-Task 5-3.2,d: Conduct field trials on concrete highway structures. These should include pavements, bridge decks, and structural elements. A variety of different concrete mixtures and materials should be selected for these field trials.

Sub-Task 5-3.2,e: Prepare an operation manual for the equipment. Calibration procedures, operations sequences, maintenence requirements, schematics, and troubleshooting information should be included.

Estimated Cost of 5-3.2: $420,000

Task Time (months): 36

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-3.2,a	Review of Technology	2	1	--	0.5	3.5
Sub-Task 5-3.2,b	Construct Equipment and Test	6	8	8	2	24
Sub-Task 5-3.2,c	Construct Prototype	4	6	4	2	16
Sub-Task 5-3.2,d	Field Trials	1	2	2	0.5	5.5
Sub-Task 5-3.2,e	Manual	2	1	--	1	4
	Total	15	18	14	5	53

Task 5-3.3 Title: Test Method to Determine the Air Void Characteristics of Freshly Mixed Concrete.

Task 5-3.3 Statement: It is well known that simply achieving the specified volume of air in concrete does not assure adequate freeze-thaw durability. More important is the size distribution of entrained air voids and the average spacing of voids. The most desirable time to determine these parameters is prior to placement and hardening of the concrete. Presently, methods for making these determinations exist only for hardened concrete. Thus, a serious need exists to have available a test method that will rapidly and reliably determine the size distribution of air voids in freshly mixed concrete, both before and immediately after placement.

Objectives: Major objectives of Task 5-3.3 are:

1. To develop a rapid and reliable procedure for determining the air void characteristics of freshly mixed concrete, both before and immediately after placement.

2. To demonstrate the usefulness of the procedure at mixing plants and construction sites.

3. To establish guidelines for use of the procedure in determining the adequacy of the entrained air void system to provide frost protection for concrete.

Sub-Task Descriptions:

Sub-Task 5-3.3,a: Conduct a literature search to identify whether any previous procedures may hold merit for further development or whether an original approach is needed to develop a usable procedure. Consideration should be given to methods such as ultra-sonic testing and variations of measurements using pressure meters.

Sub-Task 5-3.3,b: Conduct laboratory research to develop a procedure capable of determining the air void characteristics of freshly mixed concrete.

Sub-Task 5-3.3,c: If the work in Sub-Task 5-3.3,b is successful, validate the procedure with respect to air void requirements for freeze-thaw and deicer scale resistance of concrete. This should include verification against linear traverse measurements on hardened concrete. A variety of concretes should be utilized in this task, including those containing crushed stone, natural gravel, lightweight aggregate, different mineral and chemical admixtures, and concretes with different cement factors, water-cement ratios, and workability characteristics.

Sub-Task 5-3.3,d: Demonstrate the usefulness of the procedure at three mix plants and at three construction sites.

Sub-Task 5-3.3,e: Prepare a final report on this work and include guidelines and procedures for utilizing the test method.

Estimated Cost of 5-3.3: $300,000

Task Time (months): 30

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-3.3,a	Literature Search	2	--	--	--	2
Sub-Task 5-3.3,b	Lab Research	3	3	3	1	10
Sub-Task 5-3.3,c	Verification	1	3	6	--	10
Sub-Task 5-3.3,d	Demonstration	1	--	3	--	4
Sub-Task 5-3.3,e	Report	2	1	--	1	4
	Total	9	7	12	2	30

Task 5-3.4 Title: Residual Functional Capability.

Task 5-3.4 Statement: To develop a nondestructive technique to monitor the condition of a concrete pavement or concrete structure. Techniques for measuring the residual strength and condition of the concrete should be developed. This task should enable more effective planning of maintenance, repair, and rehabilitation activities. The system should provide valuable diagnostic information to highway engineers and thus prolong the service life of concrete pavements. At present, there is no simple and reliable

nondestructive means to evaluate the internal condition of hardened concrete. Typically, to determine the residual strength of concrete after years in service, cores are extracted from pavements and various destructive tests are performed. This task should enable highway department personnel to monitor the condition of the concrete after years of service in harsh exposure conditions such as freeze-thaw, deicer scaling, repeated loadings, and experiencing alkali-aggregate reaction, etc. This task should provide information with regard to the potential condition of the structure thus resulting in more effective maintenance of pavements and safer roadway conditions. The expert system to be developed in Task 5-2.5 should be utilized as a diagnostic tool.

Objectives: The objective of Task 5-3.4 is to develop nondestructive equipment and techniques to determine the residual strength and condition of a concrete pavement. This equipment should have the capability of detecting imperfections in pavements that could influence the service life. This equipment could be adapted to other concrete highway structures.

Sub Task Descriptions:

Sub-Task 5-3.4,a: Conduct a literature search to identify candidate techniques that might be used to determine the residual strength and condition of concrete. It is strongly suggested that other industries be checked to determine whether their equipment may be suitable (technology transfer).

Sub-Task 5-3.4,b: Based on findings of Sub-Task 5-3.4,a, select the most appropriate method for further study. For the method selected, develop the necessary equipment. The equipment should be tested in the laboratory. Concrete pavements should be cast and subjected to repeated loadings while exposed to harsh environmental conditions. Potential for alkali-aggregate reactivity should be included. Both high and low quality concretes should be used. The developed equipment should be used to characterize the internal condition of the pavement after application of loads and environmental conditions. Cores should be obtained and examined to verify the condition of the pavement.

Sub-Task 5-3.4,c: After successful prediction of residual strengths and condition in the laboratory, Sub-Task 5-3.4,b, evaluate the capabilities of the equipment as to accuracy, sensitivity, and reproducibility in at least five field trials, and develop field techniques. Obtain cores from each structure examined and verify the accuracy of the equipment.

Sub-Task 5-3.4,d: Based on results obtained in the laboratory and field trials, establish criteria for determining the residual strength and condition of field concrete. Prepare a final report.

Estimated Cost of 5-3.4: $650,000

Task Time (months): 48

Man-Months:		SP	RA	T	S	Total
Sub-Task						
Sub-Task 5-3.4,a	Literature Search	1.5	3.5	-	4.5	9.5
Sub-Task 5-3.4,b	Equipment	2.5	10.0	9.5	3.5	25.5
Sub-Task 5-3.4,c	Evaluation	1.5	6.0	11.0	2.5	21.0
Sub-Task 5-3.4,d	Criteria	2.5	5.0	1.5	2.5	11.0
Totals		8.0	24.5	22.0	13.0	67.5

Project 5-4 Title: Mechanical Behavior of Concrete

Project 5-4 Statement: The mechanical behavior of concrete during its exposure to traffic loads plays an important role in the performance of the pavement system. While much is known about the mechanical behavior of most present-day concretes, relatively new developments in concrete technology may be of significance in improving the function and durability of pavement systems. The use of materials such as fly ash, ground granulated blast-furnace slag, and silica fume is playing an increasingly important role in enhancing durability. Fiber reinforcement in concrete and shotcrete is assisting in mitigating cracking problems, and high strength concrete is providing the capability for longer span bridges. To utilize these materials properly, more information on the mechanical properties of such concretes is required.

Project 5-4 includes four tasks as follows, in order of priority. The interrelationship of these tasks is shown in Figure 5.

5-4.1 The fatigue and strain capacity of high strength concrete subjected to repetitive loading.

5-4.2 The properties of early high strength concrete.

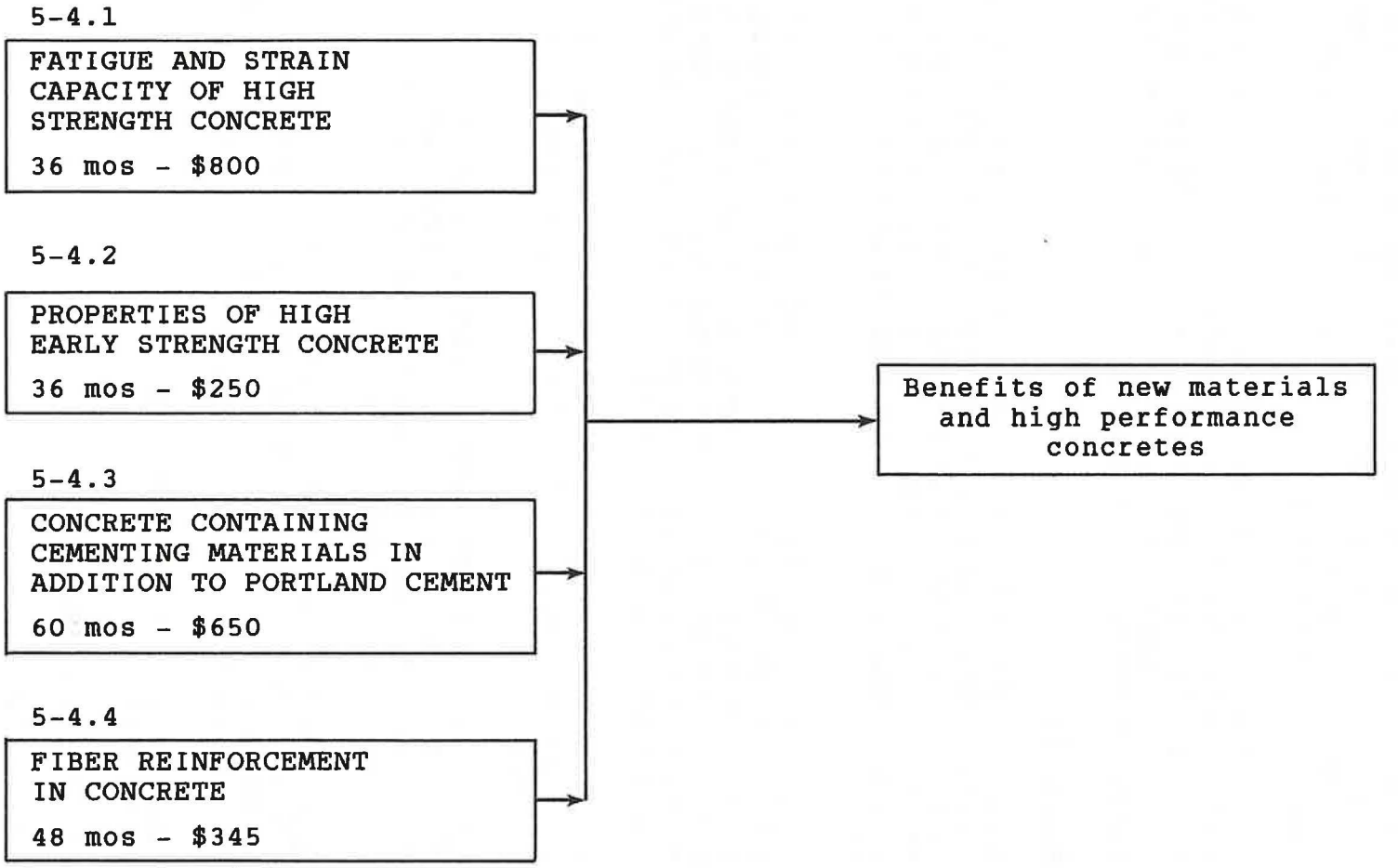
5-4.3 The influence of additional cementing materials such as fly ash, slag, and silica fume on the mechanical behavior of concrete.

5-4.4 The effect of random fiber reinforcement, including combinations of different fibers on structural properties of concrete.

Task 5-4.1 Title: Determination of Fatigue and Strain Capacity of High-Strength Concrete.

Task 5-4.1 Statement: To develop data on the fatigue behavior and strain capacity of high strength concrete. To date there is very limited published information regarding fatigue and strain capacity of high strength concrete. Limited tests have shown that the fatigue strength of high strength concrete is the same as that for concrete of lower strength. With the increasing use of high strength concrete in not only long-span bridges but in deck overlays and pavement overlays, more information is needed to properly design such elements for fatigue and strain capacity. Both concrete component materials as well as full-size structures should be investigated. Data should be developed to determine the relationship of strength to modulus of

FIGURE 5
PROJECT 5-4 FLOW CHART



Footnote: $ in Thousands

elasticity under fatigue conditions, i.e, check on validity of ACI-318 Modulus of Elasticity formula. Deflections and strains should be established for full size structures. S-N curves at different stress levels should be developed. The following variables should be among those investigated: concrete materials such as fly ash, water reducers, silica fume, ground blast-furnace slag (GBFS), type of aggregate (including maximum aggregate size and particle shape), steel (bond and anchorage, type, epoxy coating), and external condition (moisture and temperature). Fatigue and strain capacity tests should be compared to moderate strength concrete.

Objectives: The objective of Task 5-4.1 is to develop detailed fatigue limit and strain capacity data for high strength concretes. Tests should be conducted to characterize both component concrete and full-size members for fatigue resistance and strain capacity so that designers can adequately design structures containing high strength concrete.

Sub-Task Descriptions:

Sub-Task 5-4.1,a: Conduct a literature search to gather available data on fatigue strength and strain capacity of high strength concrete. The literature search should direct attention to the relationship with compressive, flexural, and tensile strength, modulus of elasticity, concrete material composition, environmental conditions, and bond and anchorage of steel reinforcement.

Sub-Task 5-4.1,b: Cast a variety of high strength concretes with different materials such as fly ash, GBFS, silica fume, water reducers, aggregate types and sizes, and a lower strength control concrete. Conduct compressive, flexural, and tensile fatigue tests. Develop data on strain capacity. Data on modulus of elasticity and residual strength for companion specimens subjected to fatigue loading should be developed.

Sub-Task 5-4.1,c: Conduct fatigue tests to determine the effect of external conditions (moisture and temperature) on Task 5-4.1,b specimens, including strain capacity data.

Sub-Task 5-4.1,d: Perform dynamic bond and anchorage tests on steel reinforcement. Check the effect of epoxy coated steel reinforcement. For selected high strength concretes, determine the fatigue strength (bond) with respect to bar size, shape, and deformations.

Sub-Task 5-4.1,e: Cast at least five full size beams with selected high strength concretes. Include lower strength concretes. Repeated loadings should be applied in a flexural mode to full-size members. Beams should be instrumented for continuous readout of deflections and strains.

Sub-Task 5-4.1,f: Prepare a final report with design criteria for structural engineering needs.

Estimated Cost of 5-4.1: $800,000

Task Time (months): 36

Sub-Task

Man-Months:		SP	RA	T	S	Total
Sub-Task 5-4.1,a	Literature	1.5	2.5	1.5	2.0	7.5
Sub-Task 5-4.1,b	Laboratory	2.5	7.0	12.0	2.0	23.5
Sub-Task 5-4.1,c	Fatigue Tests	1.5	3.5	5.0	1.0	11.0
Sub-Task 5-4.1,d	Bond Tests	1.5	2.5	5.0	1.0	10.0
Sub-Task 5-4.1,e	Beam Tests	4.5	8.0	24..0	4.5	41.0
Sub-Task 5-4.1,f	Report	3.5	5.0	2.5	2.5	13.5
Totals		15.0	28.5	50.0	13.0	106.5

Task 5-4.2 Title: Properties of High Early Strength Concrete.

Task 5-4.2 Statement: Repair and rehabilitation operations to increase the service life of existing pavements and structures require the use of cementitious systems which will develop relatively high strength at early ages and which will be durable. In terms of avoiding costly traffic tie-ups and safety provisions, adequate strength to carry traffic as early as four hours would provide this much-needed capability. In addition to compressive strength, more data are required concerning flexural and tensile strengths, modulus of elasticity, volume stability (creep and drying shrinkage) and, most importantly, durability. Durability is a prime consideration if service life is to be significantly increased. The system needs to be amenable to construction requirements.

Objective: The major objective of Task 5-4.2 is to develop technical data on properties such as rate of strength development (compressive, flexural, and tensile), volume stability (creep, drying shrinkage, and thermal coefficient), and resistance to freezing and thawing and deicer scaling of mortar and concrete systems which develop high strength at early ages.

Sub-Task Descriptions:

Sub-Task 5-4.2,a: Conduct a literature search to develop currently available data on such mortar and concrete systems, with respect to the properties of interest, utilizing where possible, information from other than published sources, i. e. studies currently underway by various investigators.

Sub-Task 5-4.2,b: Develop and execute a laboratory program designed to provide the data desired on the properties enumerated in the objective. Materials to be utilized should include portland cements and blended cements, fly ash, ground granulated blast furnace slag, silica fume, other possible cementing materials, and chemical admixtures such as accelerators and high range water reducers. Properties to emphasize are strength development, volume stability, durability, and capability of use under varied construction conditions.

Sub-Task 5-4.2,c: Select at least three of the most promising systems for field demonstration in typical maintenance applications in moderate and severe climate locations. Evaluate early performance data such as mixing, handling, placing, and finishing characteristics, in addition to early

strength development. Monitor performance for a period of at least three years.

Sub-Task 5-4.2,d: Prepare a final report with guidelines and criteria for the use of such systems.

Estimated Cost of 5-4.2: $250,000

Task Time (Months): 36 months

Man Months		SP	RA	T	S	Total
Sub-Task 5-4.2,a	Literature	1.0	2.0	0.5	0.5	4.0
Sub-Task 5-4.2,b	Lab Tests	2.0	4.0	8.0	1.0	15.0
Sub-Task 5-4.2,c	Field Tests	3.0	2.0	7.0	1.0	13.0
Sub-Task 5-4.2,d	Report	2.0	2.0	--	2.0	6.0
Totals		8.0	10.0	15.5	4.5	38.0

Task 5-4.3 Title: Determination of Structural Properties of Concrete Containing Cementing Materials in Addition to Portland Cement.

Task 5-4.3 Statement: This task will provide detailed information on the effect of cementing materials in addition to portland cement in concrete. The task will include the use of fly ash and ground blast-furnace slag (GBFS), with some limited use of silica fume and other potential cementing materials. In line with the national policy of energy conservation, this work is to be conducted to provide a basis for intelligent use of these materials. The use of such products is to enhance the performance of concrete, particularly durability in aggressive environments. These materials may improve the performance of concrete under certain circumstances, however, each may have limiting use or have some adverse effects on concrete performance. Data should be developed to predict concrete performance. Tests should be conducted to determine optimum amount of these waste products from economic and technical standpoints. This task should provide pavements that have better durability to certain exposures and a reduced first cost.

Objectives: To evaluate the effect of cementing materials in addition to portland cement on concrete performance. To determine the optimum amount of such materials that can be introduced into concrete without jeopardizing concrete performance, particularly durability. Concrete containing fly ash, ground blast-furnace slag, silica fume, and other cementing materials should be evaluated.

Sub-Task Descriptions:

Sub-Task 5-4.3,a: While there is a significant amount of published data concerning fly ash, GBFS, and silica fume in the available literature, a limited literature search for optimum quantities and utilization of these materials and other cementing materials in specific aggressive environments, particularly to enhance durability, should be conducted.

Sub-Task 5-4.3,b: Tests of laboratory concrete mixtures with varying percentages of replacement for cement should be conducted. While this project

should not focus on silica fume, cast concretes with 3 to 5% silica fume by weight of cement should be studied to establish the effect on permeability. Combinations of fly ash, slag, silica fume and other possible cementing materials should be studied to evaluate the potential for significant decreases in permeability and resistance to chloride penetration. Various properties should be characterized, such as compressive and flexural strength, modulus of elasticity, drying shrinkage, creep, cracking tendency, and permeability. The relative costs of replacement should be considered to optimize costs (economic analy- sis), as well as performance. Some durability tests should be performed to evaluate the effect of reduced permeability.

Sub-Task 5-4.3,c: From testing and economic analysis in Sub-Task 5-4.3,b, select four concrete mixtures with fly ash, two mixtures with GBFS, one with silica fume, and one with another potential cementing material for conducting field tests. This sub-task should be integrated with TRA 2, Long-Term Pavement Performance. Select four geographical areas, varying in environmental conditions, to conduct these trials. Cast test sections of pavements. Pavements should be instrumented with strain gages or other devices to evaluate performance, in addition to visual observations.

Sub-Task 5-4.3,d: Evaluate performance of field tests and establish criteria for selection and use of supplementary cementitious materials. Prepare a final report with guidelines for use of the materials.

Estimated Cost of 5-4.3: $650,000

Task Time (months): 60

Man Months		SP	RA	T	S	Total
Sub-Task 5-4.3,a	Literature	1.5	5.0	1.0	5.0	12.5
Sub-Task 5-4.3,b	Lab Tests	2.5	7.0	9.0	1.5	20.0
Sub-Task 5-4.3,c	Field Tests	2.5	7.0	8.0	2.5	20.0
Sub-Task 5-4.3,d	Criteria	1.5	5.0	2.0	3.5	12.0
Totals		8.0	24.0	20.0	12.5	64.5

Task 5-4.4 Title: Effect of the Use of a Combination of Fibers in Concrete.

Task 5-4.4 Statement: Considerable research has been conducted with fiber reinforced concrete (FRC) using one type of fiber within the concrete. There has been little development work with combinations of fiber types for FRC. Concretes have been made with steel, glass, polypropylene, asbestos, Kevlar, and other fibers, each fiber resulting in advantages for concrete and some disadvantages. This project will attempt to use different fiber types in combination to improve performance of concrete. Generally, the mechanical properties of concrete with steel fibers are better than concrete without these fibers. Other fibers, such as polypropylene, impart to concrete improved crack control; however, polypropylene fibers have some drawbacks.

Objectives: To develop information on FRC using various combinations of fibers. Tests should be conducted to establish the best combination of fibers, and methods for handling and placing should be examined.

Sub-Task Descriptions:

Sub-Task 5-4.4,a: Conduct a literature search to determine whether published or unpublished data exist concerning FRC with different combination of fiber types. It is believed that very little published data is presently available. If the literature search uncovers some data, select the most appropriate for further examination.

Sub-Task 5-4.4,b: Conduct trial mixes in the laboratory to determine optimum ratios of various fibers from the standpoint of flexural strength and crack control. In these laboratory trial mixes, aspect ratio should be varied as well as fiber type. Select two or three combinations and conduct a full series of mechanical property and durability tests. Mechanical properties checked should at least include: flexure, tensile and compressive strength, modulus of elasticity, Poisson's ratio, crack development, ductility, abrasion, friction, skid resistance, and toughness. Durability tests should include: freeze-thaw, deicer scaling resistance, and corrosion resistance. During the casting laboratory specimens, determine possible techniques necessary for handling and placing FRC.

Sub-Task 5-4.4,c: Establish optimum fiber types and combinations. Establish techniques for handling fibers and methods for handling and placing. Prepare a final report.

Estimated Cost of 5-4.4: $345,000

Task Time (months): 48

Man Months		SP	RA	T	S	Total
Sub-Task 5-4.4,a	Literature	1.5	3.5	--	3.5	8.5
Sub-Task 5-4.4,b	Lab Tests	3.5	7.0	19.0	2.5	32.0
Sub-Task 5-4.4,c	Report	2.5	7.0	1.0	2.5	13.0
Totals		7.5	17.5	20.0	8.5	53.5

SECTION 5
TRA 5 - RESULTS TO BE ACHIEVED

The results to be achieved by this research plan on cement and concrete cover a wide range of possibilities. Most of these have been described in detail in the goals and objectives set forth in the description of the projects, tasks, and sub-tasks in Section 4. These are summarized in the following paragraphs.

SUMMARY OF PROJECT AREAS

- Chemistry and Physics of Cement and Concrete, Proj. 5-1
- Durability of Concrete, Proj. 5-2
- Quality Control and Condition Analysis Through Non-Destructive Testing, Proj. 5-3
- Mechanical Behavior of Concrete, Proj. 5-4

Chemistry and Physics of Cement and Concrete, Proj. 5-1

The cost effectiveness of this project is difficult to determine. However, success in a significant number of the tasks will contribute to longer service life and significant savings. There are three tasks which have been developed to achieve the goals and objectives of this project. These are shown below, along with the results to be achieved in each:

Task 5-1.1 Development of the Microstructure of Concrete for Improved Performance

- Capability of controlling and optimizing the microstructure of the hydrated paste system in order to reduce permeability to the point where resistance to freezing and thawing, deicer salts, and aggressive chemicals in the environment is greatly increased, thus increasing service life.

- Improved understanding of hydration processes which will lead to potential adaptations of the use of materials, possibly some from other technologies, which can contribute to improved performance.

- Development of predictive models for performance.

- New instrumentation and test techniques which will assist in the development of specification requirements and standard test methods to assist in quality assurance/quality control programs.

Task 5-1.2 Mechanisms of Chemical Deterioration Processes and Their Control

- Reduction of the probability of deterioration resulting from alkali-silica reaction in new concrete pavement systems.
- Increased knowledge concerning the mechanism of alkali-silica reaction will lead to the development of more rational specifications and more reliable test methods.
- Increased knowledge concerning the mechanism of alkali-silica reaction will assist in achieving the objectives of Task 5-2.1 on Minimizing Deterioration Due to D-Cracking and Alkali-Silica Reactivity in Existing Concrete Pavements.

Task 5-1.3 Development of Superior Concrete for Highways

- Will provide the capability to utilize available cementitious materials to provide a concrete which develops strength rapidly and has greatly extended service life.

Durability of Concrete, Proj. 5-2

There are five tasks which have been selected to achieve the goals and objectives of this project. All of them show a high probability of achieving useful results which will extend the service life of not only newly-constructed pavement systems, but also existing systems with lives shortened by the deterioration they are undergoing. The tasks and results anticipated are as follows:

Task 5-2.1 Minimizing Deterioration Due to D-Cracking and Alkali-Silica Reactivity in Existing Concrete Pavements

- Will provide a means for halting or significantly reducing the deterioration which has resulted in existing structures from the use of aggregates susceptible to producing D-cracking in freezing and thawing environments, including a field demonstration of effectiveness.
- Will provide a means for halting or significantly reducing the expansion and cracking leading to deterioration of concrete due to the alkali-silica reaction pre-existing, including a field demonstration of effectiveness.

Task 5-2.2 Develop Technique to Characterize Moisture and Relative Humidity Gradients in Field Concrete

- Will provide equipment and techniques to monitor the internal moisture condition of concrete in the field to provide a more accurate characterization of the environment to enable (1) designing for longer life new structures, and (2) providing a basis for the adoption of remedial and maintenance measures to extend service life.

Task 5-2.3 Improved Assessment of the Freeze-Thaw Durability of Concrete and Aggregates and Air Void Criteria

- Will provide more rapid and reliable test methods to evaluate aggregate suitability for concrete exposed to freezing and thawing.
- Will provide more reliable criteria for specification use re: freeze-thaw durability of aggregates.
- Will provide more reliable criteria for the specification of needed entrained air void characteristics as a function of the use of chemical and mineral admixtures and in different environmental exposures, including the use of chemical deicers.

Task 5-2.4 Requirements for Aggregates, Pozzolans, and Alkali Levels to Avoid Expansions Due to Alkali-Aggregate Reactivity

- Will provide a test procedure to rapidly identify slowly reactive aggregates.
- Will provide more definitive information on the effectiveness of pozzolans, such as fly ash, silica fume, etc., and slags for inhibition of the reaction.
- Characterization of the environment conducive to attack will enable preventive measures.
- Above will aid in the adoption of practical measures to avoid or alleviate such distress and thus increase service life.

Task 5-2.5 Computerized Expert System for Durability and Service Life of Concrete

- Will provide an expert system to assist in the diagnosis of concrete performance in existing structures to aid in the selection of reconstruction and maintenance procedures to increase service life.
- Will provide an expert system to enable the selection of concrete components for new pavement systems exposed to a variety of environments.

Quality Control and Condition Analysis Through Non-Destructive Testing, Proj. 5-3

This project is made up of four tasks designed to achieve the goals and objectives set forth. There is a reasonably high probability that these tasks will produce useful results. The tasks and results anticipated are as follows:

Task 5-3.1 Adapting Non-destructive Tests to a Quality Assurance System for Acceptance, Form Stripping, and Placing in Service

- Will provide more reliable data on the precision, accuracy, and reliability of current and newly developed non-destructive testing techniques.

- Will provide a quality assurance system utilizing non-destructive tests which will significantly raise the quality level of newly constructed pavement systems.

Task 5-3.2 Measurement of the In-Place Permeability of Hardened Concrete

- Will provide a rapid and reliable technique and new test equipment to measure the permeability of hardened concrete in place, a property which has a significant impact on all aspects of concrete durability.

Task 5-3.3 Test Method to Determine the Air Void Characteristics of Freshly Mixed Concretes

- The development of a rapid and reliable procedure for determining the air void characteristics, particularly size and distribution, of the entrained air system in freshly-mixed concrete, thus enabling greatly increased assurance of resistance to freezing and thawing and deicing chemicals.

Task 5-3.4 Residual Functional Capability

- Will provide a non-destructive testing technique which can determine the residual strength and condition of concrete in service, thus providing a basis for more rational maintenance procedures for extending service life.

Mechanical Behavior of Concrete

Four tasks have been selected to provide more data on performance properties of concretes resulting from relatively recent developments in concrete technology. The tasks and the results anticipated are as follows:

Task 5-4.1 Determination of Fatigue Limit and Strain Capacity of High Strength Concrete

- Will provide designers utilizing high strength concrete with needed data on fatigue strength and strain capacity of such concretes so that the structure will perform properly for its intended service life.

Task 5-4.2 Properties of High Early Strength Concrete

- The major development will be the provision for high early strength concretes, particularly for maintenance and rehabilitation purposes, which will be durable in addition to high in strength.

Task 5-4.3 Determination of Structural Properties of Concrete Containing Cementing Materials in Addition to Portland Cements

- Will provide reliable performance data on concretes made with fly ash, silica fume, ground granulated blast-furnace slag, and other potential cementing materials so that concrete properties can be enhanced when these are used.

Task 5-4.4 Effect of the Use of a Combination of Fibers in Concrete

- Will provide data on the use of combinations of different fiber types to enhance both structural capability and volume stability.

Summary

The probabilities for successful attainment of the results to be achieved vary over a fairly wide range. Many of the innovative tasks selected are extremely important and, if successful, would provide a pay-off far beyond the cost of the work. However, in such tasks the probabilities for success are lower than for other, more traditional tasks. The challenge is worth the effort.

SECTION 6
TRA 5 - IMPLEMENTATION OF RESULTS

It is anticipated that the results achieved in a successful completion of this research plan will be implemented where needed by all state departments of transportation, federal agencies concerned with transportation, and equipment manufacturers, particularly in the latter case manufacturers of testing equipment. To be successful, implementation will require the development of a concerted effort to bring the results achieved to the attention of all involved in a manner which will increase the level of understanding to a point where the advantages of utilizing these results are evident. It may be necessary, however, to adopt a more positive approach which would include not only the individual research reports flowing from this work but also meetings such as symposia and workshops, training programs in the various agencies, and the development of new test methods and procedures and new or modified specifications by specification and standards writing organizations.

As described in the Executive Summary of TRB Special Report 202, proper implementation of the results of research must increase the understanding of what can be accomplished, must develop an enthusiasm for the potential in trying the changes proposed, must provide for more flexible standards where information and judgement show this to be possible, must avoid preoccupation with first costs and consider service life costs, and instill confidence in the work and results of a properly designed and integrated research program.

GENERAL APPROACH TO IMPLEMENTATION

The general approach to implementation should include the following steps:

- Publish the research reports prepared at the conclusion of a task, or perhaps a sub-task. Interim reports may also be useful.

- Present a summary paper based on the report at meetings of the Transportation Research Board (TRB), American Association of State Highway and Transportation Officials (AASHTO), American Concrete Institute (ACI), and ASTM.

- Organize workshops to discuss in detail the implications of the research. This might be inaugurated first on a national scale and subsequently on a regional basis. The subject area should be centered on individual high priority items which promise

rapid pay-off, i.e. only one narrow area to promote complete discussion.

- Work with standards and specification writing organizations so that the criteria proposed to effect changes and the necessary new or modified test methods can be prepared and adopted in as short a time as possible.

- Work with equipment manufacturers, both construction and testing equipment, to fabricate equipment required.

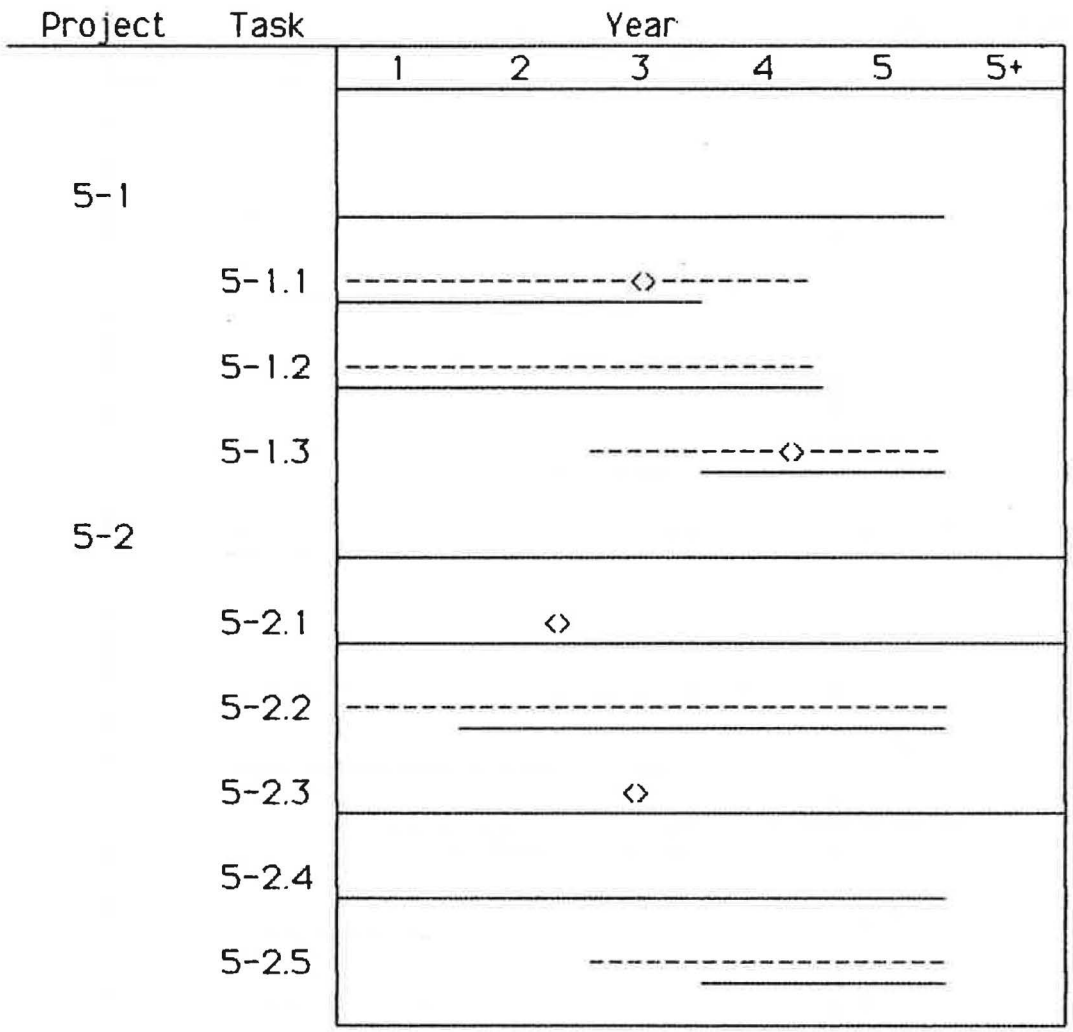
- Develop training programs which can be utilized by Departments of Transportation to instruct personnel how to utilize the results achieved properly in order to accomplish the goals and objectives of the program.

- Promote the concept of minimum annual cost over the service life of the pavement system rather than the first cost concept.

SECTION 7
TRA 5 - SCHEDULE OF PROJECTS AND TASKS

The schedule of projects and tasks included in this research plan for TRA 5, Cement and Concrete, is shown in Figure 6. Shown are the recommended schedule (solid lines), the earliest start and latest finish (dashed lines), and the milestones or decision points as to continuation (diamonds). Wherever possible, some tasks within projects are proposed for start in the second year of the five-year program to avoid having to begin a large number of tasks in the first year.

The milestones or decision points are those points in time at which it may be helpful to sit back and assess the work performed and make a decision as to the probability of success in achieving the goals and objective required. This may result in a decision to continue on the planned work, to modify the plan, or to discontinue the work. Such an interim review effort should be built into each task undertaken.



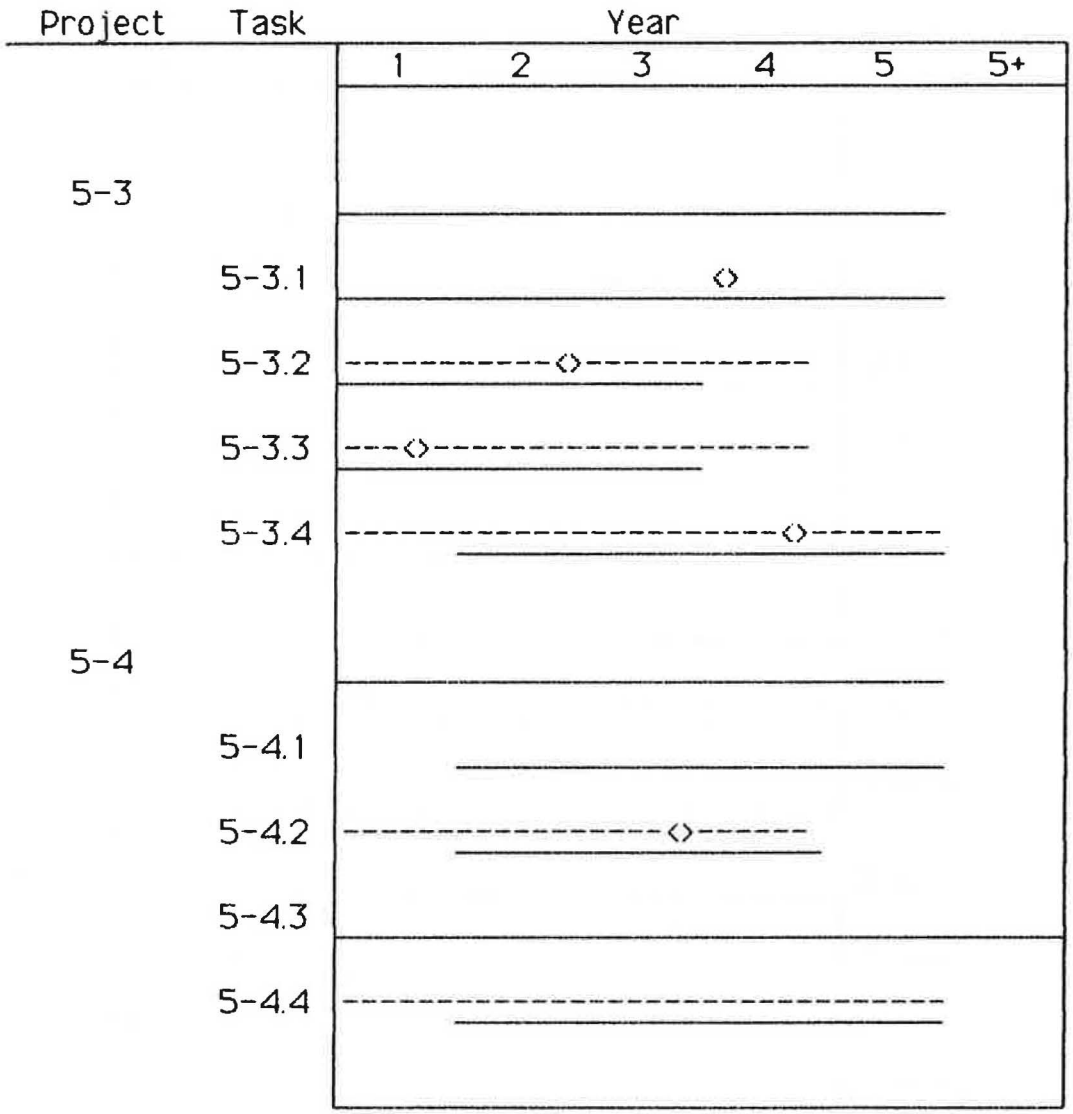
Footnote:

Recommended Schedule _____

Earliest start, latest finish - - - - - - - - - - - - - - - - - -

Milestone ◇

FIGURE 6. SCHEDULE OF PROJECTS AND TASKS



Footnote:
Recommended Schedule _____

Earliest start, latest finish - - - - - - - - - - - - - - - - - -

Milestone ◇

FIGURE 6 (cont'd). SCHEDULE OF PROJECTS AND TASKS

SECTION 8
TRA 5 - BUDGET

The funds available for the conduct of TRA 5 on Cement and Concrete total $12,000,000 over the five-year program. Section 3 described the formulation of the plan and the procedure used to prioritize projects, tasks, and sub-tasks so that lower priority work could be eliminated in order to meet this limitation on available funds.

The budget for TRA 5 is shown in Table 1. This shows the four projects and their tasks, with the funds recommended for each task in each of the years during the task schedule. In addition, where field evaluation is recommended as a part of TRA 2, Long-Term Pavement Performance, the amounts recommended are shown in the column headed "5+". Note that the total funds recommended for such work is $285,000, with a recommendation of $11,715,000 to perform the remainder of the tasks. The grand total recommended is $12,000,000, as assigned.

Special equipment costs, where such equipment is required, are shown in the man-power estimates for tasks and sub-tasks contained in Section 4.

The costs have been estimated on the basis of average man-power costs and a load factor which includes overhead and direct costs. These estimated costs were made available by SHRP to the six contractors developing the research plans.

TABLE 1

TRA 5 BUDGET
(in Thousands of Dollars)

Project	Task	Year						Cost	
		1	2	3	4	5	5+	(Yr1-5)	Total
5-1								3620	3620
	5-1.1	700	825	690	-	-	-	2215	2215
	5-1.2	165	200	175	195	-	-	735	735
	5-1.3	-	-	-	380	290	-	670	670
5-2								4480	4615
	5-2.1	310	340	250	240	205	75	1345	1420
	5-2.2	-	225	200	215	160	-	800	800
	5-2.3	275	300	190	150	45	60	960	1020
	5-2.4	160	150	175	85	55	-	625	625
	5-2.5	-	-	-	470	280	-	750	750
5-3								1720	1720
	5-3.1	50	100	100	50	50	-	350	350
	5-3.2	130	215	75	-	-	-	420	420
	5-3.3	150	100	50	-	-	-	300	300
	5-3.4	-	150	200	200	100	-	650	650
5-4								1895	2045
	5-4.1	100	200	200	200	100	-	800	800
	5-4.2	-	100	100	50	-	-	250	250
	5-4.3	90	135	135	90	50	150	500	650
	5-4.4	-	95	115	90	45	-	345	345
	Totals	2130	3135	2655	2415	1380	285	11715	12000

APPENDIX A
TRA 5 - OTHER RESEARCH PROJECTS CONSIDERED

During the formulation of the TRA 5 research plan on Cement and Concrete, a number of worthy research projects or tasks were discussed which, if undertaken, would make significant contributions to the goals and objectives of the program. However, budget limitations and priority considerations militated against their inclusion.

These projects or tasks are presented here in order to provide SHRP with the necessary flexibility in choosing substitute projects or tasks, either as a result of elimination or reduction of scope of recommended projects and tasks due to failure or lack of sufficient progress or a change in direction in certain portions of the effort.

This listing will also serve as a reservoir of tasks which could be recommended for funding to FHWA, AASHTO, NCHRP, and other funding organizations. The listing is not in order ot priority.

- Chloride Phase Equilibria in Concrete

  Relationships between cement composition, total and water soluble chloride contents are not well-defined. To control the effects of chloride salts in concrete it will be necessary to have an improved understanding of the physical chemistry and mechanisms of these processes. Fundamental to this understanding is knowledge of the compositions of the phases formed by reactions between the cement hydrates and the salts, and the ranges of temperature and pore solution compositions in which they can exist in equilibrium. Such data enable chemists to predict the ultimate reaction products of mixtures of various compositions. Without such data it is not possible to predict the long-term effects of chlorides in concretes, how the effects depend on compositions of cements and concretes, or define the mechanisms of attack by such processes, the mechanisms by which they might be controlled, and the requirements for such control. This project would include a literature review on the chemistry of reactions of chlorides with cement hydrates, studies of phase equilibria using pure compounds, cement slurries, and blended cements, and determinations of the composition of liquid and solid phases over a range of temperatures and moisture contents.

- Fundamental Studies on the Mechanism of Steel Corrosion in Concrete

  While a certain amount of work has been devoted to electrochemical studies of steel corrosion caused by chloride salts, little information exists which could be used to predict the progress of corrosion given such parameters as steel condition, amount of chloride present, quality of concrete, and construction details. A study on the relationship between corrosion of steel and resultant damage to concrete is needed. This project would include studies on corrosion rate of steel in concrete, stress analysis of concrete containing corroding reinforcement, and quantification of the combined effects of chloride salts, temperature, moisture, and concrete quality on the corrosion process. The project would also include development of a mathematical model which would allow one to predict the future cause of corrosion given the state of the steel and concrete under existing conditions.

- Latex-Modified Concrete (LMC)

  Provide data to enable the use of LMC in highly aggressive environments for other highway structures. LMC can retain its wearing surface longer than ordinary portland cement concrete (OPCC). Retention of wearing surfaces would provide motorists with better riding conditions (safety) in that friction would be less varied for point to point on a pavement.

- Mechanical Properties of Thin-Layer High-Fiber Content Concrete

  Possible use of such material should be evaluated as to its potential use as a protective overlay.

- Roller-Compacted Concrete

  Significant economies in construction would result from greater use of roller-compacted concrete. Greatest problem appears to be assurance of durability in a freeze-thaw environment, particularly where deicers are used.

- Fiber Shotcrete

  More data needed on the physical properties of the material, on factors influencing bond to substrate, on equipment to be used, and on durability.

- Influence of Aggregate Gradation on Concrete Performance

  Optimization of aggregate gradation may be helpful in providing more workable and more cohesive concrete, less prone to segregation, thus aiding in placing and compacting.

- Control of Plastic Shrinkage Cracking

  Plastic shrinkage cracks early in the life of the pavement are not aesthetically pleasing and pose a potential threat to durability. Means for prevention under a variety of circumstances are needed.

- Recycling Concrete

  Depletion of existing aggregate sources prompts a closer look at the use of recycled concrete as aggregate for concrete for new construction. More data are needed on the physical properties of freshly-mixed and hardened concretes made from such aggregates, and on the durability. Of particular concern is the use of concrete suffering from D-cracking and alkali-aggregate reaction.

- Aggregate Beneficiation

  Some aggregates are prone to develop D-cracking, or popouts, or general deterioration when used in concrete which becomes wet and is subject to freezing and thawing. Economical beneficiating techniques would assist in greater use of the country's resources.

- Free Moisture in Aggregates

  Control of the water content of freshly mixed control is important in controlling concrete strength and quality. The free water content in aggregates prior to mixing varies and this variation makes control of concrete water content difficult. Rapid and accurate measuring devices would help control.

- Adequacy of Curing

  More reliable information is needed on the adequacy of curing currently being provided. Test equipment is needed to provide for a quantitative measure of curing. Guidelines need to be developed and criteria set forth for the types and amounts of curing needed for different elements of the system (slabs on grade, decks, etc.) and different environments.

TRA 5 - BIBLIOGRAPHY

Powers, T.C., The Properties of Fresh Concrete, 664 pp., New York, John Wiley & Sons, 1968.

Proc. Fifth International Symposium on the Chemistry of Cement, Tokyo, 1968, Part I, 384 pp.: Part II, 513 pp.: Part III, 601 pp.: Part IV, 519 pp.: Tokyo, The Cement Association of Japan, 1969.

Lea, F.M., The Chemistry of Cement and Concrete, 3rd Ed., 727 pp., New York, Chemical Publishing Co., 1971.

Hydraulic Cement Pastes: Their Structure and Properties, Proc. of a Conference held at University of Sheffield, 8-9 April 1976, 334 pp., Wexham Springs, Cement and Concrete Assn., 1976.

Proc. Fourth International Conference on the Effects of Alkalies in Cement and Concrete, June 4-7, 1978, Purdue Univ., Publ. No. CE-MAT-1-78, 376 pp., West Lafayette, IN, Purdue Univ. Press, 1978.

Rixom, M.R., Chemical Admixtures for Concrete, 234 pp., London, E&FN Spon Ltd., 1978.

Mehta, P.K., Ed., Cement Standards - Evolution and Trends, ASTM STP 663, 107 pp., Philadelphia, American Society for Testing and Materials, 1978.

Proc. Seventh International Congress on the Chemistry of Cement, Paris 1980, 4 Vols., Paris Editions Septima, 1980.

Skalny, J.P., Ed., Effect of Surface and Colloid Phenomena on Properties of Fresh Concrete, Proc. Symposium M, Materials Research Soc., Annual Meeting Nov.
1982, 233 pp., University Park, PA, Materials Research Soc., 1982.

Young, J.F., Ed., Characterization and Performance Prediction of Cement and Concretes, Proc. Eng. Foundation Conf., July 1982, 219 pp., Engineering Foundation, New York, 1982.

Annual Book of ASTM Standards Vol. 04.01 [Part 13 before 1983]/Cement; Lime; Gypsum, 692 pp., Philadelphia, American Society for Testing and Materials, 1984.

Annual Book of ASTM Standards Vol. 04.02 [Part 14 before 1983]/Concrete and Mineral Aggregates, 902 pp., Philadephia, American Society for Testing and Materials, 1984.

Young, J.F., Ed., Cements Research Progress 19. Annual survey of the literature on the science of cements. Columbus, OH, American Ceramic Society, 1974-1982.

Diamond, S., Ed., Effects of Fly Ash Incorporation in Cement and Concrete, Proc. Symposium N, Materials Research Soc., Annual Meeting Nov. 1981, 331 pp., University Park, PA, Materials Research Soc., 1981.

Bakker, W.T., Ed., Workshop Proceedings: Research and Development Needs for Use of Fly Ash in Cement and Concrete, March 1982, CS-2616-SR, Palo Alto, CA, Electric Power Research Inst., 1982.

Halow, J.S., and Covey, J.N., The Challenge of Change-- Sixth International Ash Utilization Symposium, DOE/METC/82-52 Vol. 1, 491 pp; Vol. 2, 426 pp., U.S. Dept. of Energy, Morgantown, WV, and National Ash Association, 1982.

Malhotra, V.M., Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, SP-79, 2 Vols., 1182 pp., Detroit, American Concrete Institute, 1983.

Clifton, J. R., Oltikar, B. C. and Johnson, S. K., Development of Durcon, An Expert System for Durable Concrete; Part I, NBSIR 85-3186, National Bureau of Standards, Gaithersburg, MD,July 1985, 23 pp.

Bickley, J. A., The Evaluation and Acceptance of Concrete Quality by In-Place Testing, ACI SP-82 In Situ/Nondestructive Testing of Concrete, V. M. Malhotra, Ed., pp. 77-94 (Oct. 1984).

Malhotra, V. M., In Situ/Nondestructive Testing of Concrete - A Global Review, ACI SP-82, 1984, pp. 1-16.

Whiting, D., In Situ Measurement of the Permeability of Concrete to Chloride Ions, ACI SP-82, 1984, pp. 501-24.

Hanson, J. A., Ottosen, N. S., Peterson, C. G., Gas Permeability of Concrete In-Situ, ACI SP-82, 1984, pp. 543-56.

Klieger, P., Durability Studies at the Portland Cement Association, ASTM Special Technical Publication NO. 691, pp. 282-300 (1980).

Guide to Durable Concrete, J. American Concrete Institute, Vol. 74, No. 12, Chap. 1 - Freezing and Thawing, pp. 575-582 (Dec. 1977).

Lang, F. C. and Hughes, C. A., Discussion on Relation Between Durability of Concrete and Durability of Aggregates, Proceedings, Highway Research Board, Vol. 10, 10 pp. 116-131 (1930).

Klieger, P., Studies of the Effect of Entrained Air on the Strength and Durability of Concretes Made with Various Maximum Sizes of Aggregates, Proceedings, Highway Research Board, Vol. 31, pp. 177-201 (1952).

Fears, F. K., Correlation Between Concrete Durability and Air-Void Characteristics, Highway Research Board, Bulletin No. 196 pp. 17-28 (1958).

Khalil, S., Ward, M. A. and Morgan, D. R., Freeze-Thaw Durability of Non-Air-Entrained High Strength Concretes Containing Superplasticizers, Durability of Building Materials and components, ASTM STP-691 pp. 509-19 (1980).

Verbeck, G. and Klieger, P., Studies of 'Salt' Scaling of Concrete, Highway Research Board Bulletin No. 150, pp. 1-13 (Jan. 1956).

Klieger, P., Curing Requirements for Scale Resistance of Concrete, Highway Research Board Bulletin NO. 150, pp. 18-31 (Jan. 1956).

Browne, F. P. and Cady, P. D., Deicer Scaling Mechanisms in Concrete, ACI SP-47, Durability of Concrete, pp. 101-19 (1975).

Thornton, H. T., Natural Weathering Exposure Station for Concrete and Concreting Materials -- Treat Island, Maine, in Performance of Concrete in Marine Environment, ACI Special Publication 65, V. M. Malhotra, Ed. pp. 83-94 (August 1980).

Durability of Concrete Bridge Decks - Final Report, Portland Cement Association (1965).

Lankard, D. R., Field Experiences with Steel Fibrous Concrete, presented at American Ceramic Society Meeting, Chicago, April 26, 1971.

Award, M. E. and Hilsdorf, H. K., Strength and Deformation Characteristics of Plain Concrete Subjected to High Repeated and Sustained Loads, Structural Research Series No. 373, Department of Civil Engineering, University of Illinois, Urbana, Feb. 1971.

ACI Committee 325, A Design Procedure for Continuously Reinforced Concrete Pavements for Highways, ACI Journal, Proceedings V. 69, No. 6, June 1972, pp. 309-319.

AASHTO Interim Guide for the Design of Pavement Structures, American Association of State Highway Officials, Washington, D. C., 1972.

Yoder, E. J., Principles of Pavement Design, John Wiley and Sons, Inc., New York, 1959, 569 pp.

Hudson, W. Ronald, and Matlock, Hudson, Analysis of Discontinuous Orthotropic Pavement Slabs Subjected to Combined Loads, Highway Research Record, Highway Research Board, No. 131, 1966, pp. 1-48.

State of the Art Rigid Pavement Design, Research on Skid Resistance, Pavement Condition Evaluation, Special Report No. 95, Highway Research Board, Washington, D.C., 1968, 68 pp.

Davis, R. E., A Summary of Investigations of Volume Changes in Cements, Mortars and Concretes Produced by Causes Other Than Stress, Proceedings ASTM, V.30, 1930, Part I, p. 668.

Gaynor, Richard D., High-Strength Air-Entrained Concrete, National Ready Mixed Concrete Association Joint Research Laboratory Publication No. 17, March, 1968.

Saucier, Kenneth L., Smith, Eugene F., and Tynes, William D., High-Compressive-Strength Concrete: Development of Concrete Mixtures, U.S. Air Force Weapons Laboratory RTD-TDR-63-3114, February, 1964.

Saucier, Kenneth L., Tynes, Smith, and Eugene F., William D., High-Compressive-Strength Concrete, U.S. Air Force Weapons Laboratory TR-65-16, September, 1965.

Klieger, Paul, Early High-Strength Concrete for Prestressing, Portland Cement Association, R&D Bulletin No. 91, 1958.

Mather, Bryant, High-Compressive-Strength Concrete: A Review of the State of the Art, U.S. Army Corps of Engineering Waterways Experiment Station Misc. Paper No. 6-520, 1962.

ACI Committee 215, Considerations for Design of Continuous Structures Subjected to Fatigue Loading, ACI Journal, Proceedings, V. 71, No. 3, March 1974, pp. 97-121.

Clear, K. C., Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, Volume 3: Performance After 830 Daily Salting Applications, Report No. FHWA-RD-76-70, Federal Highway Administration, 1976, 59 pp.

Bishara, A. G., Latex Modified Concrete Bridge Deck Overlays - Field Performance Analysis, Report No. FHWA/OH/79/004, Ohio Department of Transportation and Federal Highway Administration, 1979, 96 pp.

Brown, B. C., A Further Evaluation of Concrete Bridge Deck Surfacing in Iowa, Iowa Department of Transportation, 1979, 98 pp.

Hoffman, P. A., A Performance Evaluation of Latex Modified Concrete Bridge Deck Overlays in Indiana, Federal Highway Administration, Indianapolis, Indiana, 1979, 4 pp.

Monfore, G. E., A Review of Fiber Reinforcement of Portland Cement Paste, Mortar, and Concrete, Journal of the PCA Research and Development Laboratories, Vol. 10, September 1968, pp. 43-49. Also Research Department Bulletin 226.

Romualdi, J. P., and Batson, G. B., The Mechanics of Crack Arrest in Concrete, Journal of the Engineering Mechanics Division, American Society of Civil Engineers, Vol. 89, June 1963, pp. 147-168.

Shah, Surendra, P., and Rangan, B. Vijayua, Fiber Reinforced Concrete Properties, ACI Journal, Proceedings V. 68, No. 2, Feb. 1971, pp. 126-135.

Abdun-Nur, Edward A., Fly Ash in Concrete: An Evaluation, Bulletin No. 284, Highway Research Board, Washington, D.C., 1961, 238 pp.

Pasko, TR. J., and Larson, T. D., Some Statistical Analyses of the Strength and Durability of Fly Ash Concrete, Proceedings, ASTM, V. 62, 1962, pp. 1054-1067.

Lovewell, C. E., and Hyland, Edward J., Effects of Combining Two or More Admixtures in Concrete, Highway Research Record No. 370, Highway Research Board, 19171, pp. 90-98.

High Strength Concrete in Chicago High-Rise Building, Report No. 5, Task Force, Chicago Committee on High-Rise Buildings, 1977.

Bloem, Delmar L., Effect of Fly Ash in Concrete, Publication No. 48, National Ready Mixed Concrete Association, Silver Spring, 1954, 36 pp.

Perenchio, William F., and Klieger, Paul, Further Laboratory Studies of Portland-Pozzolan Cements, Research and Development Bulletin RD041-01T, Portland Cement Association, Skokie, 1976, 9 pp.

Dikeou, J. T., Fly Ash Increase Resistance of Concrete to Sulfate Attack, Research Report No. 23, U.S. Bureau of Reclamation, Denver, 1970, 17 pp.

Relationship of Fly Ash and Corrosion, ACI Journal, Proceedings V. 47, No. 1, Sept. 1950, p. 74.

Wolsiefer, J., Ultra High Strength Field Placeable Concrete in the Range 10,000 to 18,000 psi, paper presented at the 1982 ACI Annual Convention, Atlanta and accepted for publication.

Mehta, P. K., and Gjørv, O. E., Properties of Portland Cement Concrete Containing Fly Ash and Condensed Silica-Fume, Cement and Concrete Research, V. 12, No. 5, Sept, 1982, pp. 587-595.

Hogan, F. J. and Meusel, J. W., 1981, The Evaluation for Durability and Strength Development of Ground Granulated Blast-Furnace Slag, Cement Concrete and Aggregates, Vol. 3, No. 1 (Philadelphia), pp. 40-52.

Klieger, P. and Isberner, A., 1962, Laboratory Studies of Blended Cement -- Portland Blast-Furnace Slab Cement, Journal of PCA Research and Development Laboratories, Vol. 9, No. 3, pp. 2-22.

Malhotra, V. M., 1980, Strength and Freeze-Thaw Characteristics of Concrete Incorporating Granulated Blast-Furnace Slag, Canmet, R. E. 79-38, Capitalization, Energy, Mines & Resources, Canada, Ottawa.

Mather, Bryant, 1957, Laboratory Test of Portland Blast-Furnace Slag Cements, Journal of the American Concrete Institute, pp. 205-233.

Stanton, Thomas E., Expansion of Concrete Through Reaction Between Cement and Aggregate, Proceedings of the American Society of Civil Cngineers, 1940, Vol. 66, pp. 1781-1811.

Hansen, W. C., Studies Relating to the Mechanism by Which the Alkali-Aggregate Reaction Produces Expansion in Concrete, Journal of the American Concrete Institute, January, 1944, Proceedings, Vol. 40, pp. 213-227.

Powers, T. C. and Steinow, H. H., An Interpretation of Published Researches on the Alkali-Aggregate Reaction, Part I and Part II, Journal of the American Concrete Institute, February and April, 1955, Proceedings, Vol. 51, pp. 497-516 and 785-812.

Whiting, D. and Stark, D., Control of Air Content in Concrete, NCHRP Report 258, May 1983.

Stark, David and Klieger, Paul, Effect of Maximum Size of Coarse Aggregate on D-Cracking in Concrete Pavements, Highway Research Record Number 441, Highway Research Board, 1973, pp 33-43.

Stark, David, Characteristics and Utilization of Coarse Aggregates Associated with D-Cracking, ASTM STP597, 1976, pp. 45-58.

TECHNICAL RESEARCH AREA 6
SNOW AND ICE CONTROL ON HIGHWAYS AND BRIDGES

Prepared for:
NCHRP Project Number 20-20(8)
Pre-Implementation Activities for the
Strategic Highway Research Program (SHRP)

January 1986

Prepared by:

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

TABLE OF CONTENTS

		Page
	LIST OF FIGURES	TRA 6-ii
	LIST OF TABLES	TRA 6-iii
	ABSTRACT	TRA 6-iv
	ACKNOWLEDGEMENTS	TRA 6-v
SECTION 1	STATEMENT OF THE PROBLEM	TRA 6-1
SECTION 2	GOALS AND OBJECTIVES OF THE PLAN	TRA 6-4
SECTION 3	FORMULATION OF THE PLAN.	TRA 6-5
SECTION 4	RECOMMENDED RESEARCH PLAN.	TRA 6-8
SECTION 5	RESULTS TO BE ACHIEVED	TRA 6-19
SECTION 6	IMPLEMENTATION OF RESULTS.	TRA 6-21
SECTION 7	SCHEDULE OF PROJECTS, TASKS AND SUBTASKS	TRA 6-22
SECTION 8	BUDGET	TRA 6-25
APPENDIX A	OTHER RESEARCH PROJECTS CONSIDERED	TRA 6-A-1
APPENDIX B	DATA REQUIREMENTS FOR SNOW AND ICE STUDY	TRA 6-B-1
	BIBLIOGRAPHY	TRA 6-C-1

LIST OF FIGURES

Figure 1. Salt used for highway deicing, 1947-1985 . . . . . TRA 6-3

Figure 2. TRA 6 - Project and task start year and elapsed time . . TRA 6-23

Figure 3. TRA 6 - Flowsheet . . . . . TRA 6-24

LIST OF TABLES

Table 1. TRA 6 Budget . . . . . TRA 6-3

ABSTRACT

The great dependence on highway transportation for the movement of goods and people in the United States has led to the demand for rapid, effective clearance of snow and ice from roads. This in turn has led to the use of large quantities of environmentally undesirable chemicals to assist in improving traction between rubber tire and pavement. Concern about the effects of the most heavily used deicing chemical, salt (sodium chloride), on the roadside environment, water supplies, and highway structures, has increased along with the increase in quantities applied, now over 10,000,000 tons per year. A research plan is presented which has as its primary objective the reduction of the dependence on environmentally undesirable chemicals. Reducing the quantity of deicing chemicals applied to the nation's highways can be accomplished by the development of innovative products and techniques and the incorporation of some existing sophisticated technology in snow and ice control organizations. The principal approach to achieving this is the development of physical methods of disbonding ice from pavements, or preventing the bond from developing. Fundamental studies of bond formation and prevention are proposed as the most promising and cost-effective initial attacks on the problem rather than pursuing the largely empirical approaches of past research on snow and ice control. These fundamental studies will provide the background for developing pavement modifications to reduce or eliminate ice adhesion. Increased reliance on physical methods will require improvements in the backbone of the snow and ice control organization: the displacement plow and its cutting edge. Research is also proposed to improve control of snow and ice removal operations by providing management with real-time information on pavement and weather conditions over the entire system, improving storm warning capabilities and timeliness, and developing a communications system to ensure rapid and thorough response to changing conditions.

ACKNOWLEDGEMENTS

L. David Minsk was the author of this report. He was assisted in this study by two other members of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) staff:

Gunars (Chuck) Abele, Research Civil Engineer

Dr. Kazuhiko Itagaki, Research Physicist

SECTION 1
STATEMENT OF THE PROBLEM

The economic well-being and livelihood of the United States depends to a significant extent on the year-round mobility of trucks, buses and passenger cars on the highway network. Winter conditions of snow and ice can and do cause serious disruptions in the economies of nearly all states (with the exception of Hawaii and, to a lesser extent, Florida) when traffic is slowed or stopped until the pavement surface can be restored to a near-normal condition. Although over $1 billion is spent anually on snow and ice control by all levels of government, and additional large sums are lost due to delays resulting from inefficient control methods, relatively little has been spent on improvement of equipment and techniques in the past. Furthermore, work in progress is only addressing a small segment of a very large problem. Most current activity is the exploitation of calcium magnesium acetate (CMA) as a potentially effective, non-corrosive deicing chemical.

THE SITUATION TODAY

Two factors are of paramount importance in addressing the problem of snow removal/ice control on roads: the lack of an integrated national research program to develop effective, efficient, and environmentally acceptable materials and equipment, and the great dependence on chemicals to treat an ice-covered or compacted snow surface to improve traction of rubber-tired vehicles.

Research Activity

Snow and ice control activities are performed by all levels of road administrations: federal (e.g., National Park Service, U.S. Army, U.S. Air Force, and U.S. Navy), states, counties, cities, and towns. In general, each jurisdiction attacks the task in its own way based on its unique experience. Each sets its own standards, adopts techniques and procures equipment based on its needs and the perceived solutions. Only at the upper levels of major administrative units: states, major cities, some counties, large airports, is there significant interchange of ideas and technology transfer. Resources of all these jurisdictions do not permit research beyond short-term limited objective studies, most of which are focused on local problems with little transportability to other areas. The snow removal/ice control industry is dispersed and fragmented; no individual equipment manufacturer has the resources or the incentive to conduct long-range studies to improve equipment performance or operational techniques. With very few exceptions, significant improvements in design and performance of snow control equipment have originated in Europe or Scandinavia, with later transfer of some of the resulting technology to the United States. Research on a national scale has

been performed by the Federal Highway Administration (FHWA), either in-house, by administrative contracts, or through the Transportation Research Board. The U.S. Army, the U.S. Air Force, and the U.S. Navy have also conducted research which has applicability to winter maintenance of highways. With the exception of the search for a deicing chemical as an alternative to chlorides, and its continuing testing and development, most snow and ice control research has been pursued piecemeal. The lack of adequate funding forestalled the preparation and implementation of an integrated, long-range national plan for research into improved methods, materials, and equipment for government more efficiently, at less cost, with less harm to the environment, and with no deterioration in safety standards.

Dependence on Chemicals

Salt, sodium chloride, has been applied to winter highways since early in this century. Until 1941 very little straight salt was applied; most was mixed with sand or other abrasives to freeze-proof stockpiles and to promote embedding the grit into the slick surface. Salt alone was used on the entire road system in some areas of New England beginning in 1941, but the total amount applied across the country remained low until the mid-'50s when usage surged dramatically (Fig. 1), spurred by the lower treatment cost of salt vs. abrasive. Concern about the effects of both calcium and sodium chlorides had already arisen by 1930, but this concern was confined to the scaling of portland cement concrete. Later, corrosion of automobile bodies appeared. Effects of sodium chloride on the natural environment became evident in some parts of the country by about 1958, and measurement of sodium and chloride levels in roadside vegetation commenced soon after in Connecticut, Massachusetts, Minnesota, and New Hampshire, followed by measurements of water quality in areas of heavy use. The consequences of the large annual applications of sodium and calcium chlorides on roads are now apparent to all, and though steps have been taken to develop alternative approaches to winter maintenance, the dependence on these chemicals for fast, effective ice control on the country's critical road network remains deeply rooted.

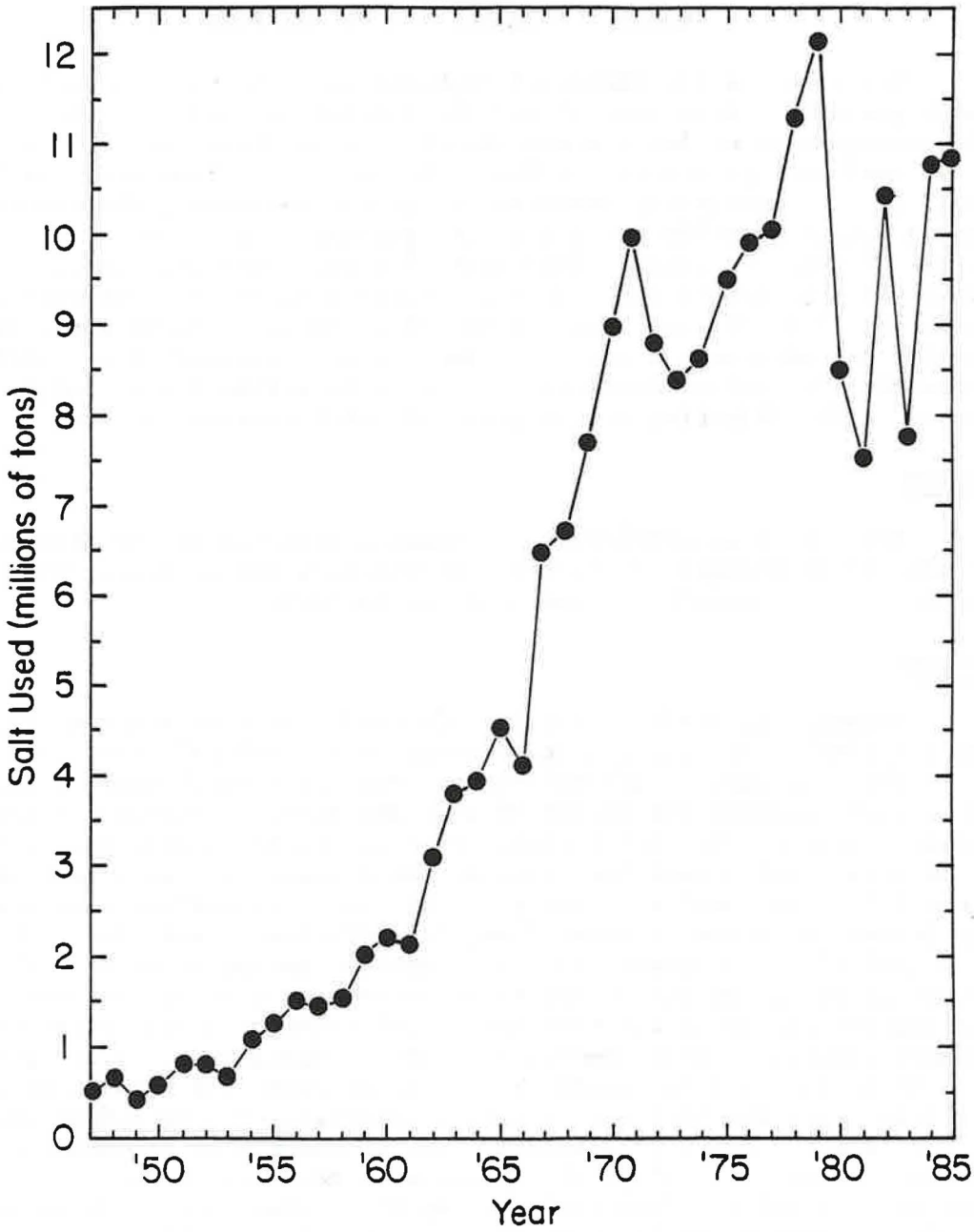


FIGURE 1. SALT USED FOR HIGHWAY DEICING, 1947-1985.

SECTION 2
GOALS AND OBJECTIVES OF THE PLAN

The stimulus for increased emphasis on an integrated national research program on snow removal and ice control has arisen from observation of the consequences of large-scale use of deicing chemicals. Though any chemical used in huge quantities (up to 40 tons/centerline mile/year) is potentially environmentally undesirable, if not hazardous, the concern has fallen on sodium chloride because of its predominance. The reasons for the great use of salt are clear: low material cost, ready availability, and effective deicing action over most-frequently encountered temperatures. If a chemical like salt did not exist, research probably would be undertaken to synthesize and manufacture it. Many factors are involved in a coordinated snow removal/ice control operation, and will be elaborated on later. First a statement of the objective of the proposed TRA 6 research program is in order.

OBJECTIVE

Provide safe, serviceable highways during winter conditions, reduce deterioration of bridges, pavements and vehicles, and mitigate other adverse environmental consequences of snow and ice control.

DISCUSSION

Maintaining roads in trafficable condition with minimum reduction in safety and within cost constraints imposed by the public's sufferance of its taxes is the objective of all maintenance engineers worth their salt. More is involved than reducing the amount of salt and other deleterious deicing chemicals, however. Greater reliance must be placed on physical methods in order to reduce the demand for chemical approaches. However, physical methods have not filled the need adequately in the past: mechanical snow removal is energy intensive, prone to break-down, low efficiency, and slow. Thus a primary goal of the research plan is to devise innovative methods of applying non-chemical energy at the ice-pavement interface to break the adhesive bond, and to improve the materials handling capabilities of displacement plows. Management control of snow removal/ice control operations, if improved, has the potential not only to reduce the amount of chemicals applied by providing more timely storm and pavement condition reporting, but to reduce costs resulting from unnecessary call-outs. The research plan as constructed addresses both the technological improvements necessary to achieve complete removal of snow and ice from pavements by the minimum use of deleterious chemicals and maximum reliance on physical methods, and the structuring of an operational organization utilizing modern storm warning, communications, and sensor technology to achieve rapid deployment of mechanized equipment during critical periods.

SECTION 3
FORMULATION OF THE PLAN

Section F of the report of the AASHTO Select Committee on Research to the AASHTO Executive Committee entitled "Strategic Transportation Research Study Technical Design", dated May 7, 1984, formed the basis for the plan presented in Section 4 of this report. The structure of the plan has undergone change, however, as is discussed below.

EVOLUTION OF THE PLAN

Meetings

The principal mechanism for modifying the research design presented in the AASHTO report was through meetings of an advisory committee with the principal investigator. Four meetings were held during 1985.

- April 25-26 Washington, DC
- August 7-9 Hanover, NH
- September 18-20 Dallas, TX (with SHRP National Workshop)
- October 29-30 Indianapolis, IN

Rationale

Early in the research plan formulation the need for a fundamental study of the ice-pavement bond was strongly endorsed by the advisory committee as an approach far more promising than the largely empirical approaches that have marked past snow and ice control research. This view was so strongly held that two parallel fundamental studies were suggested: one studying the ice-pavement bond from the point of view of preventing its development, and the other from the point of view of destroying the bond once it has formed. These studies would receive the highest priority and a significant share of the funding since their research findings would provide guidance and resource information for nearly all follow-on studies which have products or processes as their goal.

A second guiding principle in the formulation of the research plan was the avoidance of a large number of small studies with low levels of funding. It was the consensus that a few well-funded studies offered the highest probability of success, and therefore the task was deemed the selection of appropriate studies. Guiding the selection were the questions

- is the subject researchable?
- will it answer a critical need?
- will it result in a significantly improved product or process?
- is it achievable within the five-year study period?
- are sufficient resources available to complete it?

Studies Omitted from Plan. Four studies were considered seriously for inclusion in the proposed research plan but had to be eliminated because of lack of funds. This decision followed from the view stated above, that the recommended studies receive adequate funding. These studies listed here are discussed in Appendix A-1. The project/task numbering system assigned during the advisory committee meetings is maintained since they are part of a coordinated program which should be pursued if alternative funding sources can be found. The studies eliminated from the recommended program also appear on the budget and scheduling tables for the same reason.

- Task 6-1.4 Thermal methods of snow and ice control
  - though the potential for use of low-grade thermal energy to heat large areas of criticl urban highways was considered promising, greater resources than are available to SHRP would be required, and therefore even the first step of making a low-level preliminary study is deferred.
- Task 6-2.5 Test and evaluation of CMA
  - since research on environmental effects, corrosion, and production optimization is currently being conducted under FHWA and NCHRP contract it is desirable to await the results upon their completion to determine if further research is warranted.
- Task 6-5.2 Improvement of resource planning and program evaluation
  - though the need for more effective planning and evaluation procedures continues, projects and tasks having products are considered to have the bigger pay-offs.
- Project 6-6 Demonstrations of technology-based winter maintenance operations systems

- the resources required for a large-scale integrated demonstration exceed those presently available within SHRP, so the alternative of smaller scale field tests of one or two technologies within other projects and tasks was adopted.

Other Studies Outside Scope. Two other aspects of snow and ice control activities could be considered for inclusion in a coordinated research plan: improvement in use of abrasives, and improvement in design of rotary snowplows. Both were placed outside the scope of the SHRP recommended research program since both are considered sufficiently advanced in current practice to make expediture of new money questionable. A third field was also considered outside the scope of a snow and ice control study: investigation of the rubber tire-ice interface. This has been attempted by tire manufacturers, and though there is fair probability of improvements stemming from additional research, this was not considered here.

Coordination. During the development of the research plan, members of the advisory committee or the principal investigator attended at least one of the working sessions of the other five Technical Research Areas to ensure that their interests were fairly represented in the final product. The most-frequently expressed concern of the other TRA's was that any pavement treatment or modification to enhance snow/ice removal not affect structure or pavement integrity. Five members of the Snow and Ice Advisory Committee were assigned as liaison to each of the other Technical Research Areas at the National Workshop. They attended those TRA sessions and reported their observations to the Snow and Ice Advisory Committee during the concluding session.

SECTION 4
TRA 6 RECOMMENDED RESEARCH PLAN

PREVENTION OF ICE-PAVEMENT BOND (Project 6-1)

Ice and refrozen compacted snow bond exceedingly tenaciously to most materials of construction, particularly asphalt and portland cement concrete pavements. The nature of this bond and the mechanism by which it develops are not clearly understood. Past attempts to develop effective chemical or physical methods to disrupt the ice-substrate bond have been approached empirically, and consequently progress in developing improved, effective, energetically favorable equipment or chemicals has been only partially successful. Prevention or modification of bond formation is the preferred method of control rather than destruction of the ice-substrate bond once formed because of the avoidance of a stage of low coefficient of friction between tire and pavement. The objective of this study is to investigate the mechanism of bond formation and to apply this knowledge to the development of innovative methods for preventing or modifying the bonding.

Fundamental Study of the Ice-Pavement Bond from Viewpoint of Prevention (Task 6-1.1)

Most of the research heretofore conducted on this subject has been approached empirically. Thus there is neither a foundation on which to build a more complete picture of ice-pavement bonding nor on which to base development of methods for preventing bond development. This study is considered to be one of the most critical since other tasks will utilize its findings for informed guidance. It is important to understand, however, that this is not just a pure research study but rather research of a fundamental nature directed towards a very clear goal: development of methods to prevent ice from bonding to pavements. The objective of this study is to conduct a fundamental study of ice-substrate bond structure and mechanics of formation in order to provide the basis for developing techniques and devices for interfering with or preventing bond formation without adversely affecting desirable pavement properties such as friction. Though it is probable that a technique or material for preventing bond formation may result from this task, that is not its principal intent. Rather, it is to provide an improved knowledge of bond structure and formation sufficient to guide development of techniques, materials, and equipment for weakening or preventing the ice-pavement bond with low energy input and without the use of environmentally undesirable physical or chemical energy sources.

This task will include the following sub-tasks:

- Literature search and review of related interfacial and surface physics studies.

- Utilize microscopic and macroscopic physical methods to characterize surface bond parameters.

- Investigate methods of preventing bond development or disrupting it during incipient formation. Develop new approaches toward achieving this objective.

Evaluation: medium risk, high payoff.

Chemical Surface Modification (Task 6-1.2)

One of the most effective techniques for prevention of ice adhesion to pavements involves the introduction of some treatment over the entire pavement surface prior to the onset of freezing precipitation. To accomplish this by chemical means two methods are currently practiced: application of a deicing chemical in liquid form by spraying or flooding, or by incorporating the chemical into the pavement surface so that it is continuously renewed. The former is an approach used in Europe and in Japan where fixed facilities have been installed on important roads or bridges to distribute deicing chemical solutions (generally sodium chloride) over the entire travelled way. The second approach has been pioneered by the Swiss invention Verglimit, which incorporates calcium chloride coated with linseed oil dispersed in the wear course of asphalt concrete. Both techniques are effective over a relatively narrow range of conditions, but Verglimit is applicable only to asphalt concrete. The objective of this task is to investigate methods for concentrating a deicing chemical or chemicals on and near the surface of pavements which will effectively reduce snow/ice adhesion at temperatures as low as practicable (0 deg F or lower), will have a service life which is cost effective, is non-toxic and noncorrosive, and is economical to manufacture and apply. The materials and process should be adaptable to both new construction and to existing portland cement and asphalt concretes.

This task will include the following sub-tasks:

- Review findings of Task 6-1.1 for applicability to design of chemical additives, and follow promising paths.

- Investigate encapsulation and other methods for controlled release of bond-inhibiting chemicals as a function of decreasing temperature.

- Select or develop a chemical which is less corrosive, less toxic and more environmentally benign than chlorides, but is cost-effective, compatible with asphalt and portland cements, exhibits a low eutectic temperature in the case of freezing point depressants, and can be encapsulated or otherwise released on the pavement surface to form an ice-release exudate.

- Develop method(s) for incorporating the ice-control chemical into existing pavements by such approaches as grooving, very high pressure jets, or areal pressure treatments.

- Demonstrate effectiveness of material(s) developed by conducting accelerated wear and trafficking tests on a laboratory scale.

- Evaluate effects of pavement modification on long-term pavement performance and on recyclability.

Evaluation: medium risk, high payoff.

Physical Surface Modification (Task 6-1.3)

Reduction of dependence on deicing chemicals requires consideration of physical methods. One of the benefits of chemicals, however, is the long-term bond-inhibiting effects of the residual chemical. At times this is not only sufficient to give a beneficial effect during a single storm but also to carry over to the next storm. Physical methods that have this long-term action must involve a modification of the pavement surface; in order to increase the life of the treatment, the modification may have to be extended into the wear course. One physical pavement modification to reduce ice adhesion has been investigated: a coating consisting of an icephobic material, i.e., one to which ice does not bond strongly. This method is presently effective over a limited range of climatic and traffic conditions and would have to be improved to make it a satisfactory approach. The objective of this task is to develop a physical modification of pavement which prevents formation or bonding of ice and which is economic, long-lived, effective over a wide range of climatic and traffic conditions, is relatively easy to apply and maintain, and does not greatly reduce coefficient of friction between rubber tire and pavement.

This task will include the following sub-tasks:

- Review findings of Task 6-1.1 for applicability to design of physical processes and follow promising paths.

- Investigate effects of pavement grooving or other surface texture modification on ice formation.

- Design low-energy (icephobic) treatments which will meet the requirements stated in the objective.

- Design other types of surface which will prevent ice from forming on the pavement.

- Perform laboratory friction, durability, and ice prevention tests.

- Evaluate effects of pavement modifications on long-term pavement performance and on other effects such as recyclability.

- Conduct field tests of candidate surface modifications.

Evaluation: high risk, high payoff.

DESTRUCTION OF ICE-PAVEMENT BOND (Project 6-2)

Project 6-1 presents the case for a study of the ice-pavement bond from the viewpoint of preventing its development and pursuing this approach in designing materials and processes. This project is a parallel study to be conducted from the viewpoint of destroying the bond once it has formed. Most present techniques depend on this approach, and therefore there is a much greater probability of success in developing new techniques, materials, and equipment to make radical improvements in ice removal by following this approach. The objective of this study is to investigate mechanism of bond formation and apply this knowledge to development of methods of bond destruction.

Fundamental Study of the Ice-Pavement Bond from Viewpoint of Disbonding (Task 6-2.1)

Research on ice disbonding has been approached empirically for the most part. A fundamental study will provide direction for subsequent studies to follow and represents the most efficient research path. The basic approach is considered of such high value that two parallel studies are planned. This task will study the ice-substrate bond from the point of view of disbonding, and Task 6-1.1 will study the bond from the point of view of prevention. The objective of this task is to conduct a fundamental study of ice-substrate bond structure and mechanics of formation to provide a sound basis for developing techniques and devices for disbonding ice after it has formed on a pavement surface.

This task will include the following sub-tasks:

- Literature search and review of related interfacial and surface physics studies. Coordinate research plan with Task 6-1.1.
- Utilize microscopic and macroscopic techniques to characterize surface bond parameters.
- Investigate physical and chemical processes for disbonding ice on pavement materials. Develop new approaches to achieving this objective.

Evaluation: high risk, high payoff.

Physical Surface Modification (Task 6-2.2)

This study is parallel with Task 6-1.3 but approached from the point of view of bond destruction. The objective of this task is to develop an effective pavement physical modification which is economic, long-lived, effective over a wide range of conditions, is relatively easy to incorporate and maintain, and does not greatly reduce friction between rubber tire and pavement.

This task will include the following sub-tasks:

- Review findings of Task 6-2.1 for applicability to design of physical processes and follow promising paths.
- Develop treatments or admixtures which will meet the requirements stated in the objective.
- Design deformable or other surface which will disbond ice from pavement.
- Investigate effects of pavement grooving or other surface texture modification on ice disbonding.
- Investigate practicability of a sacrificial coating applied to the pavement surface for ice disbonding.
- Perform laboratory friction, durability, and ice release tests.
- Evaluate effects on long-term pavement performance and on such factors as recyclability.

Evaluation: medium risk, high payoff.

Snow/Ice Disbonding by Physical Methods: Non-Contact (Task 6-2.3)

The ice-pavement bond when fully developed is stronger than the tensile strength of ice. The practical result of this is the great difficulty of removing ice completely to bare pavement by purely mechanical means, and thermal and conventional chemical methods to achieve complete removal may in many cases be economically or environmentally proscribed. Preferential destruction of the interfacial bond between ice and pavement is the energetically favorable approach to ice removal but practical constraints have prevented implementation of any successful method. The potential also exists for minimizing the amount of chemical used if it can be applied at the interface; this in turn would make it economically acceptable to use a more costly but more desirable chemical. A non-contact method of applying energy preferentially at the pavement-ice interface without excessive dissipation of energy within the ice mass has the potential for significant savings of time and money, and for minimizing damage to equipment and pavement. The objective of this task is to investigate methods of applying energy at the pavement-ice interface to achieve disbonding without directly contacting the pavement surface; develop a practical device or devices to achieve this.

This task will include the following sub-tasks:

- Investigate physical and chemical approaches that do not depend on modification of the pavement bulk or surface properties. Include feasibility and efficacy of using electromagnetic energy in all forms (e.g., microwave and laser radiation) and chemical solutions applied to the interface with minimum loss of energy

in the ice (e.g., by high pressure jets penetrating the ice to reach the pavement).

- Investigate physical methods that require minimum modification of the surface or bulk properties of pavement materials to concentrate electromagnetic or other energy for disbonding ice or compacted snow at the ice-pavement interface with minimum loss in the ice. Modification of pavement surfaces must not greatly reduce the coefficient of friction.

- Construct prototype device or devices and demonstrate capabilities and effectiveness.

Evaluation: high risk, high payoff.

Snow/Ice Disbonding by Physical Methods: Contact (Task 6-2.4)

Though current methods of physical ice removal rely principally on cutting and lifting with a blade attached to a displacement plow, few studies on blade geometry and dynamics have been conducted to improve cutting efficiency and to minimize damage to both pavement and equipment. The objective of this task is to investigate methods of separting ice frozen on both asphalt and portland cement concretes by use of a contacting device in order to improve mechanical efficiency and reduce wear and damage to equipment and pavement.

This task will include the following sub-tasks:

- Investigate mechanics of compacted snow and ice removal from a surface by mechanical scraping and lifting, determine optimum angle of attack, cutting edge configuration and material, and contact pressure for minimum expenditure of energy with complete disponding and minimum wear of cutting edge and pavement.

- Investigate the mechanics of separating ice frozen on both asphalt and portland cement concretes by other means.

- Design devices(s) to separate ice from pavement.

- Integrate preferred design into the displacement plow designs produced in Project 6-3, where appropriate.

- Construct prototype(s) and subject to test.

- Prepare design drawings of successful products.

Evaluation: medium risk, high payoff.

Development of Evaluation Procedures for Deicing Chemicals (Task 6-2.5)

Deicing chemicals currently used exhibit a wide variation in their properties, many of which affect their usefulness as a freezig point depres-

sant. Maintenance organizations need a uniform procedure by which they can test, monitor, and evaluate the pertinent characteristics of both routinely purchased chemicals as well as new materials entering the market place. The objective of this task is to establish criteria for evaluating deicing chemical effectiveness, characteristics, and impacts, and develop standard procedures for monitoring and testing.

This task will include the following sub-tasks:

- Review and synthesize research on and testing of deicing chemicals which has been completed in the United States and in other countries.
- Establish required criteria, including ice-melting characteristics; corrosion; effects on water quality and concrete pavement; other environmental effects; storage, spreading and other handling practices; worker safety; and friction.
- Develop evaluation procedures.
- Extend evaluation procedures to cover any category of chemical that may be proposed for deicing.

Evaluation: low risk, medium payoff.

Improvement of Performance and Characteristics of Sodium Chloride as a Deicer (Task 6-2.7)

The low first cost, ready availability, and inexhaustible supply of salt--sodium chloride--points to its use as a deicing agent wherever there are no overriding environmental or safety concerns. Because of the continued probable large-scale use, adverse environmental and corrosion effects should be reduced if this is possible. The need also exists to improve the ice-melting characteristics of salt by enhancing its solubility or rate of solution beyond values presently possible. The objective of this task is to reduce the deleterious effects of salt and improve its ice-melting properties.

This task will include the following sub-tasks:

- Investigate methods for reducing or eliminating the deleterious corrosion effects of salt.
- Investigate methods for reducing or eliminating the undesirable effects of salt on vegetation.
- Investigate methods for improving the ice-melting characteristics of salt while being economical and not creating additional environmental or corrosion problems.
- Investigate use of additives which will accomplish the same purposes.

- Subject candate materials to outdoor winter trafficking tests and monitor corrosion and environmental stresses.

Evaluation: high risk, high payoff.

DEVELOPMENT OF IMPROVED DISPLACEMENT PLOWS (Project 6-3)

Present displacement plow design has evolved very empirically with scant attention paid to the physical properties of the material being handled and with little consideration given to the aerodynamic and hydrodynamic principles involved in the flow of fluidized snow. As a consequence, energy expended in displacing snow is disproportionate to the work performed, cast distance is not optimized resulting in unnecessary rehandling of snow and wasted energy, and the lack of standardization based on performance specifications increases the costs incurred by highway agencies. Though the primary function of a blade plow is the lifting and casting of snow to clear the travelled way, mechanical removal of ice to minimize the residue requiring chemicals to expose bare pavement is an increasingly important additional function of blade plows and one that requires experimental design. Underbody blades are utilized for removal of compacted snow and ice as well as for clearance of light snow accumulations, but their design has not been optimized. Front-mounted blade plows have greatest utility for snow displacement, but improvement in their capabilities for ice cutting is possible. Past practice has generally treated plow design independently of the design and capabilities of the prime mover; plow and truck must be considered as a system for optimum performance. No scientifically based plow design improvement efforts have been undertaken in the United States; fundamental plow design improvements have resulted from studies in Sweden, Japan, Switzerland, Germany, and Great Britain, and are optimized for their particular conditions. With the exception of Japan, no work is currently underway, and the particular needs of U.S. maintenance engineers are not being addressed. The need for this effort was identified as one of the four recommended by the Highway Maintenance Research Needs workshop in 1974 (see Project Statement R2 in Report No. FHWA-RD-75-511). No action has been taken to implement the recommendation for research on this topic, and the need still remains. The objective of this study is to establish design criteria and prepare design details and specifications for displacement plow system based on aerodynamic/hydrodynamic principles, material handling characteristics of snow, and ice cutting mechanics leading to standard designs for different types of snow and climatic conditions; consider plow and carrier as a system for optimum design.

This project will include the following sub-tasks:

- Conduct literature search on the flow properties of fluidized dry cohesionless, wet cohesionless, and cohesive particulates and relate to the flow of snow over smooth geometric shapes. Determine the important parameters influencing the flow of snow with increasing degree of fluidization, i.e., as a function of the liquid water and air contents.

- Conduct a simulation study using computer-aided design techniques to model the flow of cohesionless and cohesive particles over parameterized simple geometric shapes with the objective of minimizing energy loss and achieving the range of functions from low-speed short cast to high-speed long cast.

- Investigate mechanics of compacted snow and ice removal from a surface by mechanical scraping and lifting, determine optimum angle of attack, cutting edge configuration and material, and down-loading for minimum expenditure of energy with complete clearance and minimum wear of cutting edge and pavement.

- Evaluate effectiveness of and need for plow add-on devices such as blowers, brooms, brushes, coatings.

- Construct scale models of displacement plows and test using natural snow over a range of conditions; measure forces on blade as a function of important parameters identified in the first sub-task and optimized in the second subtask.

- Construct full-scale prototypes of representative types of displacement plows (designed for short cast, long cast, high speed, low speed, slush, or combination designs) and subject to force measurements in natural snows with a range of critical properties. Place the plows in routine service to obtain user reactions.

- Prepare detailed design drawings and specifications.

Evaluation: low risk, high payoff.

IMPROVED METHODS OF CONTROLLING BLOWING SNOW (Project 6-4)

Reduction of the amount of snow reaching a roadway is one of the fundamental approaches to cutting costs of clearance, reducing the potential for formation of compacted snow, and reducing the need for chemicals. An additional benefit arises from the improved visibility and the lessened frequency that roads are closed by drifts. Wind-blown snow can be controlled in many situations by use of properly designed snow fences installed in the proper location. Snow fences clearly aren't an economic answer to snow control in all cases, but they have been neglected in many situations where their potential holds promise for net savings in total costs of snow removal. Considerable progress has been made in the engineered design of snow fences over the last few years, yet more remains to be done to increase their effectiveness in a diversity of conditions. It may be possible to improve the effectiveness of snow fences by pursuing research on free-turbulent mixing in the vicinity of barriers to allow prediction of surface shear stress; it is the surface shear stress that determines the shape, i.e., slope, of the deposition surface. Improper design and/or location of roads, overpasses, guard rails, and vegetation creates many severe drifting situations that could be avoided if information on better designs were available. The objective of this study

is to develop improved methods for controlling blowing snow and refine design criteria for reducing snow drifting on highways.

This project will include the following sub-tasks:

- Apply principles of free-turbulent mixing to develop mathematical models for predicting the shape of snowdrifts formed by two-dimensional features. Verify models by both laboratory modeling and field experimentation and observations.

- Determine feasibility of extending approach used in the first sub-task to the problem of three-dimensional features.

- Apply the results from the above sub-tasks to the improvement of snow fence design and to the development of improved guidelines for permanent and temporary fence placement, with emphasis on terrain interactions.

- Apply results from the first two sub-tasks to improvement of existing methods of designing drift-free roads (e.g., improving the "Wyoming Drift Prediction Subroutine for Earthwork Design").

- Prepare design drawings and specifications and a procedure for selection and implementation of measures to reduce or prevent snow drifting on new and existing roads.

Evaluation: medium risk, medium payoff.

MANAGEMENT OF SNOW AND ICE CONTROL OPERATIONS (Project 6-5)

Snow and ice control is the single most costly maintenance function performed by many northern states and cities. We estimate that the direct cost for this activity amounts to $1.4 billion annually for states alone. Staffing levels and equipment specifications are very often based on winter maintenance functions and affect all other seasonal activities. Many maintenance management activities have been improved by research but winter maintenance has not received adequate attention. This study is intended to provide the maintenance manager with the means to answer the questions who, what, where, why, when and how in connection with his operation. The objective of this study is to adapt commercially available equipment components to provide rapid assessment of storm warnings and pavement condition; develop procedures for improving allocation of limited resources and evluating alternative programs.

Improvement of Storm Monitoring/Communications Technology (Task 6-5.1)

The snow or ice removal task is reduced if remedial treatment is initiated at the start of a storm and the appropriate treatment is selected on the basis of knowledge of the pavement surface condition and the forecasted weather. This requires mobilization of personnel and equipment and effective communicating of conditions within the organization and to the public prior to the start of a storm. However, if storm warning is false, resources are wast-

ed by the unnecessary mobilization, and the organization's credibility is undermined. Therefore, the need exists to obtain accurate forecasts of impending weather or information from upwind observing stations on approaching weather sufficiently in advance of the time required for mobilization. Knowledge of pavement state is necessary both to assess current conditions and to facilitate prediction of future conditions. Rapid communication both on a regional basis and within the structure of the jurisdiction itself is necessary for effective control of snow removal forces. The public needs to be informed of anticipated road conditions on a timely basis. The objective of this task is to improve the capabilities of a snow and ice control organization to make rapid and cost-effective response to winter maintenance requirements with minimum inconvenience to the public and with maximum public awareness of road conditions.

This task will include the following sub-tasks:

- Establish the communication functions and systems required by different levels in snow and ice control organizations.
- Survey commercial sources of communications components for equipment meeting requirements for implementing system design.
- Investigate applicability of pavement sensors and micrometeorological stations for providing real-time information on pavement state and for enabling prediction of pavement conditions 4-12 hours later for use by public authorities.
- Investigate methods for identifying optimum locations for all types of sensors to provide the necessary information with minimum cost.
- Establish criteria for evaluating alternative responses to the full range of conditions that can be encountered in a snow and ice control situation; develop a procedure for selecting the appropriate mechanical, chemical, or other treatment based on the exising and projected conditions.
- Conduct field test of candidate equipment and procedures.

Evaluation: medium risk, high payoff.

SECTION 5
RESULTS TO BE ACHIEVED

Successful completion of the projects and tasks to be undertaken within the $8,000,000 funding allocation will significantly improve the materials, methods, and equipment available to maintenance managers for snow and ice control. One might question the justification for devoting nearly 20% of the total budget to fundamental studies of the ice-pavement bond. However, this approach is the keystone to the entire structured research plan, and much depends on its accomplishment. As was stated in Section 3, most prior snow and ice control research has been pursued empirically, but a large-scale research program as outlined in this report is conducted most effectively by starting with the fundamentals. The fundamental studies may not themselves produce a product or usable technique, but the intent is to provide insight into the basic physics to direct the other studies along the most promising paths.

The consequential cost of using salt for deicing has been variously estimated from $800,000,000 to $2,000,000,000. Most of this represents automobile corrosion, a problem that has been diminishing in magnitude for many years as automobile designs, structural materials, and coatings have improved. Automobile corrosion would not stop if salt use were to end, however. Effects of deicing chemicals on highway structures have been a more serious problem driving the search for alternative chemicals. The development of an alternative chemical which would avoid many of the deleterious effects of salt would have a great effect on costs of pavement and bridge deck repairs, though it should be realized that surface deterioration is a physical effect which will occur with any freezing point depressant. Though no funds will be spent on CMA research unless the need arises, an important product of Task 6-2.5 is the preparation of a standard method of test for evaluating deicing chemicals which may be developed by industry, by states, or by organizations in other countries. There is economic incentive for developing cheaper and better alternative deicing chemicals, but proof of effectiveness and environmental acceptability must satisfy users. The results to be expected from the study to improve the characteristics of salt as a deicer are more questionable, and success depends to a large extent on the findings of the fundamental bonding studies to reduce the amount of chemical needed. However, if additives or other modifications of sodium chloride can be developed to reduce distress on the roadside environment or to interfere with ion mobility into ground water or concrete, significant savings will result.

The physical methods of ice removal to be developed will reduce the quantity of chemicals of any kind needed for pavement clearance. These methods will have a high first cost -- pavement overlay, energy-intensive devices for applying energy at the ice-pavement interface, for example -- but

they have the potential for providing rapid, thorough, non-polluting ice removal with less damage to equipment and pavement.

Two studies can result in the saving of millions of dollars: improvement in efficiency of displacement plows, and development of a monitoring-communications systems for snow and ice control organizations. Surveys made by CRREL show that more than $1 billion is spent annually in the United States for snow and ice removal, and fully three-fourths of this represents the cost of clearance by plows. Snow removal is a materials handling process, and the design of an efficient materials handling device requires application of a thorough knowledge of the properties of the material being handled. This has been done only to a very limited extent, and improved designs resulting from Project 6-3 could cut fuel consumption by 5-10% and at the same time reduce forces on equipment leading to early wear or failure. Similar large savings are possible from Task 6-5.1 by developing an effective pavement monitoring, storm warning, and integrated communications system, savings resulting from reduced false call-outs, improved determination of chemical application rate requirements, and improved storm traffic control.

SECTION 6
IMPLEMENTATION OF RESULTS

The greatest obstacle to putting the projected research results into practice will be the resistance on the part of some maintenance authorities to attempt something new and untried (by them) in their system. It is the purpose of the field tests included in six of the tasks to address that reluctance; field tests will not only serve to improve the products and techniques that will be the research results but will also demonstrate the efficacy of the products and what they can accomplish. The inclusion of the large-scale demonstration project (Project 6-6) in the original plan was meant, inter alia, to test and to demonstrate the interactions of a number of new products and techniques in a large system. The elimination of this project from the final recommended plan still leaves this question unanswered. An alternative would be for several states to select some new products and techniques considered most aplicable to their needs and put them into practice using their own funds, reporting to other states the results of their experience. The drawback to this alternative lies in the problem that has occurred in all previous tests using an operational system: too few trained and experienced test personnel can be assigned to the test at the times they are needed. The sporadic nature of snow/ice removal events makes it mandatory that test personnel be available without delay during those times. One or two large-scale tests using observers whose primary duty is to obtain data during operational periods would assure coverage during those important test times.

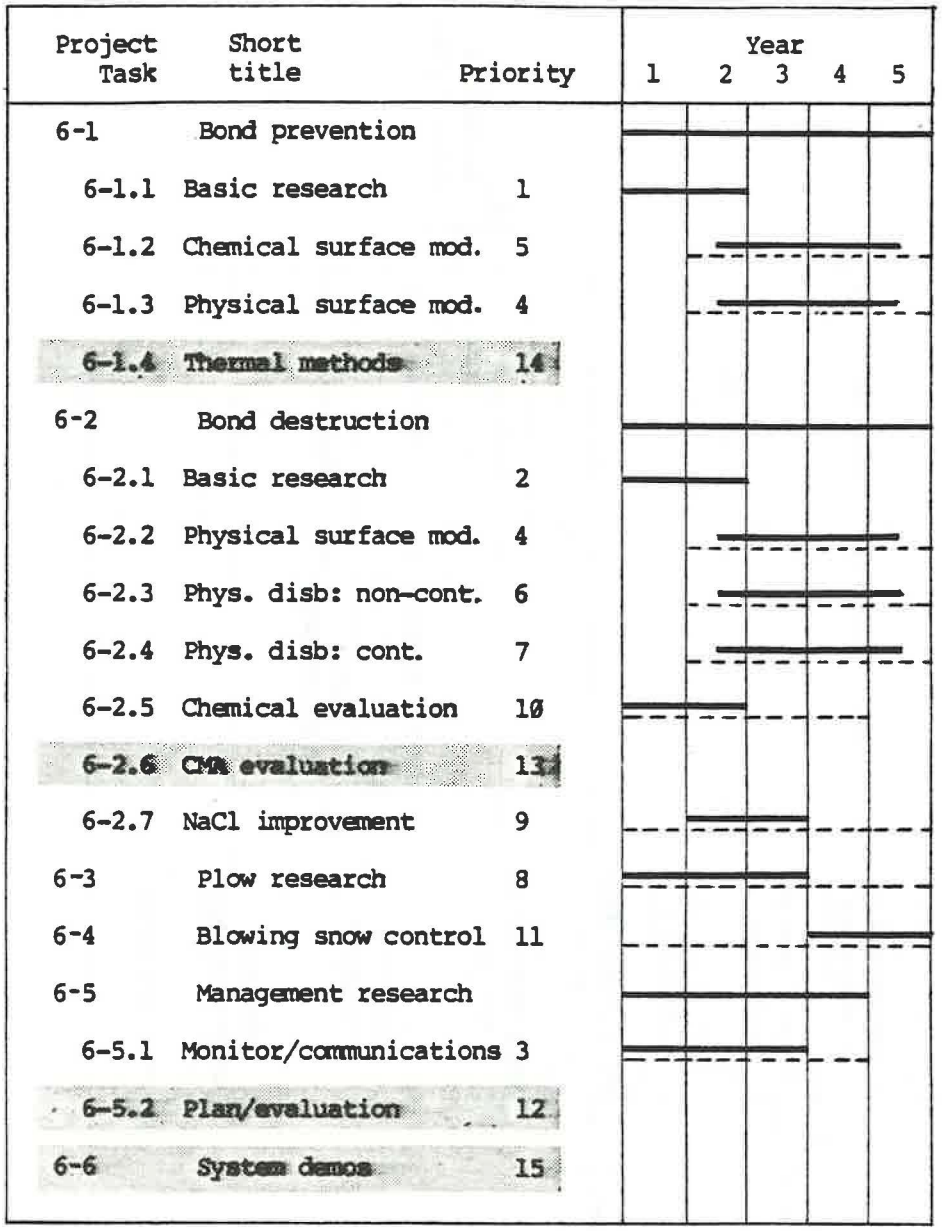
Nearly all the research products are technologically based and therefore hard data can be obtained during the development and test period to indicate their effectiveness and to provide a basis for evaluating the economics of implementation. The one exception is Task 6-5.1; development of monitoring/communications system can be approached systematically on a technological basis, but evaluation of its operational effectiveness poses the problems cited above in obtaining adequate observations. However, gross measures of effectiveness such as cost of treatment per inch of snowfall, time to return system to original condition, and vehicle miles can be used. Other measures of effectiveness would necessarily have to be used for convincing proof, however.

SECTION 7
SCHEDULE OF PROJECTS, TASKS, SUB-TASKS

The accompanying Figure 2 presents the scheduling of recommended projects and tasks by year. No milestones are indicated since it is desirable to review progress of all studies annually to determine if redirection of effort should be made, or funding levels changed.

A flowchart is given in Figure 3 showing the relationship of the fundamental studies, the studies that will depend on the fundamental results, and the studies requiring field tests.

All projects and tasks considered by the advisory committee for inclusion in the recommended research program are shown; since all the studies constitute an integrated program, it is desirable to show the relationship of the four projects and tasks that had to be eliminated because of funding constraints, in the event other funds are forthcoming. The four studies eliminated from the recommended program are indicated by stippling (Fig. 2) or broken-line boxes (Fig. 3).



Recommended but unfunded

Recommended schedule

Earliest start, latest finish

FIGURE 2. TRA 6 - PROJECT AND TASK START YEAR AND ELAPSED TIME.

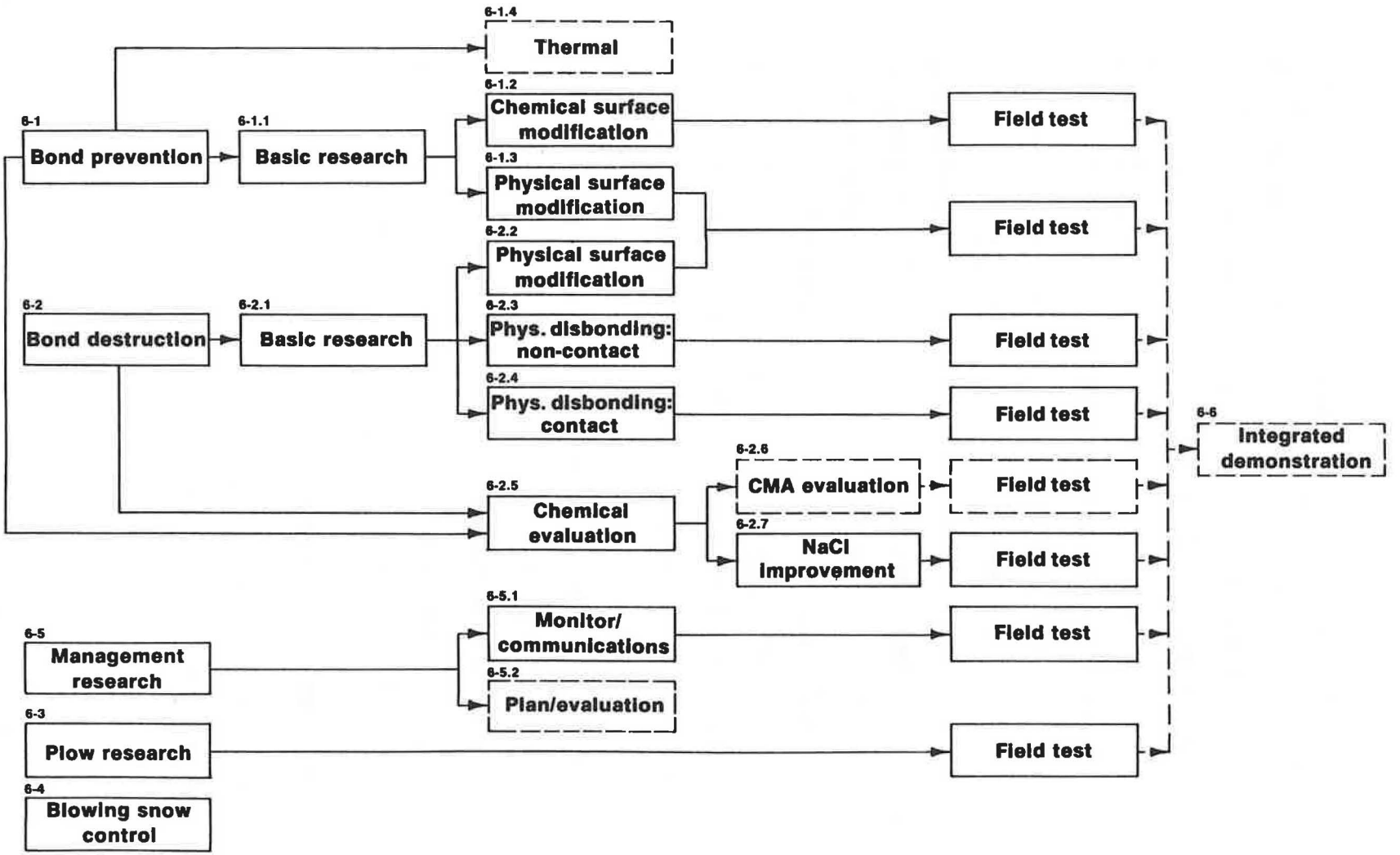


FIGURE 3. TRA 6 - FLOWCHART.

SECTION 8
BUDGET

The budget shown in Table 1 gives personnel costs for each project and task for each of the five years, the total personnel costs, estimated costs for equipment, and costs of field tests. The stippled projects and tasks have been eliminated from the recommended research program but are listed to indicate their relationship to the recommended studies.

TABLE 1

TRA 6 BUDGET

Project Task	Short title	FUNDING ($000) Personnel Funding by Year 1	2	3	4	5	Total	Equip.	Field Tests	GRAND TOTAL
6-1	Bond prevention									
6-1.1	Basic research	325	325	-	-	-	650	100	-	750
6-1.2	Chemical surface mod.	-	100	200	200	100	600	-	250	850
6-1.3	Physical surface mod.	-	50	125	125	50	350	100	50	500
6-1.4	Thermal methods									
6-2	Bond destruction									
6-2.1	Basic research	325	325	-	-	-	650	100	-	750
6-2.2	Physical surface mod.	-	50	125	125	50	350	100	50	500
6-2.3	Phys. disb: non-cont.	-	100	200	200	100	600	125	75	800
6-2.4	Phys. disb: cont.	-	75	125	125	50	375	75	50	500
6-2.5	Chemical evaluation	150	150	-	-	-	300	-	-	300
6-2.6	CMR evaluation									
6-2.7	NaCl improvement	-	200	200	-	-	400	-	-	400
6-3	Plow research	200	200	200	-	-	600	400	200	1200
6-4	Blowing snow control	-	-	-	150	100	250	-	-	250
6-5	Management research									
6-5.1	Monitor/communications	200	200	200	-	-	600	600	-	1200
6-5.2	Plan/evaluation									
6-6	System demos									
	Total:	1200	1775	1375	925	450	5725	1600	675	8000

Recommended but unfunded

APPENDIX A
OTHER RESEARCH PROJECTS CONSIDERED

Four projects or tasks included in the research plan presented to the advisory committee were eliminated from the final plan when their priorities placed them below the cut-off for available funding. One additional study was proposed by an advisory committee member but was considered outside the scope of this research plan and more appropriate for another organization. It is reproduced below substantially as presented to the advisory committee.

STUDIES CONSIDERED BUT ELIMINATED

Thermal Methods of Snow and Ice Removal (Task 6-1.4)

A positive method of destroying the ice-pavement bond is the introduction of heat into the interfacial layer. This can be accomplished by irradiating the interface "from above," i.e., by introducing the radiant energy through the ice and absorbing it in the substrate. A second approach involves the addition of thermal energy into the pavement itself. Thermal energy in the quantity necessary using fossil fuel sources has proved uneconomic in all but critical applications. Low grade heat from localized earth sources has proved a practical source of energy for relatively small area heating using heat pipes, but this will not be practicable for extensive area heating. Heat pipes for coupling low grade energy sources to pavements for snow and ice control have been investigated in the United States, Japan, and Germany, and several small-scale installations have been made. However, no studies have been carried out to investigate scale-up to heat extensive stretches of highway. In an urban environment both the need for a positive method of snow and ice control and the availability of vast quantities of low grade heat may converge to justify investment in this system if its economics can be ascertained and a viable engineering design demonstrated. The objective of this task is to investigate the practicability of utilizing a technologically feasible method of tapping large reservoirs of low grade heat and transporting the energy to extensive highway sections; to determine the economics of competing designs and energy sources.

This task will include the following sub-tasks:

- Determine the nature and availability of sources that have the potential to provide the necessary quantity of heat for ice control, and make survey to find locations where such sources are close enough to highways requiring a high level of protection.

- Investigate practicability of developing (1) efficient and economic methods of extracting low grade heat from the various types of sources identified in the above sub-task; (2) efficient and economic methods of transporting the thermal energy from these sources to the pavements to be protected. Identify critical design elements affecting achievement of the goal.

- Make feasibility study of retrofitting asphalt and portland cement concrete pavement with a surface heating system.

- Evaluate economics of a total heated pavement system including extraction, transport and distribution of thermal energy into the pavement.

- If the economics are deemed satisfactory, prepare general design guidelines, specifications, and operating procedures for application with the energy sources and environments identified in the first sub-task.

Evaluation: high risk, medium payoff.
Recommended funding: $175,000.

Test and Evaluation of CMA (Task 6-2.6)

Many questions remain to be answered about calcium magnesium acetate (CMA) before widespread use is initiated as a replacement for other deicing chemicals, questions such as its ice-melting characteristics, long-term environmental fate, application, storage and handling procedures, and optimum application rates for a wide range of conditions. The precise scope of the study will depend on the outcome of present NCHRP and FHWA contracts on CMA. The objective of this task is to characterize the properties, determine optimum application rates, and establish recommended storage and handling procedures for CMA.

This task will include the following sub-tasks:

- Review products of completed FHWA, NCHRP, and other studies on CMA and determine unmet needs following completion of other research.

- Conduct laboratory-scale tests to fill in gaps in knowledge.

- Design and conduct large-scale field tests as necessary in two or more climatic regimes to develop recommended application rates and to assess their validity.

- Prepare a manual of recommended practices for handling, storing and applying CMA.

Evaluation: low risk, medium payoff.
Recommended funding: $200,000.

Improvement of Resource Planning and Program Evaluation (Task 6-5.2)

There is no universal and practicable method for evaluating the quality and effectiveness of existing snow and ice control programs and for designing new, more effective programs. There is a need for a model which will accomplish this. The objective of this task is to improve program evaluation and design.

This task will include the following sub-tasks:

- Establish criteria characteristics of effective snow and ice control organizations. Make case studies of winter maintenance responses to identify effective measures.

- Define requirements of snow and ice control programs and attributes for comparison of effectiveness, including considerations of equipment selection (types, quantities) and routing plans.

- Develop a model for effective evaluation of snow and ice control operations which will focus attention on most significant areas of improvement to achieve a specified objective.

- Apply current research results in artificial intelligence to develop an expert system for evaluating the effectiveness of a snow and ice control program and for designing improved programs.

Evaluation: medium risk, medium payoff.
Recommended funding: $220,000.

DEMONSTRATIONS OF TECHNOLOGY-BASED WINTER MAINTENANCE OPERATION SYSTEMS
(Project 6-6)

Many of the materials, procedures and devices which will be the products of Projects 6-1 to 6-5 may prove useful and workable when used by themselves but may offer even greater advances when integrated into a larger system making use of a number of new developments. Care must be taken in merging the various developments, however, to avoid conflicts. This study will investigate the problems that may arise in implementing multiple techniques and equipment and devise system integration procedures. The objective of this project is to demonstrate the value of research products for winter maintenance integrated into systems of various sizes and complexities and ensure their effective integration into existing systems.

This project will include the following sub-tasks:

- Establish the characteristics of each implementable technique, material, and equipment that will affect its integration into systems of varying degrees of size and complexity.

- Survey potential sites for implementing demonstrations of two or more elements in one test. Products or methods developed under all projects of this TRA will be given field tests either singly or in combination as they reach an appropriate developmental stage.

- Design test installations and procedures and conduct tests.

- Observe operations of controlled demonstrations over one or more winters; prepare report of effectiveness, integration requirements, and costs of various combinations of elements.

Evaluation: medium risk, high payoff.
Recommended funding: $2,030,000.

STUDY PROPOSED BUT NOT ACCEPTED

Improvement of productivity through improved labor/management relations.

Although the major emphasis of the snow and ice Technical Research Area is to increase productivity through technological improvements, it is likely that snow and ice control, and in fact highway maintenance in general, will remain labor intensive. Consequently, further improvements in productivity must come from improved labor-management relations. Furthermore, the anticipated technical improvements from the proposed research will bring change which will require labor cooperation where organized labor is involved. Substantial progress has been made in other fields, most recently in the transit industry (see NCTRP Reports 5 and 6) to identify and adapt "quality of worklife" programs. Similar research is needed early in the snow and ice control program so that the results will be timely in the development of (1) implementation plan for technological improvements, and (2) the brainstorming required in the conduct of technological research.

The objective of this study is the development of appropriate quality of worklife programs for the purpose of (1) improving productivity, (2) developing plans for change involving technological improvements, and (3) involving labor in brainstorming ideas for technological change.

The products of the study would be a research report and training manual for instructors, managers, and labor representatives in the use of appropriate quality of worklife programs.

Subtask 1 Describe or develop an appropriate problem-solving process that will include brainstorming techniques for use by labor and management participants.

Subtask 2 Identify potential programs that will include quality circles, and incentive and award programs.

Subtask 3 Evaluate the appropriateness of the potential programs for use in snow and ice control organizations. This would include an assessment of success and failure in fields where they have been applied.

Subtask 4 Adopt or adapt appropriate programs for the snow and ice field.

Subtask 5 Determine implementation barriers and design model implementation programs to overcome them.

Subtask 6 Develop training materials for regional seminars to train instructors, managers, and labor representatives from state and local governments.

Subtask 7 Conduct seminars.

Proposed funding: $400,000

APPENDIX B
DATA REQUIREMENTS FOR SNOW AND ICE STUDIES

Most field tests which would be conducted by projects and tasks in TRA 6 probably will not be done at test sections planned by any of the other Technical Research Areas. However, a few of the sections to be instrumented and observed as part of the long-term pavement performance study may serve as supplementary snow and ice test sites. A list of the important data that would be required for these studies is given here. Note, however, that this is a complete listing of all relevant factors; not every study would require all these data but the appropriate selection would be made from this list. This was complied by the TRA 6 representative on the Data Requirements Subcommittee, Dr. Kynric Pell, from Requirements voiced by the advisory committee.

Meteorological Environment

Ambient temperature	Data required at
Wind speed	10 min. intervals
Wind direction	continuously
Humidity	
Solar radiation	
Long-wave radiation	
Precipitation	
Type	
Rate	
Visual range	
Blowing or drifting snow	

Pavement Characteristics

Type	Once for site
Surface condition	
Wet	10 min. intervals
Dry	during storms
Ice	
Snow	
Frictional properties	

Site Factors

Rural/urban	Once for each site
Snow fences, shelter belts	
Open country	
Fetch distance	
Vegetation	
Relative elevation	
Buildings/structures	

Traffic Factors — Throughout storms

- Traffic count
- Traffic speed
- Traffic mix

Surface Treatment — Throughout storms

- Chemical
  - Type
  - Time
  - Rate
- Plowing
  - Equipment used
  - Blade contact/pressure
  - Time

Treatment Results

- Surface conditions
  - Visual observation
  - Photographic
  - Sensor measurements
- Residue after storm or treatment
- Accident rates

BIBLIOGRAPHY

"Effects of Deicing Salts on Water Quality and Biota. Literature review and recommended research," R.E. Hanes, L.W. Zelazny, and R.E. Blaser. Report 91, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, 1970.

"Minimizing Deicing Chemical Use." Synthesis of Highway Practice 24, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, 1974.

"Highway Maintenance Research Needs." Report No. FHWA-RD-75-511, Federal Highway Administration, Washington, DC, 1975.

"Highway Maintenance Research Needs-1980." Prepared by Transportation Research Board for Federal Highway Administration, Washington, DC, May 1981.

"Ice-Melting Characteristics of Calcium Magnesium Acetate," Roy U. Schenk, Bjorksten Research Laboratories, Madison, WI, for Federal Highway Administration, Washington, DC, February 1985.

"Survey of Salt, Calcium Chloride and Abrasives Use in the United States and Canada" (annual compilations by fiscal year). Salt Institute, Alexandria, VA.

"Environmental Degradation by De-Icing Chemicals and Effective Countermeasures" (9 reports). Record 425, Transportation Research Board, Washington, DC, 1973.

"An Economic Analysis of the Environmental Impact of Highway Deicing." Report EPA-600/2-76-105, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, OH, May 1976.

"Economic Impact of Highway Snow and Ice Control." Report No. FHWA-RD-77-95, Federal Highway Administration, Washington, DC, December 1977.

"A Search: New Technology for Pavement Snow and Ice Control." Report EPA-R2-72-125, Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, DC, December 1972.

"Investigation of the Basic Forces Involved in the Adhesion of Ice to Highway Surfaces," T. Ashworth and J.A. Weyland, South Dakota School of Mines and Technology, for Federal Highway Administration, Washington, DC, June 1982.

"Construction and Benefits of Rubber-Modified Asphalt Pavements," David C. Esch. Record 860, Transportation Research Board, Washington, DC, pages 5-13, 1982.

"Proceedings of the Northstar Workshop on Noncorrosive Winter Maintenance." Report FHWA/MN/RD-84-03, Minnesota Department of Transportation, St. Paul, MN, October 1983.