SHRP-P-416

SHRP-LTPP Overview:

Five-Year Report

William O. Hadley
Hadley and Associates

Strategic Highway Research Program
National Research Council
Washington, DC 1994

SHRP-P-416
ISBN 0-309-05815-5
Product No.: 5000

Program Manager: *Neil F. Hawks*
Five-Year Report Manager: *A. Robert Raab*
Program Area Secretaries: *Cynthia Baker, Francine A. Burgess*
Production Editor: *Margaret S. Milhous*

June 1994

key words:
asphalt concrete
jointed plain concrete pavement
jointed reinforced concrete pavement
continuously reinforced concrete pavement
portland cement concrete
DIPstick
load equivalence factors

Strategic Highway Research Program
National Research Council
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

1.5M/NAP/694

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

The authors/editors of this Overview Report are Dr. William O. Hadley (all sections), Dr. Virgil Anderson (Section 3), Mr. Jonathan Groeger (Sections 2 and 4), Mr. John German (Section 8), and Mr. Charlie Copeland (Section 6). All authors were associated with Texas Research and Development Foundation (TRDF) during the Long-Term Pavement Performance program. Contributions by Mr. Gonzalo Rada of PCS/Law (Section 5), Mr. Amir Hanna of SHRP and Dr. Shiraz Tayabji of PCS/Law (Section 3), and Dr. Brent Rauhut of Brent Rauhut Engineering Inc. (BRE) and Dr. Gilbert Baladi of Michigan State University (Section 7) are gratefully recognized. The manuscript was prepared by Ms. Jan Zeybel.

The publication of this report does not necessarily indicate approval or endorsement by the National Academy of Sciences, by the Federal Highway Administration, or by any state highway or transportation department of the findings, opinions, conclusions, or recommendations either inferred or specifically expressed herein.

Contents

List of Figures

List of Tables

Abstract

This report provides an overview of the first 5 years of the SHRP-LTPP program. The background, LTPP history, activities and approaches, and decision-making processes of the program are detailed. Included are summaries of the studies initiated for general and specific pavement types, the characterization of pavement materials, monitoring activities, the LTPP database and Information Management System, data analysis, traffic data collection and analysis, as well as a summary of the contributions made by international participants. The general LTPP program is described and the expected results, products, and benefits are also outlined.

Section 1
Introduction

This report documents the research and analytical activities undertaken by the Strategic Highway Research Program (SHRP) and its contractors in the Long-Term Pavement Performance (LTPP) program. The goals, tasks, and accomplishments of the SHRP-LTPP program are presented in the following documents:

- Overview Report
- General Pavement Studies (GPS)
- Specific Pavement Studies (SPS)
- SHRP-LTPP Information Management System
- SHRP-LTPP Materials Characterization Program
- SHRP-LTPP Monitoring Program
- Traffic Data Collection and Analysis
- Data Analysis Studies for the SHRP-LTPP Program
- International Participation
- Selected Bibliography

This document provides an overview of the 5-year SHRP-LTPP program. It describes the background, approaches, and decision making used throughout SHRP-LTPP. It should be helpful to future researchers and users of SHRP-LTPP data and products.

This section of the overview report concerns the origins of SHRP-LTPP. The remaining sections are

2. General Pavement Studies (GPS)
3. Specific Pavement Studies (SPS)
4. Pavement Materials Characterization
5. Monitoring Activities
6. Information Management System (IMS)
7. Data Analysis Studies
8. Traffic Data Collection and Analysis
9. International Participation
10. Expected Results, Products, and Benefits

These sections summarize each portion of SHRP-LTPP. From the overview report, readers should obtain a general understanding of all aspects of SHRP-LTPP activities. The reader can pursue areas of interest in more detail by consulting the individual in-depth documents that comprise the remainder of the SHRP-LTPP Reports.

Background of SHRP-LTPP

The U.S. highway system represents a massive public investment and is essential to the economy, market competitiveness, and defense of the nation. The design and construction of the interstate highway network was launched by Congress in 1956 and was essentially completed in 1992. A 30-year investment and countless person-years of effort have created the most massive and modern transportation system in the world. However, 15 years before the system's completion, serious concerns were already being expressed about the deterioration of U.S. highways. This debate was fueled by numerous gloomy reports in the media and elsewhere concerning the status and future of the U.S. infrastructure. It appeared that the nation's massive investment in the transportation of goods, people, and services was being compromised because of the huge reinvestment needed to maintain, rehabilitate, and operate the existing network. Major steps had to be taken to find ways to rectify the situation (**1.1**).

The Strategic Transportation Research Study (STRS)

In October 1982, the Federal Highway Administration (FHWA) of the U.S. Department of Transportation commissioned the Transportation Research Board of the National Research Council to coordinate an industry-wide investigation of the role of research in revitalizing the U.S. highway transportation system. A massive infusion of funds for highway maintenance and rehabilitation using existing technology would not be cost-effective in the long run. New and improved materials, equipment, and processes were needed to operate the system efficiently.

The Strategic Transportation Research Study (STRS) was conducted in 1983 and early 1984, resulting in the Transportation Research Board publication of Special Report 202: *America's Highways: Accelerating the Search for Innovation* (**1.1**). This report documented the U.S. highway industry's allocation of a much smaller percentage of expenditures to research than virtually any other industry, and it revealed that highway research spending had steadily declined over the previous decade. The report identified six areas in which concentrated research efforts could dramatically reduce expenditures for design, construction, maintenance, and rehabilitation of highway systems. These areas were asphalt, maintenance cost-effectiveness, protection of concrete bridge components, cement concrete in highway structures, control of snow and ice on highways, and long-term pavement performance.

In each case, priorities were established for these problem areas for which major innovations would increase the productivity, effectiveness, and safe operation of the nation's highway system.

The Strategic Highway Research Program (SHRP)

A study was conducted in the 1984–86 period with financial, staff, and administrative support of the American Association of State Highway and Transportation Officials (AASHTO), FHWA, the Transportation Research Board, and the National Research Council. In this effort, detailed research plans were developed for the six strategic problem areas, with particular emphasis on long-term pavement performance. Support for the necessary funding legislation was generated. Procedures for this activity were finalized, and the Strategic Highway Research Program (SHRP) was established as an independent unit of the National Research Council. Consequently, SHRP was fully operational when funding became available in April 1987. The first SHRP contracts were signed October 6, 1987.

The 6 STRS research areas were combined into the following SHRP research programs:

- Asphalt
- Highway Operations
- Concrete and Structures
- Long-Term Pavement Performance (LTPP)

The Long-Term Pavement Performance (LTPP) Program

Approximately $20 billion per year is spent replacing and rehabilitating pavements in the United States. In addition to the repair needs of interstate and primary systems, state, county, and local highways and city streets require massive expenditures to preserve investments in pavements. Despite these expenditures, no comprehensive research on long-term pavement performance had been conducted since the AASHO Road Test—a large-scale accelerated field experiment conducted under one set of climate and soil conditions—was completed in 1960.

Fundamental questions concerning climatic effects, maintenance practices, long-term load effects, materials variations, and construction practices remain unanswered, and answers cannot be found without intensive long-term study of a large number of actual field conditions.

SHRP designated $510 million for the 5-year LTPP research effort. This research will continue for an additional 15 years after SHRP under the auspices of FHWA.

This undertaking has required an unprecedented long-term commitment of funding and human resources. Nevertheless, the cost represents less than one thousandth of what the nation will spend on pavements during the 20 years of LTPP field testing. Furthermore, it is expected that many early results and analyses will be obtained in time to reshape future pavement design and expenditures. In this manner, LTPP could reduce future costs that motorists incur from driving on deteriorated highways and could provide public officials with the information necessary to make better-informed decisions on axle load limits, cost allocations among various classes of highway vehicles, and restrictions on truck dimensions and configurations.

The overall objective of LTPP and other SHRP-related research programs is to provide the tools for increasing pavement performance and service life in order to better serve the needs of the motoring public, and to provide for the delivery of goods and services without major increases in financial resources. A major component of LTPP that will enable researchers to meet this objective is the establishment of a National Pavement Performance Database (NPPDB). The NPPDB contains inventory information and performance histories of pavements with various design features, materials, traffic loads, environmental conditions, and maintenance practices. Most of the information included in the NPPDB comes from GPS test sections located in existing or in-service pavements (see Section 2) and from SPS test sections built and instrumented for more intensive evaluation of selected factors (see Section 3).

Goals and Objectives

The goal for LTPP studies established by STRS and adopted by the SHRP Pavement Performance Advisory Committee 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" (**1.2**).

The Advisory Committee developed the following LTPP objectives (**1.2**):

- Evaluation of existing methods
- Development of improved strategies and design procedures for the rehabilitation of existing pavements
- Development of improved design equations for new and reconstructed pavements
- Determination of the effects on pavement distress and performance of 1) loading, 2) environment, 3) materials properties and variability, 4) construction quality, and 5) maintenance levels
- Determination of specific design procedures to improve pavement performance
- Establishment of a database (NPPDB) to support these objectives and future needs

It was essential that the experimental designs for LTPP be developed with a clear relationship to these objectives. The last objective, the NPPDB, has been and will be used to attain the other five objectives developed by the Advisory Committee.

Summary

It was stated early in SHRP-LTPP that "only one aspect of the project is clearly stable and non-changing. That aspect is that the entire project is in a state of evolution" (**1.3**). Those words, written in September 1987, have held true since. The project under FHWA guidance will no doubt continue to change.

References

1.1 *America's Highways: Accelerating the Search for Innovation* (Special Report 202, Strategic Transportation Research Study: Highways). Transportation Research Board, National Research Council. Washington, D.C., 1984.

1.2 *Strategic Highway Research Program Research Plans, Final Report.* Transportation Research Board, National Research Council. Washington, D.C., 1986.

1.3 Brown, J. L. "The LTPP Experiment of SHRP—An Evolving Process." Presented at the Roads and Traffic Safety on Two Continents Conference. Göteborg, Sweden, September 9–11, 1987.

Section 2
General Pavement Studies (GPS)

Introduction

The General Pavement Studies (GPS) are a series of selected in-service pavement studies structured to develop a comprehensive National Pavement Performance Database (NPPDB) that meets the objectives of the Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) program. These studies are restricted to pavements of strategic future importance that incorporate materials and designs representing good engineering practice. The studies were limited to pavement types in common use across the United States and did not include some pavement types with excellent performance characteristics but limited applicability (**2.1**).

SHRP Regions

The four SHRP regions were selected primarily on the basis of climatic considerations (**2.2**). The region boundaries were adjusted to correspond to state boundaries as illustrated in Figure 2.1 (**2.3**). The North Atlantic region corresponds to the wet-freeze American Association of State Highway and Transportation Officials (AASHTO) classification, while the Southern region is primarily a wet-nonfreeze zone. The North Central region is predominantly wet-freeze, while the Western region contains both dry-freeze and dry-nonfreeze.

Four regional offices were established to coordinate and communicate SHRP-LTPP–related activities across the United States and Canada. Each region included a group of states and/or provinces in its jurisdiction, with test sections located throughout the defined boundaries. Each regional office operated as central data collection and validation centers for GPS and Specific Pavement Studies (SPS) experiments in its region. Inventory, maintenance, rehabilitation, and traffic data were collected at the state level and were then forwarded to the appropriate regional center. The regional centers supplemented these data by collecting test and monitoring data on the various test sites.

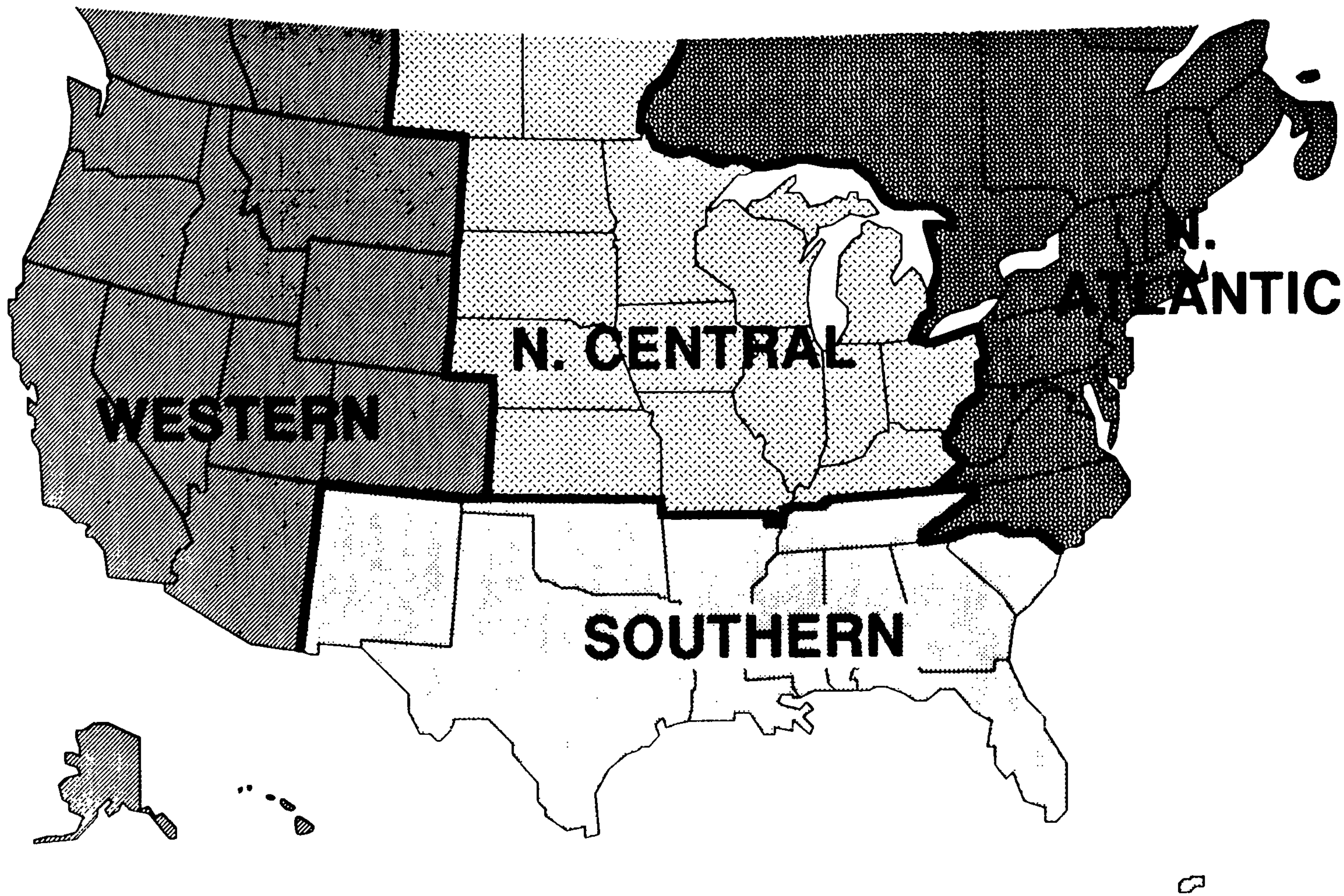


Figure 2.1. SHRP-LTPP Regional Boundaries

GPS Sampling Templates

Evolution of GPS

The goal of GPS was the development of a database consisting of materials, traffic, environment, and performance data for many different types of pavements. The nine pavement types or studies originally planned for the GPS (**2.4**) were

1. Asphalt Concrete (AC) on Granular Base
2. AC on Stabilized Base
3. Jointed Plain Concrete Pavement (JPCP)
4. Jointed Reinforced Concrete Pavement (JRCP)
5. Continuously Reinforced Concrete Pavement (CRCP)
6. AC Overlay of AC Pavement
7. AC Overlay of Jointed Concrete Pavement (JCP)
8. Bonded JCP Overlay of Concrete Pavement
9. Unbonded JCP Overlay of Concrete Pavement

Revisions to GPS

Revisions and changes in GPS occurred early in SHRP-LTPP (**2.5**). A total of ten individual studies evolved (**2.6**):

GPS-1: AC on Granular Base
GPS-2: AC on Bound Base
GPS-3: JPCP
GPS-4: JRCP
GPS-5: CRCP
GPS-6A: Existing AC Overlay of AC Pavement
GPS-6B: Planned AC Overlay of AC Pavement
GPS-7A: Existing AC Overlay of Portland Cement Concrete (PCC) Pavement
GPS-7B: Planned AC Overlay of PCC Pavement
GPS-9: Unbonded PCC Overlay of PCC Pavement

Design of GPS Program

Factors expected to affect the performance of each pavement type were selected as a basis for the development of sampling factorials (**2.6**). The factors were defined as either qualitative (i.e., values with distinct levels) or quantitative (i.e., continuous functions).

The qualitative factors included in most of the GPS sampling factorials were

- Moisture conditions: Wet or Dry
- Temperature conditions: Freeze or Nonfreeze
- Subgrade type: Fine or Coarse

Because the quantitative factors are continuous functions, midpoints were established to separate values into low and high. The quantitative factors varied with each GPS experiment but generally included characteristics such as traffic rate and material thickness. Two levels were defined for all quantitative factors, except that three levels were defined for AC thickness in GPS-1. The study of bonded JCP overlay of concrete pavement study (GPS-8) was deleted from the GPS program because of a lack of potential projects.

Sampling Design Templates

The sampling design templates were developed to illustrate how the individual SHRP sections fit within the overall design layout with respect to levels of qualitative and quantitative factors. The layouts were devised so that all combinations of levels of the design factors would appear in the template. The squares within the sampling template represent specific combinations of levels of the various factors and are known as sampling cells. The factor names are listed in the upper left-hand corner of each template, and levels of the factors are identified by appended rows and columns.

The sampling template layout for GPS-1 (Figure 2.2) includes Low (L) and High (H) designations for the various factors. (As mentioned above, the GPS-1 template also includes a Medium [M] level for AC thickness.) The midpoints of the ranges of the quantitative factors are listed at the bottom of the sampling design. The letters "L" and "H" within the template for the quantitative factors indicate that the value for the cell is lower or higher than the factor midpoint. Qualitative factor levels are defined within the sampling template by words (Wet or Dry for moisture conditions; Freeze or Nonfreeze for temperature conditions) or letters ("F" and "C" for fine- and coarse-grained subgrade types).

Initial cell assignments were made on the basis of the availability of as-built/design information provided by the responsible highway agency. After the design/construction characteristics of the project were defined by in situ drilling and sampling, the cell number was subject to change depending on the actually defined factor values. For example, if a GPS-1 project with an initial assignment of 56 was found to have an AC thickness that was low (less than 3 in.) rather than medium (3 to 8 in.), the project would be reassigned to Cell 52 in the template.

GPS-1: Asphalt Concrete (AC) on Granular Base

Acceptable pavements for GPS-1 included a dense-graded hot-mix asphalt concrete (HMAC) surface layer with or without other HMAC sublayers constructed over an untreated granular base or with no base. One or more subbase layers could be present but were not required.

AC THICKNESS	BASE THICKNESS	AC STIFFNESS																
		MOISTURE	WET								DRY							
		TEMPERATURE	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
		SUBGRADE TYPE	F		C		F		C		F		C		F		C	
		TRAFFIC RATE	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
L	L	L	1	13	25	37	49	61	73	85	97	109	121	133	145	157	169	181
		H	2	14	26	38	50	62	74	86	98	110	122	134	146	158	170	182
	H	L	3	15	27	39	51	63	75	87	99	111	123	135	147	159	171	183
		H	4	16	28	40	52	64	76	88	100	112	124	136	148	160	172	184
M	L	L	5	17	29	41	53	65	77	89	101	113	125	137	149	161	173	185
		H	6	18	30	42	54	66	78	90	102	114	126	138	150	162	174	186
	H	L	7	19	31	43	55	67	79	91	103	115	127	139	151	163	175	187
		H	8	20	32	44	56	68	80	92	104	116	128	140	152	164	176	188
H	L	L	9	21	33	45	57	69	81	93	105	117	129	141	153	165	177	189
		H	10	22	34	46	58	70	82	94	106	118	130	142	154	166	178	190
	H	L	11	23	35	47	59	71	83	95	107	119	131	143	155	167	179	191
		H	12	24	36	48	60	72	84	96	108	120	132	144	156	168	180	192

Quantitative Factor Midpoints

Traffic rate:	85 KESALs/year
AC stiffness:	650 ksi
Base thickness:	10 inches
AC thickness:	3 and 8 inches

Figure 2.2 Sampling Template and Cell Identification Numbers for GPS-1 (Asphalt Concrete on Granular Base)

Two or more consecutive lifts of the same mixture design were treated as one layer. If a treated subgrade was present, it was designated as a subbase.

"Full-depth" AC pavements were also allowed in this study. This designation was defined as an HMAC surface layer combined with one or more subsurface HMAC layers with a minimum total HMAC thickness of 6 in. placed directly on a treated or untreated subgrade. For full-depth AC pavements, a base layer of zero thickness and a material classification code for "No Base" were necessary.

Seal coats or porous friction courses were allowed on the surface, but not in combination; that is, a porous friction course placed over a seal coat was not acceptable. Seal coats were also permissible on top of granular base layers. At least one layer of dense-graded HMAC was required, regardless of the existence of seal coats or porous friction courses. Figure 2.2 shows the sampling template for GPS-1.

GPS-2: AC on Bound Base

Acceptable pavements for GPS-2 included a dense-graded HMAC surface layer with or without other HMAC layers, placed over a bound base layer. Bound bases could consist of hot-mix asphalt base, cement-treated base, lime-treated base, or cold-mix asphalt base. One or more subbase layers could be present but were not required. Seal coats or porous friction courses were permitted on the surface, but not in combination; that is, a porous friction course placed over a seal coat was not acceptable.

This experiment included a wide variety of treated bases and combinations, and an overall performance analysis could be complex and inconsistent. GPS-2 will undoubtedly require intense study to ascertain the type of analyses that should be undertaken. Figure 2.3 shows the sampling template for GPS-2.

GPS-3: Jointed Plain Concrete Pavement (JPCP)

Acceptable pavements for GPS-3 included jointed plain (i.e., unreinforced) PCC slabs placed over most types of base layer (**2.6**), excluding fine-grained soil/aggregate mixtures or cracked and seated PCC layers. A seal coat was also permissible just above a granular base layer. The joints could have no load-transfer devices or could include smooth dowel bars, but jointed slabs with load-transfer devices other than dowel bars were not acceptable. Figure 2.4 shows the sampling template for GPS-3.

GPS-4: Jointed Reinforced Concrete Pavement (JRCP)

Acceptable pavements for GPS-4 included jointed reinforced PCC pavements with doweled joints spaced less than 20 ft. apart. The slab could rest directly on a layer of most types of material, excluding fine-grained soil/aggregate mixtures, cracked and seated PCC layers, or

Binder Type	Base Thickness	Surface Thickness	Moisture: WET								DRY							
		Temperature	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
		Subgrade Type	F		C		F		C		F		C		F		C	
		Traffic Rate	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
BITUMINOUS	L	L	1	9	17	25	33	41	49	57	65	73	81	89	97	105	113	121
		H	2	10	18	26	34	42	50	58	66	74	82	90	98	106	114	122
	H	L	3	11	19	27	35	43	51	59	67	75	83	91	99	107	115	123
		H	4	12	20	28	36	44	52	60	68	76	84	92	100	108	116	124
NON-BITUMINOUS	L	L	5	13	21	29	37	45	53	61	69	77	85	93	101	109	117	125
		H	6	14	22	30	38	46	54	62	70	78	86	94	102	110	118	126
	H	L	7	15	23	31	39	47	55	63	71	79	87	95	103	111	119	127
		H	8	16	24	32	40	48	56	64	72	80	88	96	104	112	120	128

Quantitative Factor Midpoints

Traffic rate:	85 KESALs/year
AC thickness:	4.5 inches
Base thickness:	8.0 inches

Figure 2.3. Sampling Template and Cell Identification Numbers for GPS-2 (Asphalt Concrete on Bound Base)

Base Type	PCC Thickness	Dowels	WET								DRY							
		Temperature	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
		Subgrade Type	F		C		F		C		F		C		F		C	
		Traffic Rate	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
GRANULAR	L	N	1	9	17	25	33	41	49	57	65	73	81	89	97	105	113	121
		Y	2	10	18	26	34	42	50	58	66	74	82	90	98	106	114	122
	H	N	3	11	19	27	35	43	51	59	67	75	83	91	99	107	115	123
		Y	4	12	20	28	36	44	52	60	68	76	84	92	100	108	116	124
STABILIZED	L	N	5	13	21	29	37	45	53	61	69	77	85	93	101	109	117	125
		Y	6	14	22	30	38	46	54	62	70	78	86	94	102	110	118	126
	H	N	7	15	23	31	39	47	55	63	71	79	87	95	103	111	119	127
		Y	8	16	24	32	40	48	56	64	72	80	88	96	104	112	120	128

Quantitative Factor Midpoints

Traffic rate:	200 KESAL/year
PCC thickness:	9.5 inches

Figure 2.4 Sampling Template and Cell Identification Numbers for GPS-3 (Jointed Plain Concrete Pavement)

unstabilized coarse-grained subgrade soils. A base layer and one or more subbase layers could exist but were not required.

A seal coat was also permissible just above a granular base layer. JRCPs placed directly on a fine-grained soil/aggregate layer or a fine-grained subgrade were not considered for this study. JRCPs without load-transfer devices or with devices other than smooth dowel bars at the joints were not acceptable. Figure 2.5 shows the sampling template for GPS-4.

GPS-5: Continuously Reinforced Concrete Pavement (CRCP)

Acceptable pavements for GPS-5 included continuously reinforced PCC pavements placed directly on a layer of any type of material, excluding fine-grained soil/aggregate mixtures, cracked and seated PCC layers, or unstabilized coarse-grained subgrades. One or more subbase layers could exist but were not required. A seal coat was also permissible just above a granular base layer. Figure 2.6 shows the sampling template for GPS-5.

GPS-6: AC Overlay of AC Pavement

Acceptable pavements for GPS-6A and GPS-6B included a dense-graded HMAC surface layer with or without other HMAC layers placed over an existing AC pavement meeting the requirements of GPS-1 or GPS-2.

The designation "6A" refers to SHRP sections that were existing overlaid pavements when accepted in the GPS program. The designation "6B" refers to LTPP sections for which a planned overlay of existing flexible pavement was undertaken after the SHRP section had been either previously accepted in GPS-1 or GPS-2 or specifically selected for initial inclusion in GPS-6B.

Seal coats or porous friction courses were allowed, but not in combination. Fabric interlayers and stress-absorbing membrane interlayers (SAMIs) were permitted between the original surface and the overlay. The total thickness of HMAC used in the overlay was to be at least 1.0 in. Pavements that had been overlaid more than once since originally constructed were not acceptable. Figures 2.7 and 2.8 show the sampling templates for GPS-6A and GPS-6B.

GPS-7: AC Overlay of Portland Cement Concrete (PCC) Pavement

Acceptable pavements for GPS-7A and GPS-7B included a dense-graded HMAC surface layer with or without other HMAC layers placed on either JPCP, JRCP, or CRCP.

The designation "7A" refers to SHRP sections that were existing overlaid pavements when accepted in the GPS program. The designation "7B" refers to SHRP sections for which a planned overlay was undertaken after the SHRP section had either been previously accepted in GPS-3, GPS-4, or GPS-5 or specifically selected for initial inclusion in GPS-7B.

	MOISTURE	WET								DRY							
	TEMPERATURE	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
	SUBGRADE TYPE	F		C		F		C		F		C		F		C	
PCC THICKNESS	JOINT SPACING \ TRAFFIC RATE	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
L	L	1	5	9	13	17	21	25	29	33	37	41	45	49	53	57	61
	H	2	6	10	14	18	22	26	30	34	38	42	46	50	54	58	62
H	L	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63
	H	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64

Quantitative Factor Midpoints

Traffic rate: 200 KESALs/year
Joint spacing: 40 feet
PCC thickness: 9.5 inches

Figure 2.5 Sampling Template and Cell Identification Numbers for GPS-4 (Jointed Reinforced Concrete Pavement)

PCC THICKNESS	% REINFORCEMENT	WET								DRY							
	TEMPERATURE	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
	SUBGRADE TYPE	F		C		F		C		F		C		F		C	
	TRAFFIC RATE	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
L	L	1	5	9	13	17	21	25	29	33	37	41	45	49	53	57	61
	H	2	6	10	14	18	22	26	30	34	38	42	46	50	54	58	62
H	L	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63
	H	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64

Quantitative Factor Midpoints

Traffic rate:	300 KESALs/year
Percentage reinforcement:	0.61
PCC thickness:	8.5 inches

Figure 2.6 Sampling Template and Cell Identification Numbers for GPS-5 (Continuously Reinforced Concrete Pavement)

		MOISTURE	WET								DRY							
		TEMPERATURE	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
		SUBGRADE TYPE	F		C		F		C		F		C		F		C	
OL THICKNESS	OL STIFFNESS	ORIGINAL PVT. STRUCTURAL NO. / TRAFFIC RATE	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
L	L	L	1	9	17	25	33	41	49	57	65	73	81	89	97	105	113	121
		H	2	10	18	26	34	42	50	58	66	74	82	90	98	106	114	122
	H	L	3	11	19	27	35	43	51	59	67	75	83	91	99	107	115	123
		H	4	12	20	28	36	44	52	60	68	76	84	92	100	108	116	124
H	L	L	5	13	21	29	37	45	53	61	69	77	85	93	101	109	117	125
		H	6	14	22	30	38	46	54	62	70	78	86	94	102	110	118	126
	H	L	7	15	23	31	39	47	55	63	71	79	87	95	103	111	119	127
		H	8	16	24	32	40	48	56	64	72	80	88	96	104	112	120	128

Quantitative Factor Midpoints:

Traffic Rate	130 KESAL/year
Original Pvt.Structural No.	3.6
Overlay Stiffness	650 ksi
Overlay Thickness	2.5 inches

Figure 2.7 Sampling Template and Cell Identification Numbers for GPS-6A (existing Asphalt Concrete Overlay of Asphalt Concrete)

OL THICKNESS	ORIGINAL PVT. STRUCTURAL NO.	ORIGINAL PVT. CONDITION LEVEL	MOISTURE: WET								DRY							
		TEMPERATURE	FREEZE				NO FREEZE				FREEZE				NO FREEZE			
		SUBGRADE TYPE	F		C		F		C		F		C		F		C	
		TRAFFIC RATE	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
L	L	B	1	9	17	25	33	41	49	57	65	73	81	89	97	105	113	121
		G	2	10	18	26	34	42	50	58	66	74	82	90	98	106	114	122
	H	B	3	11	19	27	35	43	51	59	67	75	83	91	99	107	115	123
		G	4	12	20	28	36	44	52	60	68	76	84	92	100	108	116	124
H	L	B	5	13	21	29	37	45	53	61	69	77	85	93	101	109	117	125
		G	6	14	22	30	38	46	54	62	70	78	86	94	102	110	118	126
	H	B	7	15	23	31	39	47	55	63	71	79	87	95	103	111	119	127
		G	8	16	24	32	40	48	56	64	72	80	88	96	104	112	120	128

Quantitative Factor Midpoints

Traffic rate:	130 KESALs/year
Original pavement structural number:	3.6
Overlay thickness:	2.5 inches

Figure 2.8 Sampling Template and Cell Identification Numbers for GPS-6B (Planned Asphalt Concrete Overlay of Asphalt Concrete Pavement)

The slab could rest on any combination of base and/or subbase layer types, excluding fine-grained soil/aggregate mixtures or cracked and seated PCC layers. The existing concrete slab could also rest directly on a lime- or cement-treated fine- or coarse-grained subbase or on untreated coarse-grained subgrade soil. Slabs placed directly on untreated fine-grained subgrade were not acceptable.

Seal coats or porous friction courses were permissible, but not in combination. Fabric interlayers and SAMIs were acceptable when placed between the original surface (concrete) and the overlay. Overlaid pavements involving aggregate interlayers and open-graded AC interlayers were not considered in this study. The total thickness of HMAC used in the overlay was defined as at least 1.5 in. Pavements that had been overlaid more than once since originally constructed were not acceptable. Figures 2.9 and 2.10 show the sampling templates for GPS-7A and GPS-7B.

GPS-9: Unbonded PCC Overlay of PCC Pavement

Acceptable pavements for GPS-9 included unbonded JPCP, JRCP, or CRCP overlays with a minimum thickness of 5 in. placed over an existing JPCP, JRCP, or CRCP pavement. An interlayer was required to prevent bonding of the two slabs. The overlaid concrete pavement could rest on any acceptable base and subbase types or directly on the subgrade. Figure 2.11 shows the sampling template for GPS-9.

Initial Project Recruitment

In the early stages of SHRP-LTPP, the GPS consisted of nine separate studies: five for original pavements and four for first-time rehabilitated pavements. The designs for each study were factorial sampling templates whose cells represent all possible combinations of the design factor levels. The sampling units identified by each cell were the test sections that satisfied the GPS design specifications.

Preliminary analytical results indicated that two sections should be selected to fit the characteristics of each design cell. With six or seven factors for each pavement type and two sections for each combination of factors, a very large number of sections would be required to completely fill the sampling designs. Fractional designs were considered but not recommended for reasons related to the difficulty of locating specific types of projects at the expense of omitting others readily available.

As part of the initial LTPP recruitment process, approximately 2200 candidate projects were submitted by all fifty U.S. states and participating Canadian provinces. The set of projects defined by the GPS sampling designs essentially defined the population of pavement sections from which an appropriate sample could be selected. In addition, the projects submitted by each highway agency were assumed to be representative of highways that exist throughout each state or province. The entire range of condition levels was to be represented within the

MOISTURE			WET								DRY							
TEMPERATURE			FREEZE				NO FREEZE				FREEZE				NO FREEZE			
SUBGRADE TYPE			F		C		F		C		F		C		F		C	
TRAFFIC RATE			L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
OL THICKNESS	OL STIFFNESS	EXISTING PVT. TYPE																
L	L	JPCP	1	13	25	37	49	61	73	85	97	109	121	133	145	157	169	181
		JRCP	2	14	26	38	50	62	74	86	98	110	122	134	146	158	170	182
		CRCP	3	15	27	39	51	63	75	87	99	111	123	135	147	159	171	183
	H	JPCP	4	16	28	40	52	64	76	88	100	112	124	136	148	160	172	184
		JRCP	5	17	29	41	53	65	77	89	101	113	125	137	149	161	173	185
		CRCP	6	18	30	42	54	66	78	90	102	114	126	138	150	162	174	186
H	L	JPCP	7	19	31	43	55	67	79	91	103	115	127	139	151	163	175	187
		JRCP	8	20	32	44	56	68	80	92	104	116	128	140	152	164	176	188
		CRCP	9	21	33	45	57	69	81	93	105	117	129	141	153	165	177	189
	H	JPCP	10	22	34	46	58	70	82	94	106	118	130	142	154	166	178	190
		JRCP	11	23	35	47	59	71	83	95	107	119	131	143	155	167	179	191
		CRCP	12	24	36	48	60	72	84	96	108	120	132	144	156	168	180	192

Quantitative Factor Midpoints:

Traffic Rate	130	KESAL/year
Overlay Stiffness	650	ksi
Overlay Thickness	3.5	inches

Figure 2.9 Sampling Template and Cell Identification Numbers for GPS-7A (Existing Asphalt Concrete Overlay of Portland Cement Concrete)

MOISTURE			WET								DRY							
TEMPERATURE			FREEZE				NO FREEZE				FREEZE				NO FREEZE			
SUBGRADE TYPE			F		C		F		C		F		C		F		C	
TRAFFIC RATE			L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
ORIG. PVT. TYPE	ORIG. PVT. COND. LEVEL	OL THICKNESS																
JPCP	L	B	1	13	25	37	49	61	73	85	97	109	121	133	145	157	169	181
		G	2	14	26	38	50	62	74	86	98	110	122	134	146	158	170	182
	H	B	3	15	27	39	51	63	75	87	99	111	123	135	147	159	171	183
		G	4	16	28	40	52	64	76	88	100	112	124	136	148	160	172	184
JRCP	L	B	5	17	29	41	53	65	77	89	101	113	125	137	149	161	173	185
		G	6	18	30	42	54	66	78	90	102	114	126	138	150	162	174	186
	H	B	7	19	31	43	55	67	79	91	103	115	127	139	151	163	175	187
		G	8	20	32	44	56	68	80	92	104	116	128	140	152	164	176	188
CRCP	L	B	9	21	33	45	57	69	81	93	105	117	129	141	153	165	177	189
		G	10	22	34	46	58	70	82	94	106	118	130	142	154	166	178	190
	H	B	11	23	35	47	59	71	83	95	107	119	131	143	155	167	179	191
		G	12	24	36	48	60	72	84	96	108	120	132	144	156	168	180	192

Quantitative Factor Midpoints

Traffic rate: 300 KESALs/year
Overlay thickness: 3.5 inches

Figure 2.10. Sampling Template and Cell Identification Numbers for GPS-7B (Planned Asphalt Concrete Overlay of Portland Cement Concrete Pavement)

OL TYPE	ORIG. PVT. TYPE	OL THICKNESS	WET F	WET NF	DRY F	DRY NF
JPCP	JPCP	L	1	19	37	55
		H	2	20	38	56
	JRCP	L	3	21	39	57
		H	4	22	40	58
	CRCP	L	5	23	41	59
		H	6	24	42	60
JRCP	JPCP	L	7	25	43	61
		H	8	26	44	62
	JRCP	L	9	27	45	63
		H	10	28	46	64
	CRCP	L	11	29	47	65
		H	12	30	48	66
CRCP	JPCP	L	13	31	49	67
		H	14	32	50	68
	JRCP	L	15	33	51	69
		H	16	34	52	70
	CRCP	L	17	35	53	71
		H	18	36	54	72

MOISTURE: WET, DRY; TEMPERATURE: F, NF

Quantitative Factor Midpoints

Overlay thickness: 3.5 inches

Figure 2.11. Sampling Template and Cell Identification Numbers for GPS-9 (Unbonded Portland Cement Concrete Overlay of Portland Cement Concrete Pavement)

project. Pavements that exhibited the best performance were not to be submitted to the exclusion of poor- or average-performing pavements.

In order to complete the designs, test sections were identified and located within the existing pavement projects. From each selected project, 500 ft. test sections were identified. When a suitable section was found, it was classified as "Approved" and identified with the proper cell of the design factorials. Following approval, the various data collection activities could be scheduled. Sections that did not satisfy the GPS requirements were released from further consideration, and the highway agencies were notified when these determinations occurred.

The process used in selecting test sections involved the collection of the best estimate of each design factor and information from available historical records, followed by the assignment of a specific cell of each sampling design template (**2.6**).

The classification of sections within the respective design cells and the ensuing selection reduced the number of candidates to about 650. Approximately 550 projects were eventually approved for GPS use.

Additional Recruitment

After the initial effort was complete, many design cells still did not have identified candidate projects. This led to a major evaluation of the sampling designs. Templates were modified, design parameters were revised, allowable materials were added, and selection criteria were amended. Recruitment of additional projects was also strongly encouraged among all participating highway agencies. With the completion of additional recruitment, the number of GPS projects increased to about 780 (**2.6**).

Project Approval Process

Before a pavement test section was approved for assignment to GPS, a recruited project was first selected as a potential project and then verified by an on-site inspection. The terminology "test section" or "section" refers to the physical 500 ft. length of pavement that was actually studied for GPS, while "project" refers to a greater length of pavement including the section that exhibited the same general characteristics. The selection, verification, and approval processes for the test sections are discussed below.

Project Selection

The first step in project selection was the submission of candidate projects by the participating highway agencies for inclusion in SHRP-LTPP. The highway agencies submitted Candidate Data Forms that included information on critical site characteristics, pavement configuration, and traffic composition for each candidate project. These forms were submitted to a Regional Coordination Office (RCO) for review. If the information provided on the Candidate Data Forms matched one of the GPS sampling designs, the forms were submitted to the technical assistance contractor for further review and potential selection (2.6).

Project Verification

The selected GPS projects were subsequently verified in the field to ensure that the projects did in fact possess characteristics needed to fill the particular design cell. The verification process constituted the first on-site activity.

Project verification was performed by the RCO engineers. Prior to on-site inspection, the engineers visited participating state highway agency (SHA)* offices to familiarize themselves with the selected project. This process resulted in quicker and better data verification in the field.

During these SHA office visits, RCO engineers performed the following tasks:

- Review of project records, including as-built plans and pertinent specifications
- Confirmation of candidate project data by comparison of as-built plans and previously submitted data
- Review of traffic data, including assessment of the effect of traffic rates on the safety of materials sampling and monitoring activities
- Review of photologs or other available site-specific data
- Identification of recent or planned maintenance or rehabilitation activities that could affect the project
- Collection of information pertaining to pavement condition prior to overlay (for the GPS overlay studies)
- Identification of potential test sections within the project

Potential test sections within the project were identified using project plans and appropriate documents. Within the boundaries of the sections, the as-built profile was compared with the natural ground profile to eliminate areas with highly variable subgrade conditions. Whenever possible, test sections on deep cuts or fills were rejected to avoid inconsistent subgrade support and drainage conditions related to highway geometry rather than soil characteristics. Typical sections were located within consistent cut, fill, or at-grade conditions. Transitional areas (cut to fill, shallow fill to deep fill, etc.) were avoided.

---

* Throughout this document, all Canadian provincial highway agencies and U.S. state highway agencies will be collectively denoted "state highway agencies."

Within the uniform cut, fill, or at-grade areas, potential monitoring sections were identified as roadway sections that did not include major structures, sharp horizontal or vertical curvature, or steep grade.

Field Verification

The on-site activities of the RCO engineers are described below.

Location of Monitoring Test Section

During the field visit, the actual monitoring (500 ft.) test section was selected from among the potential test sections noted at the SHA office. In general, the longest available section was chosen that was representative of the general roadway condition and would also be safe for traffic control and monitoring personnel during lane closure.

All test sections were chosen to ensure sufficient buffer distance (ideally, 250 ft.) before and after the designated section to allow space for verification boring and subsequent materials sampling and testing. These buffer sections were of the same cross-section as the monitoring test section.

The start of the test section was located with respect to some physical feature (bridge, overpass, intersection, etc.) by measuring distances from the beginning station to the selected feature. This method provided a technique for locating the beginning of test sections for future LTPP activities.

Bore Holes

It was requested that all projects be bored to a depth of 4 to 6 ft., extending at least to the subgrade, to verify layer thickness and material types. Two borings were made in AC pavements. In PCC pavements with flexible shoulders, a bore hole at the pavement-shoulder joint was made. No bore holes were made if an SHA gave the assurance that its records were accurate and that there was no need for bore hole measurements. Approximately 5% of the sections fell into this category. (These borings were part of the verification process and should not be confused with the process described in Section 4 of this report.)

Borings for AC pavements were completed in the outer wheelpath at points located a minimum of 50 ft. before the start and beyond the end of the 500 ft. monitoring test section. Borings for PCC pavements were completed at least 50 ft. beyond the end of the test section (i.e., downstream of traffic) in the shoulder at the shoulder/pavement interface. If the buffer extended less than 50 ft. from the test section, the point farthest from the end of the test section but still considered typical of the section was chosen for the bore hole location.

Test Section Identification

The sign and paint conventions and configuration used for GPS test sections are illustrated in Figures 2.12 and 2.13. The test site sign was located 500 ft. before the beginning of the monitoring test section, and delineators were installed at the beginning and end of the section. The paint striping and site identification requirements are also indicated in Figures 2.12 and 2.13.

Videotaping of Test Section

The test section was videotaped to provide a record of site features, pavement condition, and characteristics of the surrounding area.

Field Verification Form

A verification form (2.6) was completed in the field. It included specific project and section identification information, geometric details, and measurements from the boring operations.

Distress Survey

A manual (i.e., visual) condition survey of the 500 ft. monitoring test section was conducted at each site. Type, amount, and severity level were recorded for each distress. Distresses observed for pavements with AC surface layers included alligator cracking, block cracking, patch deterioration, pumping, raveling/weathering, transverse cracking, bleeding, and rut depth. This information helped provide a record of the initial condition of the pavement surface.

Distresses observed for pavements with PCC surface layers included "D" cracking, joint seal damage, longitudinal cracking, patch or slab replacement deterioration, pumping, transverse cracking, corner breaks, and faulting.

Projects Approval

As noted above, the candidate projects were tentatively assigned to specific cells in the sampling template for each study and were selected on a study/cell basis. Final approval of projects as GPS monitoring test sections depended on the results of the verification process.

If, after field verification, the section met all other general GPS criteria and remained in the original design cell assignment, then the section was approved for GPS monitoring. If the field verification data required a transfer in design cell assignment, then an extended approval process was initiated to confirm a new cell assignment for the section. Projects not approved

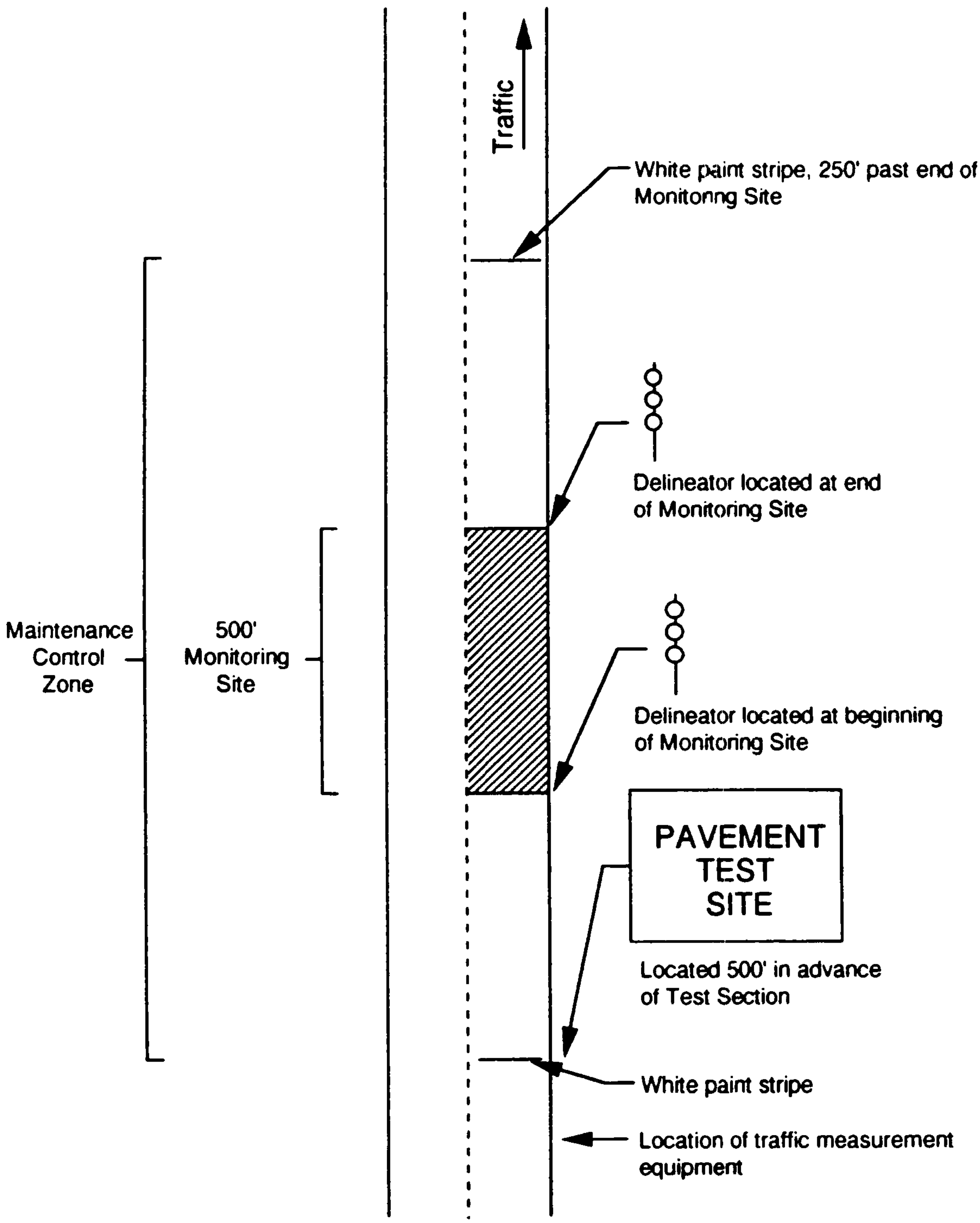


Figure 2.12. Sign and paint configuration for GPS test site.

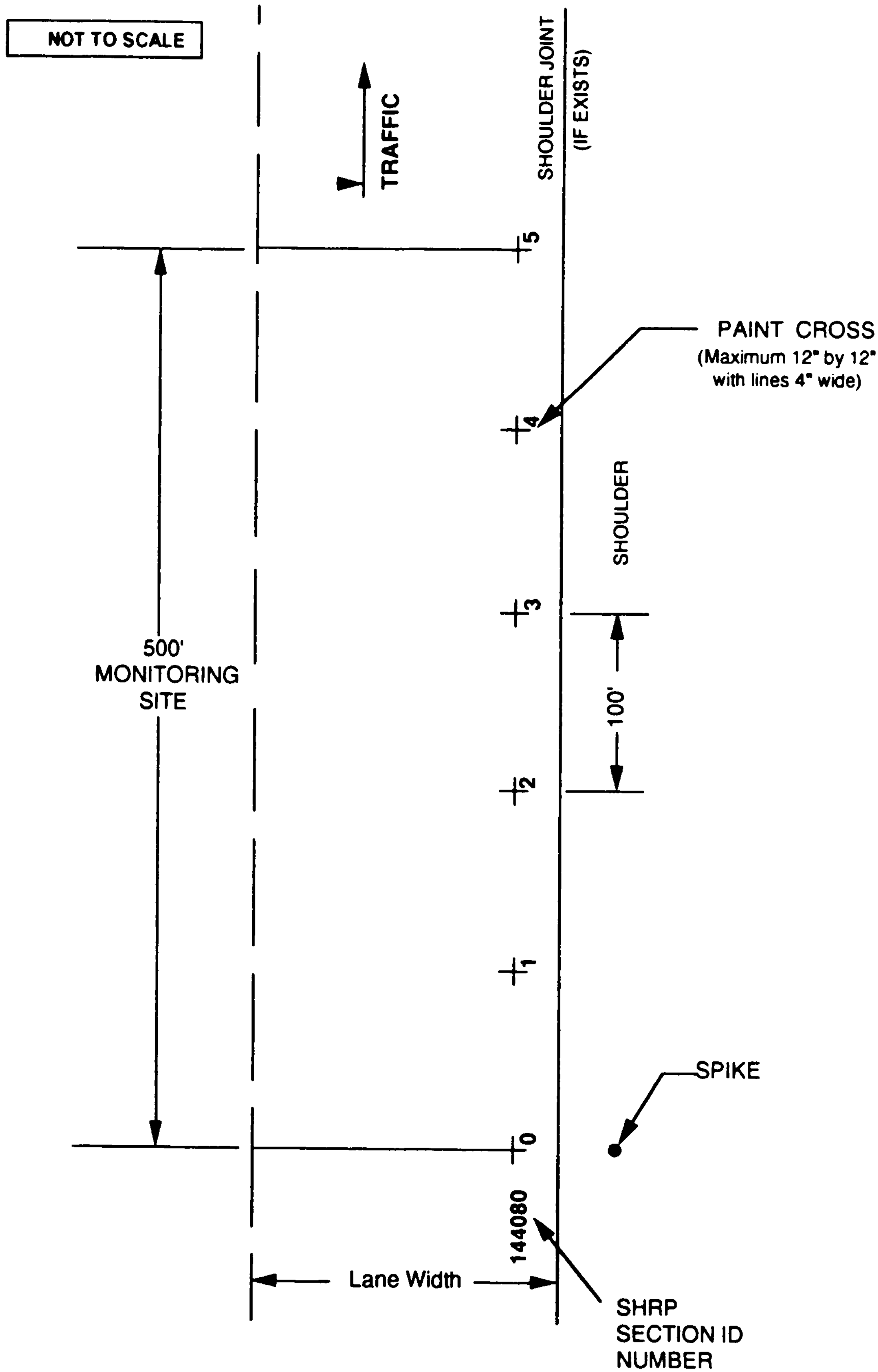


Figure 2.13. Details of GPS monitoring site paint configuration.

for inclusion in a GPS study were released. Figure 2.14 is a flow diagram of the project approval process.

Project Status Classifications

GPS test sections were classified into the following categories:

1. Selected, Not Verified: Two projects for each cell in the sampling design (when available) were selected from the "primary, not selected" classification. These projects were then forwarded to the regions for verification.

2. Approved: These projects were visited, a location for the section identified, and design factor levels verified (including pavement layer materials and thicknesses by boring). They were then officially approved for GPS.

3. Approved, Not Verified: These sections met the same conditions as "approved" sections except that pavement layer thicknesses were not verified by boring. Once pavement layer thicknesses were verified (usually during materials sampling), the status of the section was changed to "approved."

4. Verified, On Hold, Same Cell: This category indicates that a section was verified and fit within a proper design cell, but certain features of the section were such that another project with the same design factor levels, if available, was to be considered for study.

5. Verified, On Hold, New Cell: This category was similar to the previous one except that one or more of the design factor levels changed for the section and it was assigned to a new cell. If the new cell was empty or had only one section selected or approved, the section that had just moved into the new cell was approved. However, if two sections were already selected for that cell, the section that moved into the cell remained on hold until the status of the other two sections was determined.

6. Primary, Not Selected: When a project was first submitted, it was usually classified into this category. These sections served as the primary source to fill gaps in the sampling designs or to replace approved sections that were released.

7. Returned: In the early phases of GPS project selection, many more projects were originally submitted by the SHAs than could ever be selected or approved. These surplus projects were returned and were not considered for use in GPS.

8. Released: This category was reserved for previously selected or approved sections that were no longer considered suitable for inclusion in GPS for reasons unrelated to pavement condition.

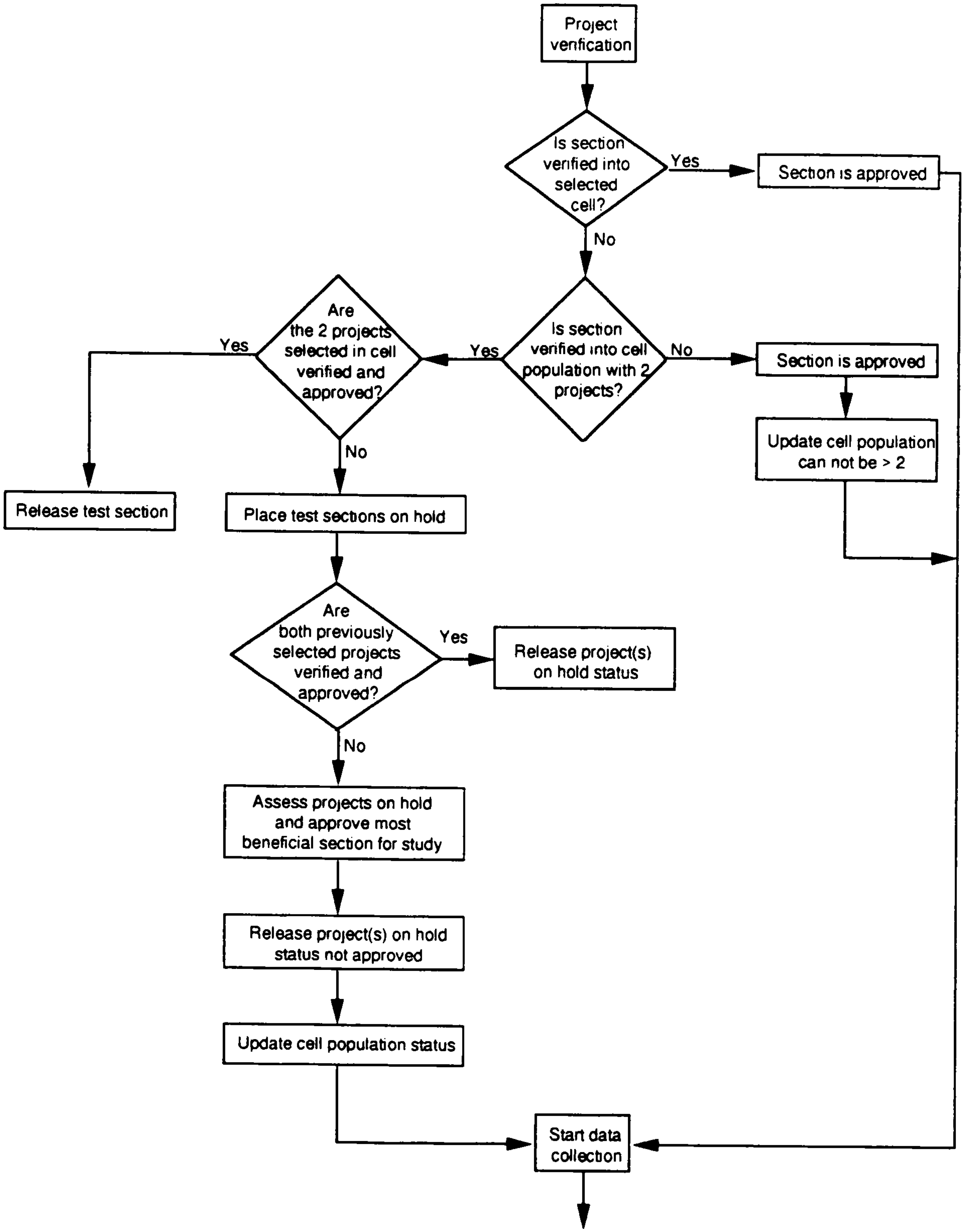


Figure 2.14 Flow diagram of the project approval process

9. Out of Study: This category contains projects that have come to the end of their performance periods and for which data collection activities have been discontinued. If an SHA plans to overlay a project and it has already been overlaid once (and is assigned to GPS-6A, -6B, -7A, -7B, or -9) or the project cannot be moved into one of the overlay sampling templates, it is taken "out of study." Data collected from these sections over time are considered the primary source to achieve overall LTPP objectives.

Status as of July 1992

Approved GPS sections are shown by location in Figure 2.15 and are listed by GPS experiment type in Table 2.1. A total of 777 sections were approved for all GPS experiments. During the verification process, 13 sections were "released" from GPS and three sections were declared "out of study."

As of July 1, 1992, the GPS program included 437 flexible pavement sections and 340 rigid pavement sections (see Figure 2.16). Figures 2.17 and 2.18 show the distribution of these sections among the various GPS experiments.

Data Collection Activities

The data to be collected in LTPP-GPS have been grouped into ten data modules (**2.6**, **2.7**):

- Inventory
- Materials and Laboratory Test
- Traffic
- Distress
- Profile
- Deflection
- Friction
- Environment
- Maintenance
- Rehabilitation

Details of the information contained in these modules are discussed in Reference 2.7.

Approved GPS Sites

Figure 2.15. SHRP-LTPP GPS Studies

TABLE 2.1. SHRP-LTPP GPS Sites
Section Totals per State/Province

State/Province	1	2	3	4	5	6A	6B	7A	7B	9	Totals
Alabama	6	3	1	2	2	2	2				18
Alaska	4					1	1				6
Arizona	16	2	2		1	4					25
Arkansas		4	1	5	2				2		14
California	4	15	11		1	1	2			3	37
Colorado	4	1	2			2	3	2		2	16
Connecticut	1			2	1						4
Delaware		1		2	2						5
District of Columbia							1				1
Florida	15	4	7				4				30
Georgia	4	7	8		1		1	1		1	23
Hawaii	3						1				4
Idaho	9		2		1	1					13
Illinois	2			3	7	1		3	2		18
Indiana	2	2	4	2	2	1			3	1	17
Iowa	1	1	5		2	1			2		12
Kansas	3		3	6		2		2		1	17
Kentucky	3		1	1		2					7
Louisiana		1		1							2
Maine	5		2					1			8
Maryland		4			1						5
Massachusetts	3										3
Michigan	5		2	1	1	1		1		2	13
Minnesota	9		2	8	1	1		1		3	25
Mississippi	3	6	2	1	4		5	2	1	1	25
Missouri	3			7	1	1	2	2	3		19
Montana	2	1				2	2				7
Nebraska	1		5	1	1		1	4	1	1	15
Nevada	2	3	3								8
New Hampshire	1										1
New Jersey	3	4		1		1					9
New Mexico	4	2	1			4					11
New York	1	2		2			1				6
North Carolina	12	4	5		3						24
North Dakota		1	2		1						4
Ohio			1	2	1			1	2	2	9
Oklahoma	3	7	4		3	2		1		1	21
Oregon		1			6	2		3			12

Table 2.1 (Continued)

State/Province	1	2	3	4	5	6A	6B	7A	7B	9	Totals
Pennsylvania	3		2	2	2		2	2	5	2	20
Rhode Island								1			1
South Carolina	4		1		3			1			9
South Dakota	1		6		3		2	1			13
Tennessee	3	6				2	4				15
Texas	39	10	3	5	19	5	3	2		4	90
Utah	3		7			4					14
Vermont	2						2		1		5
Virginia	2	2			4		4				12
Washington	5		7			5	1				18
West Virginia		1		2	1			1			5
Wisconsin			13		2			1			16
Wyoming	2	8	1			3					14
Puerto Rico		2	2								4
Alberta	3	1					1				5
British Columbia	1	1				2					4
Manitoba	1	1	1				2		1		6
New Brunswick	2		1			1					4
Newfoundland	3										3
Nova Scotia						1					1
Ontario	3	3									6
Prince Edward Island	2	1									3
Quebec	3	1	4							1	9
Saskatchewan	2				2	2					6
TOTALS	218	113	124	56	79	57	49	33	23	25	777

Pavement Type Codes:

1 - AC on Granular Base
2 - AC on Stabilized Base
3 - JPCP
4 - JRCP
5 - CRCP
6A - Existing AC Overlay of AC
6B - Planned AC Overlay of AC
7A - Existing AC Overlay of PCC
7B - Planned AC Overlay of PCC
9 - Unbonded PCC Overlay of PCC

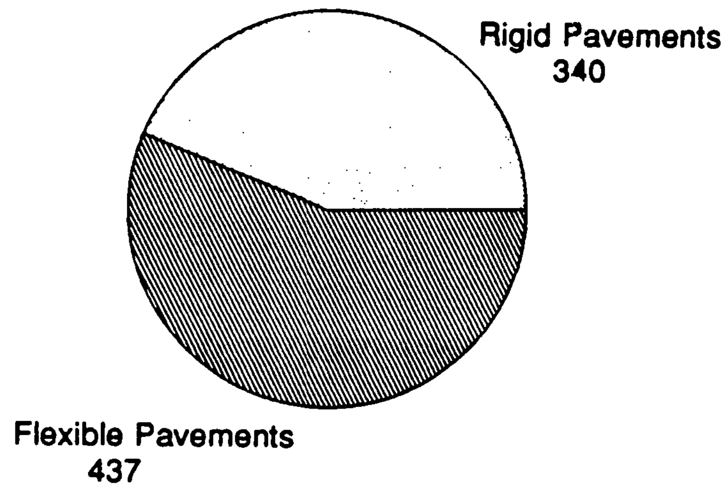


Figure 2.16 Distribution of Approved GPS Sections

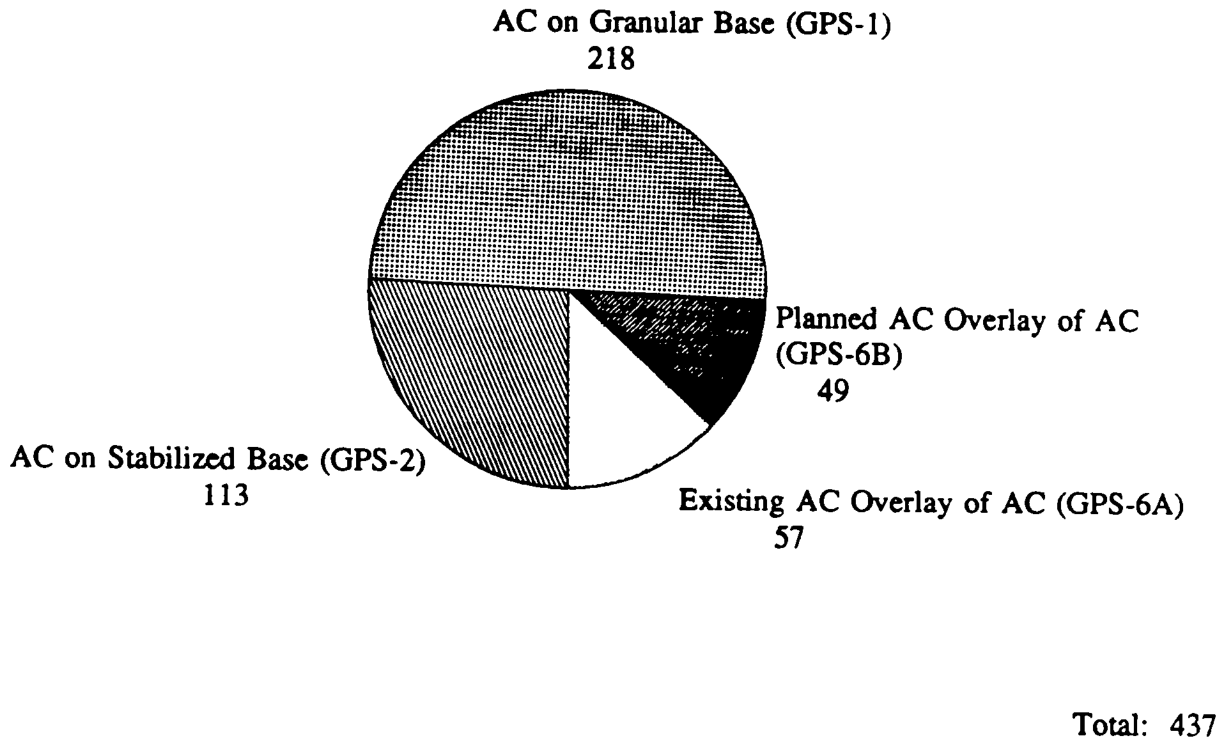


Figure 2.17 Distribution of Flexible Pavement Sections Among GPS Experiments

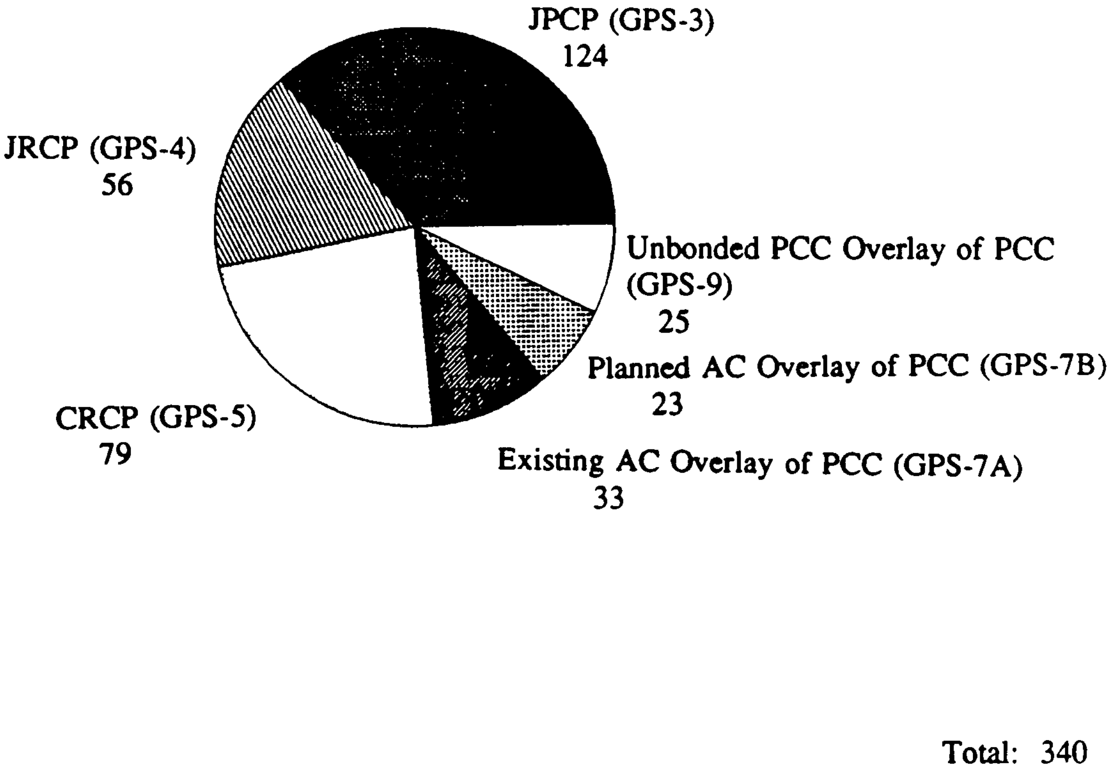


Figure 2.18 Distribution of Rigid Pavement Sections Among GPS Experiments

References

2.1 *Report on the Evolution and Development of GPS*. Texas Research and Development Foundation, Austin, Texas, December 1990.

2.2 *Operations and Quality Assurance Manual*. SAIC, Oak Ridge, Tennessee, April 1990.

2.3 *Long-Term Pavement Performance Information Management System Researchers Guide*. Strategic Highway Research Program, National Research Council, Washington, D.C., July 1991.

2.4 "Final Development of General Pavement Studies Sampling Plan." Prepared by Texas Research and Development Foundation, Austin, Texas, June 1988.

2.5 Benson, K., et al. "Recruitment Guidelines for Additional GPS Candidate Projects." Prepared by Texas Research and Development Foundation, Austin, Texas, October 1988.

2.6 "Guidelines for Initial State Visits, Section Selection, and Section Verification." Texas Research and Development Foundation, Austin, Texas, July 6, 1988.

2.7 "Data Collection Guide for Long-Term Pavement Performance Studies" (SHRP Operational Guide SHRP-LTPP-OG-001). Strategic Highway Research Program, National Research Council, Washington, D.C., revised January 1990.

Section 3
Specific Pavement Studies (SPS)

Background

The original Long-Term Pavement Performance (LTPP) program included three potential types of studies (**3.1**): General Pavement Studies (GPS), Specific Pavement Studies (SPS), and Accelerated Pavement Testing (APT). The GPS program was scheduled to consist of a large experiment involving a large number of site selection factors, with the expectation of a broad range of results and products. On the other hand, the SPS program was expected to involve more specific and limited goals, construction needs, and experimental approaches. The APT studies were not instituted but were considered as future activities.

The SPS program consists of generally limited factorials involving highway sections specifically designed and constructed or rehabilitated through a cooperative effort with interested state highway agencies (SHAs) (**3.1**). The general topics selected for intensive experiments for rigid and flexible pavements in the original plans for SPS experiment designs (1986) included

1. Portland Cement Concrete (PCC) Preventive Maintenance
2. PCC Load Equivalence Factors
3. PCC Restored Jointed Concrete Pavement (JCP)
4. PCC Subsurface Drainage
5. PCC Environmental Distress
6. High-Strength PCC
7. Continuously Reinforced Concrete Pavement (CRCP) Overlays
8. PCC with Non-Erodible High-Strength Bases
9. PCC Retrofit Shoulder
10. PCC Shoulder Design
11. Pretreated JCP with Asphalt Concrete (AC) Overlay
12. AC Subdrainage
13. AC Hot Recycling
14. AC Cold Recycling
15. AC Preventive Maintenance
16. AC Low-Volume Roads
17. AC Load Equivalency Factors (LEFs)
18. AC Environmental Distress

Initial Modification of SPS (1988)

In 1987 an effort was undertaken to reduce the number of original SPS design plans and to define the methods required to analyze the data from each (**3.2**). Because one of the contemplated analyses involved linear regression analysis (**3.1**), it would be necessary to use state-to-state variation as the basis for all statistically significant tests. This peculiarity in the original design would then require special consideration of errors in the regression analysis of the SPS data.

At that time the decision was made to divide SPS into five major categories (**3.2**):

A. Structural Factors
B. Preventive Maintenance
C. Pavement Rehabilitation
D. Environmental Factors
E. Load Equivalencies

SPS-1 and SPS-2: Structural Factors

The initial SPS structural factors experiments consisted of SPS-1 for flexible pavements and SPS-2 for rigid pavements.

SPS-1: Structural Factors for Flexible Pavements (3.2)

The experimental design for SPS-1 included eight factors, each at two levels. Three of the factors described environmental conditions at the test site: moisture (wet or dry), temperature (freeze or nonfreeze), and roadbed subgrade soil type (fine or coarse). For each of the eight factor combinations, all test sites would have relatively high rates of traffic, at least 100 KESALs (thousands of equivalent single axle loads) per year.

Four of the remaining experimental design factors were to be allocated to pavement structure from among the following: surface layer thickness and stiffness, base and subbase layer thickness, and base and subbase strength/stability. The remaining factor defined the base/subbase drainage conditions related to the absence and/or presence of different types of drainage enhancement used in construction.

SPS-2: Structural Factors for Rigid Pavements (3.2)

The experimental design for SPS-2 also included eight factors, each at two levels. Three factors described environmental conditions at the test site: moisture (wet or dry), temperature (freeze or nonfreeze), and roadbed subgrade soil type (fine or coarse). For each of the eight factor combinations, all test sites would have relatively high rates of traffic, at least 200 KESALs/yr.

The five remaining experimental design factors were to be allocated to the pavement structure. Three factors were to be allocated to the surface layer: one for thickness, one for strength, and one for type of reinforcement. Two other structural factors were to be allocated to the base/subbase: one for strength/stability and the other for drainage.

Figure 3.1 shows the test section layout for SPS-1 and SPS-2.

SPS-3 and SPS-4: Preventive Maintenance

The initial SPS preventive maintenance experiments included SPS-3 for flexible pavements and SPS-4 for rigid pavements.

SPS-3: Preventive Maintenance Effectiveness for AC Pavements

The AC preventive maintenance study (SPS-3) required that the effectiveness of four different maintenance treatments be compared with each other and with a control (nontreated) section. Within each project, one section (the control section) would receive no experimental maintenance treatment; the remaining four sections would be treated by either chip seal, slurry seal, crack seal, or thin AC overlay. All five sections were to be located within a pavement project with environmental, traffic, and structural factors at specified nominal levels and were to be treated over a range of combinations of these factors.

Figure 3.2 shows the layout for SPS-3 sections within GPS projects. The types of sections required for SPS-3 would generally be found within projects that contain sections designated for GPS-1 (AC on Granular Base). SPS-3 maintenance treatments were to be applied to existing pavements that were in good, fair, or poor condition prior to treatment. Although the major interest revolved around the first two condition levels, some effort would have been made to investigate the degree to which life extension is possible for pavements in poor condition.

SPS-4: Preventive Maintenance Effectiveness for Rigid Pavements

The preventive maintenance study for rigid pavements (SPS-4) would have examined maintenance effectiveness for JCPs that were either in a condition that warranted subsealing or in a condition for which subsealing was not unwarranted. For projects in the no-subseal state, two test sections would be identified: one control section and one section that received only joint-seal maintenance. For projects in the subseal state, one control section would receive no treatment, another would receive both joint-seal and subseal treatments, and the third would receive only the joint-seal treatment. Many but not all sections needed for SPS-4 would generally be found among projects that contain sections designated for GPS-3 (Jointed Plain Concrete Pavement [JPCP]) and GPS-4 (Jointed Reinforced Concrete Pavement [JRCP]). In all such cases the GPS test section would serve as the control section for SPS-4. Figure 3.2 shows the layout for SPS-4 test sections.

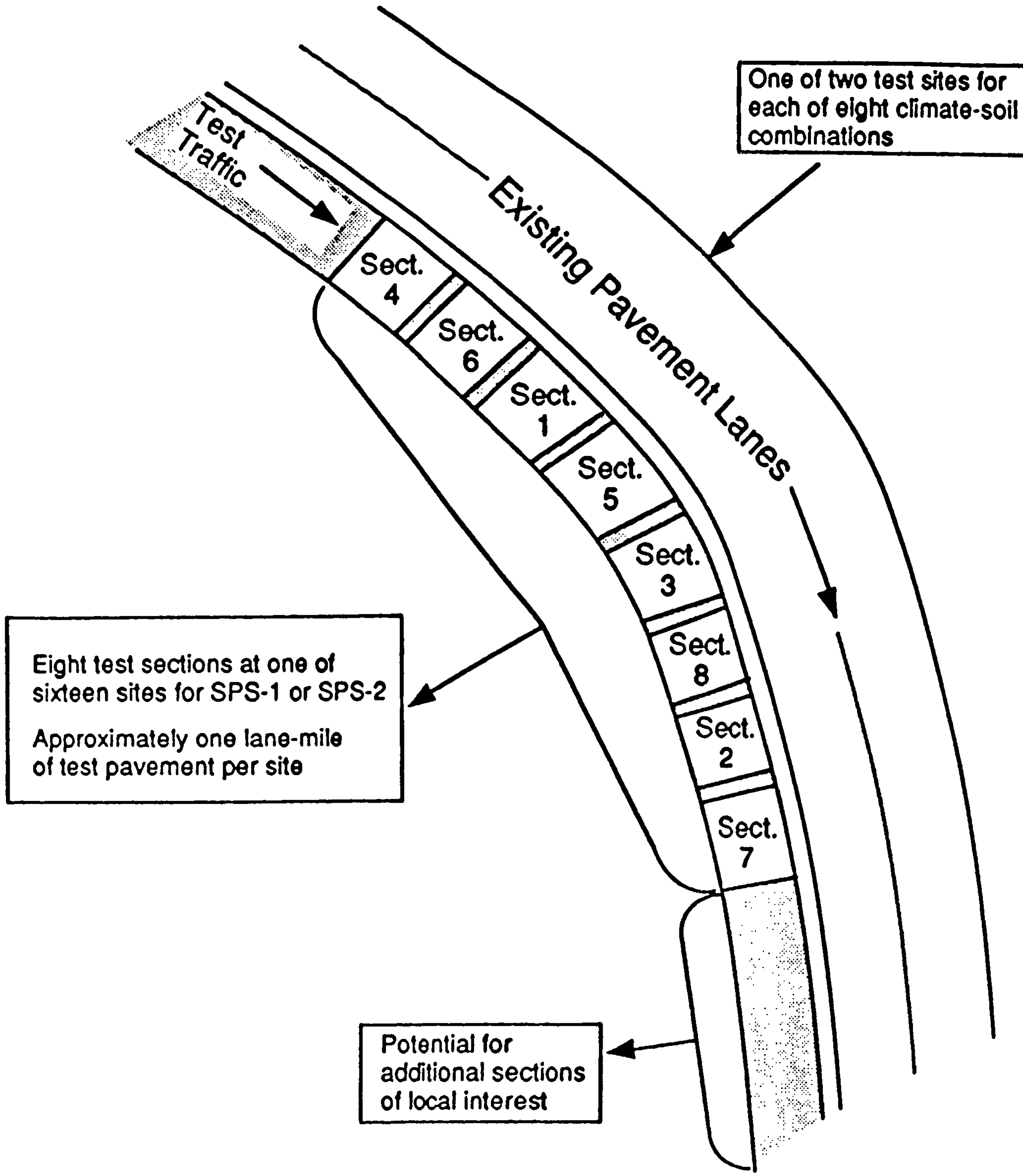
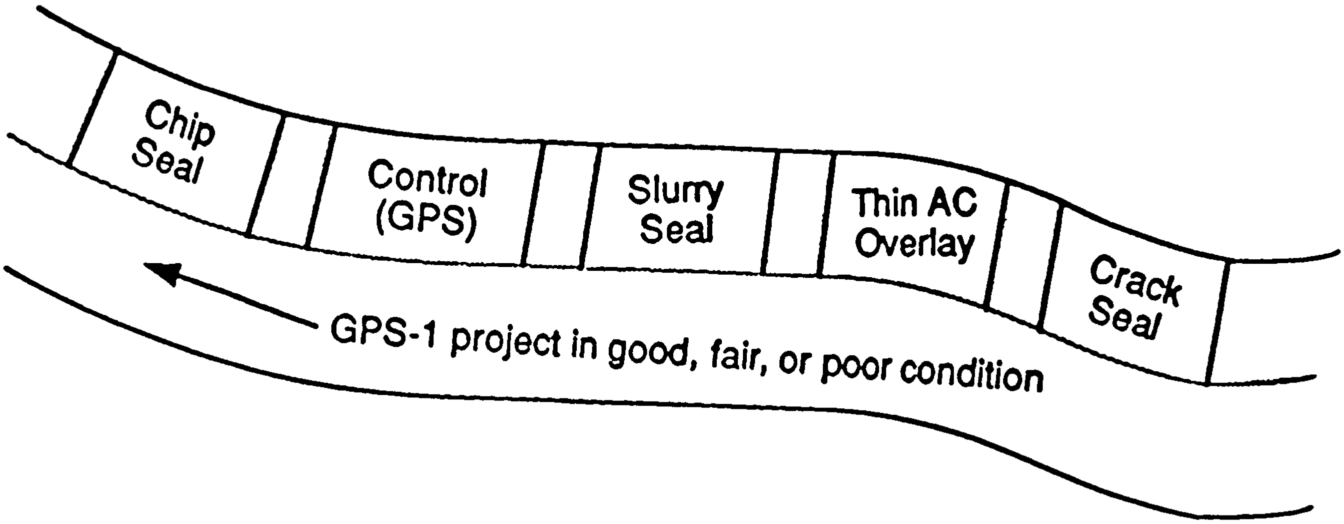


Figure 3.1. Test Section Layout for SPS-1 and SPS-2: Strategic Studies of Structural Factors



B. SPS-4: JCP Preventative Maintenance Effectiveness

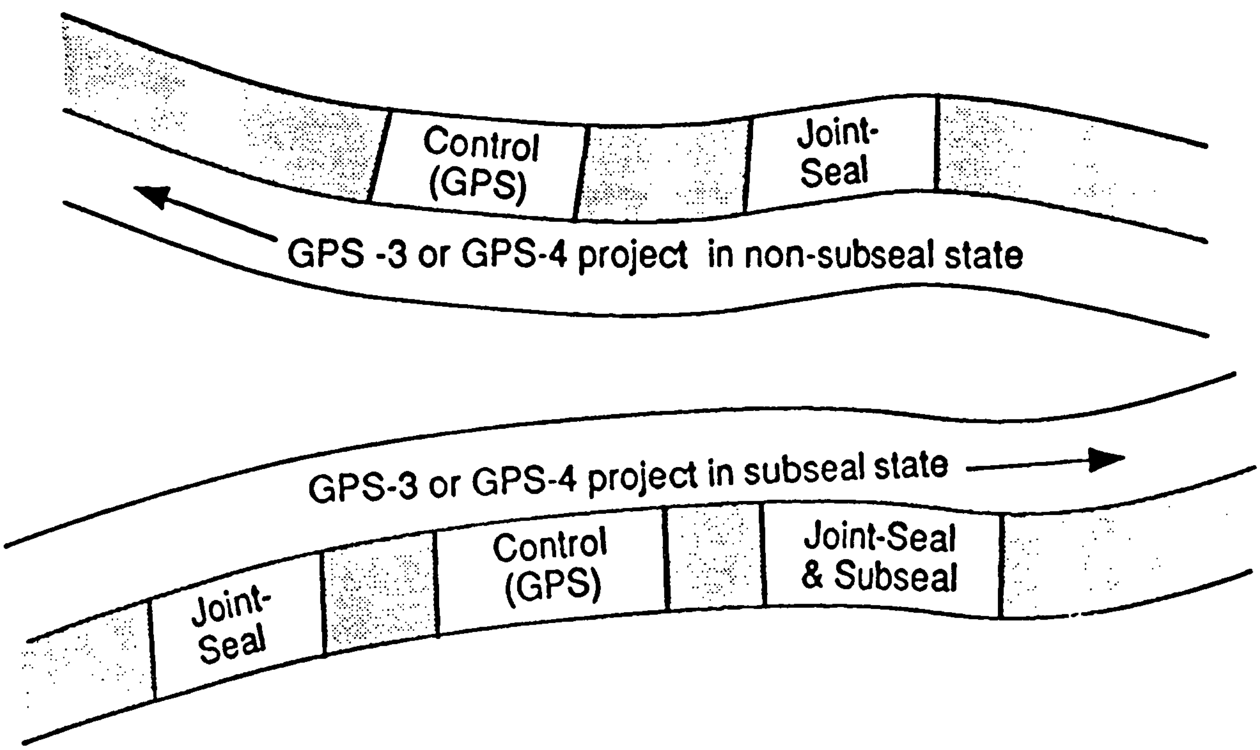


Figure 3.2. Test Section Layout for SPS-3 and SPS-4: Studies of Preventive Maintenance Effectiveness

SPS-5, SPS-6, and SPS-7: Pavement Rehabilitation Studies

These studies all required that the respective rehabilitation treatments be applied to sections of existing pavement. It was anticipated that most of the required test sites for the rehabilitation studies would be selected within projects that contain GPS test sections.

SPS-5: Hot Recycling of AC (3.2)

The initial experimental design for SPS-5 was expected to involve all four climates and would be restricted to fine roadbed soils and relatively high traffic rates. Within each climate four GPS-1 projects would be selected so that two were in poor condition and two were in fair condition. The condition criteria were not specified but might be stated in terms of rutting and/or cracking severity. Pavement designs for all projects were loosely defined to be GPS-1 designs with respect to surfacing and base/subbase thicknesses.

If some of the required SPS-5 sites did not exist among GPS-1 projects, particularly with respect to pavement condition, it was anticipated that non–GPS-1 projects would be selected from corresponding pavements that were scheduled to be overlaid by the SHAs.

Four 500 ft. test sections were to be identified within each project, two for hot-mix asphalt concrete (HMAC) recycling using two different recycling agents (A and B) and two for two thicknesses of AC overlay. The overlay sections were intended to provide direct comparisons between the effectiveness of recycling and overlay treatments. Further development of SPS-5 would specify the aggregate ratio, the two recycling agents for hot recycling, and the overlay designs.

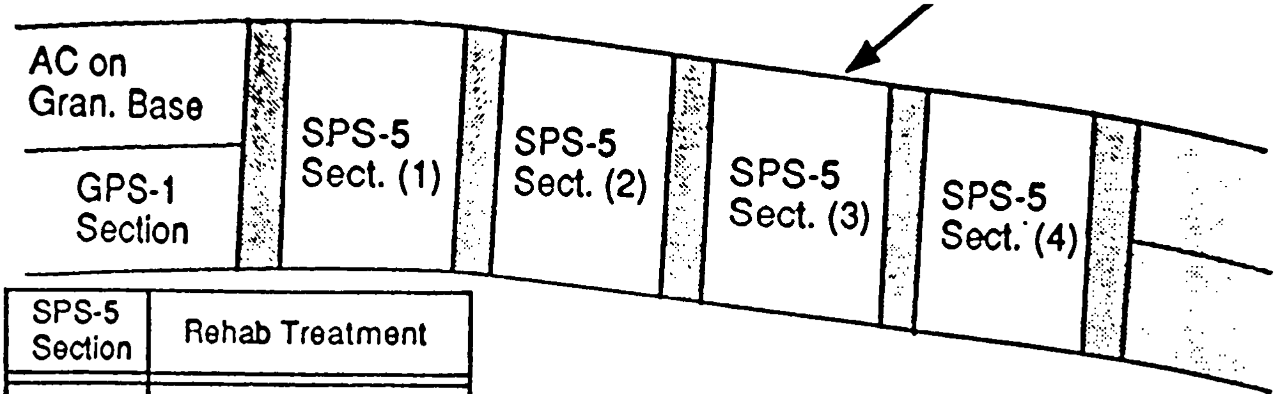
Figure 3.3 shows the layout for SPS-5 sections. Note that the GPS-1 sections that were not rehabilitated would serve as control sections for SPS-5 projects.

SPS-6: Restoration and Overlay of Jointed PCC Pavement (3.2)

The initial experimental design for SPS-6 involves six factors. Three are environmental factors (i.e., moisture, temperature, and subgrade soil); the remaining three factors are rigid pavement type (JPCP, JRCP), restoration method (A, B), and overlay thickness. The SPS-6 sites were to be limited to locations with fine-grained soils, jointed rigid pavements, and traffic rates exceeding 200 KESALs/yr. No sites in the dry-nonfreeze environmental zone were anticipated.

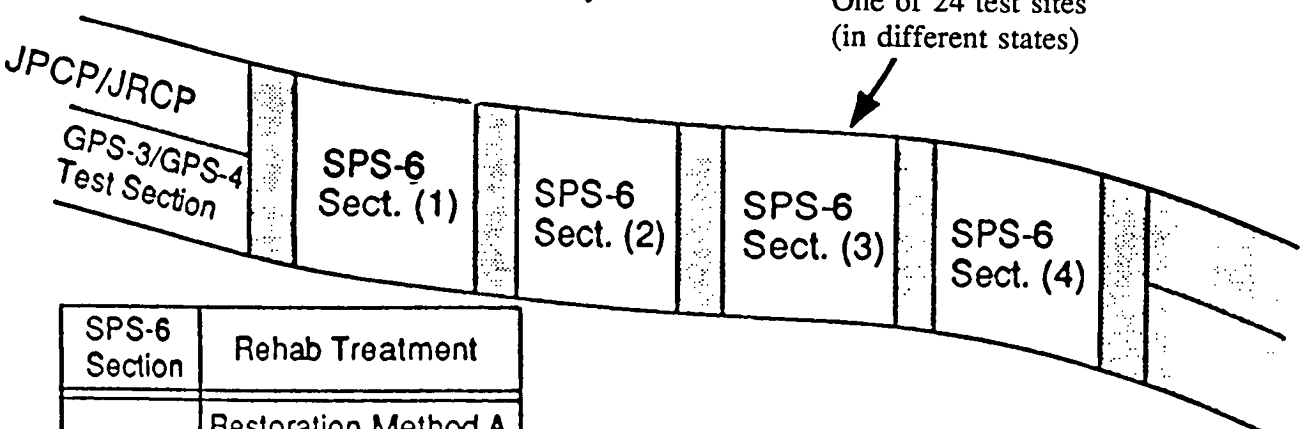
Four 500 ft test sections were proposed for each project: two each for HMAC overlays using two thicknesses (thin, thick) with two restoration methods (A and B). Figure 3.3 shows the layout for SPS-6 sections; note that GPS-3 and GPS-4 would have been used whenever possible.

(a) SPS-5: AC Hot Recycling



SPS-5 Section	Rehab Treatment
(1)	Hot Recycle, Agent A
(2)	Hot Recycle, Agent B
(3)	AC Overlay, Thin
(4)	AC Overlay, Thick

(b) SPS-6: JCP Restoration and AC Overlay



SPS-6 Section	Rehab Treatment
(1)	Restoration Method A & Thin AC Overlay
(2)	Restoration Method B & Thin AC Overlay
(3)	Restoration Method A & Thick AC Overlay
(4)	Restoration Method B & Thick AC Overlay

Figure 3.3 Test Section Layout for SPS-5 and SPS-6: Pavement Rehabilitation Studies

SPS-7: Bonded PCC Overlay of PCC Pavement

Figure 3.4 shows the layout for SPS-7 sections. The SPS-7 sites were to be located in all four climatic zones, with three projects within each zone. The three projects would consist of either two JCP projects and one CRCP project or one JCP project and two CRCP projects. All projects were to be situated at locations with fine-grained subgrade soils and a projected traffic rate of 200 KESALs/yr. Within each climatic zone, the two projects of the same type (i.e., JCP or CRCP) were to be selected from different states.

SPS-8: Study of Environmental Factors in the Absence of Heavy Loads

One of the primary purposes of SPS-8 was to provide data for the verification or revision of assumptions that have been made in the revised American Association of State Highway and Transportation Officials (AASHTO) pavement design guide with respect to serviceability losses that are induced by environmental effects rather than load. It was recommended that environmental effects for both flexible and rigid pavements should be determined from a single study that incorporated both pavement types at each test site. Figure 3.5. shows the layout for SPS-8 sections.

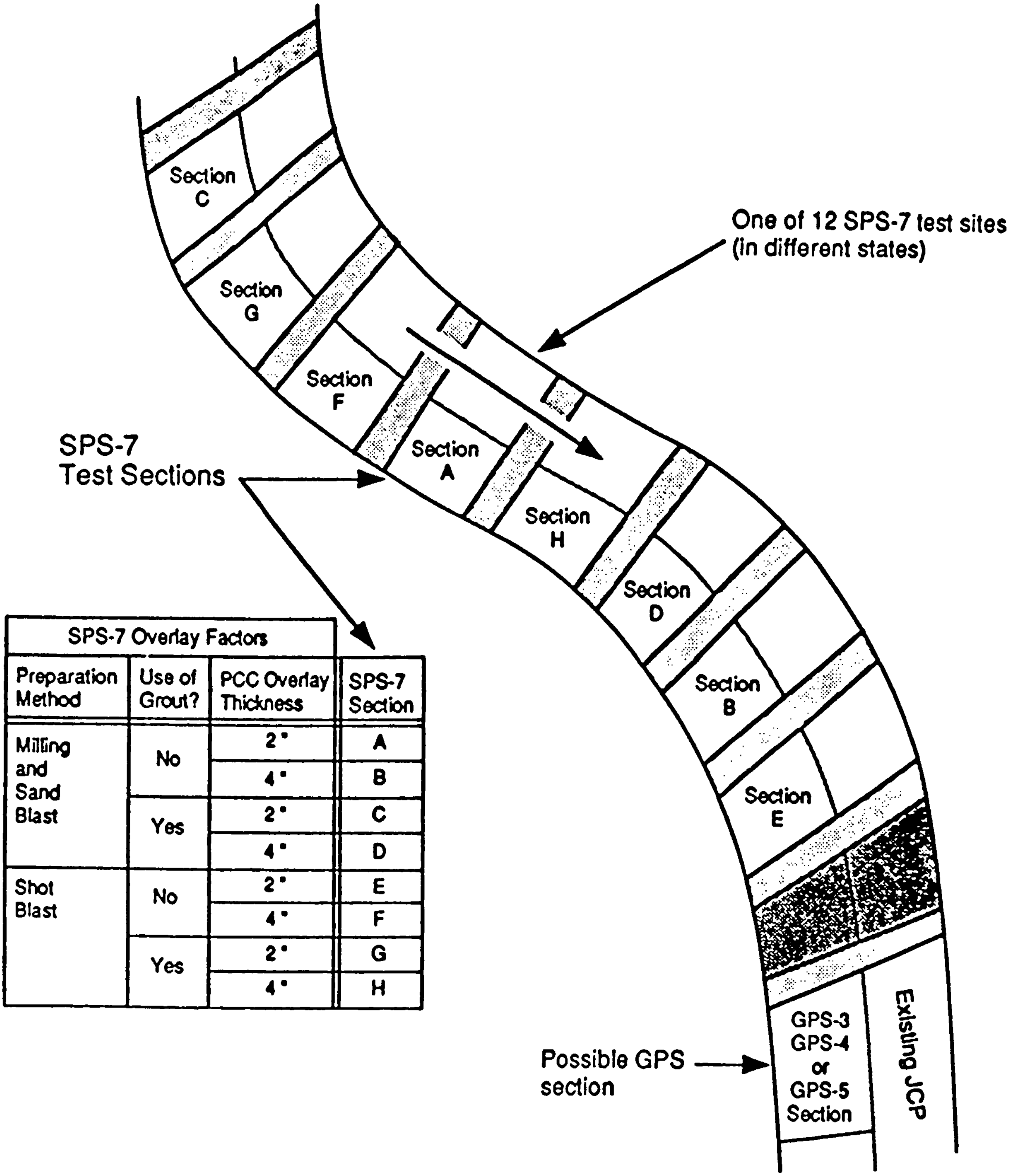
SPS-8 covered all four climates, and within each climate three types of roadbed subgrade soil were specified: fine-grained non-expansive soil, fine-grained expansive soil, and coarse-grained soil. Two test sites (in different states) would be used for eight of the twelve combinations of climate-soil conditions.

Two flexible pavement and two rigid pavement test sections were to be constructed at each of the 20 test sites. One flexible concrete pavement section was to have the same construction specifications as the "median pavement structure" defined in SPS-1 experiment. The other flexible structure was to be a "normal parkway" structure that represents current design construction practices for flexible pavements that carry only high-volume auto traffic.

Similarly, the two rigid pavement structures at each test site were to represent the "median pavement structure" specified for SPS-2 sections and a "normal parkway" structure for rigid pavements.

SPS Program Analyses (1989—90)

During 1989 and 1990 a number of studies and analyses were undertaken to further define the SPS designs. In particular, Strategic Pavement Design Initiatives for SPS-1 and SPS-2 (**3.3**) were considered and the value of fractional factorials in SPS-1 and SPS-2 was investigated (**3.4**). These investigations led to the development of experimental design and research plans for SPS-1 (**3.5**) and SPS-2 (**3.6, 3.7**). In addition, crucial analysis requirements for SPS-1 were developed (**3.8, 3.9**).



SPS-7 Overlay Factors			
Preparation Method	Use of Grout?	PCC Overlay Thickness	SPS-7 Section
Milling and Sand Blast	No	2"	A
		4"	B
	Yes	2"	C
		4"	D
Shot Blast	No	2"	E
		4"	F
	Yes	2"	G
		4"	H

Figure 3.4. Test Section Layout for SPS-7: Bonded PCC Overlay of PCC Pavements

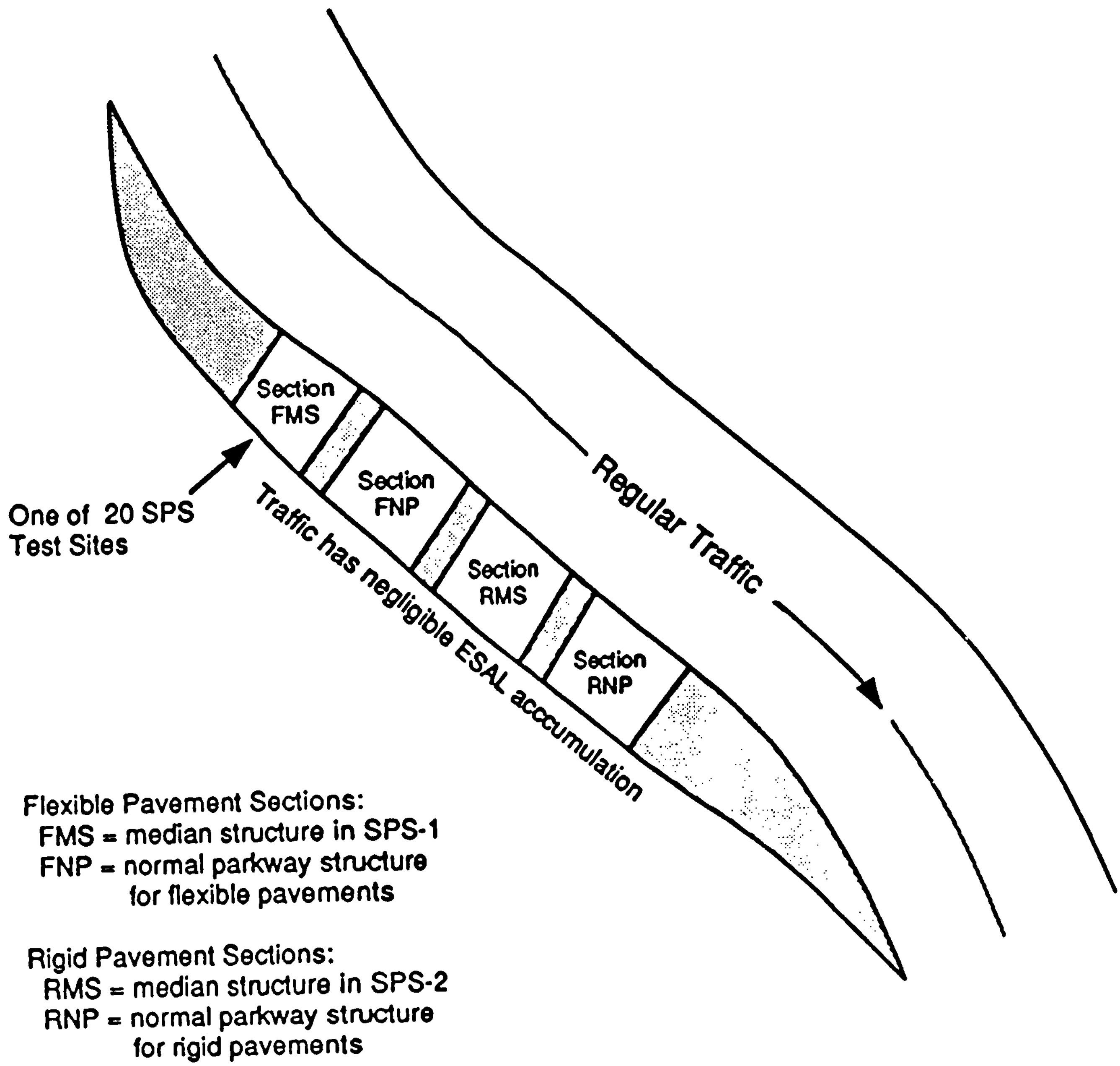


Figure 3.5. Test Section Layout for SPS-8P Study of Environmental Factors in the Absense of Heavy Loads

During the same time frame, guidelines were developed for nomination and evaluation of candidate projects for SPS-6 (**3.10, 3.11**) and SPS-7 (**3.12**). Analytical studies of error variation in the SPS experiments (**3.13**) and of the number of error terms required in the SPS experiments (**3.14**) were also conducted.

Revised SPS Experimental Designs (1990)

The experimental design and research plans for the experiments on structural factors (SPS-1 and SPS-2) and rehabilitation (SPS-5, SPS-6, SPS-7) were prepared in cooperation with SHA personnel. The final experimental design and research plan for the experiment on environmental effects (SPS-8) is still under development, but a preliminary experimental design has been included for reference (**3.14**). Guidelines and information for nominating test sites for the experiments on structural factors (SPS-1 and SPS-2) and rehabilitation (SPS-5, SPS-6, SPS-7) have been prepared (**3.14**).

SPS-1: Strategic Study of Structural Factors for Flexible Pavements

This experiment examined the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), subgrade soil (fine- or coarse-grained), and traffic rate (as a covariant) on pavement sections incorporating different levels of structural factors. These factors include drainage (presence or lack of it as provided by an open-graded permeable asphalt-treated drainage layer and edge drains), AC surface thickness (4 or 7 in.), base type (dense-graded untreated aggregate, dense-graded asphalt-treated, or combination thereof), and base thickness (8 or 12 in. for undrained sections; 8, 12, or 16 in. for drained sections). This experiment (**3.15**), designed in a fractional factorial manner to enhance implementation practicality, is presented in Table 3.1 and includes 196 test sections located at 16 test sites.

SPS-2: Strategic Study of Structural Factors for Rigid Pavement

This experiment examined the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), subgrade soil (fine- or coarse-grained), and traffic rate (as a covariant) on doweled JPCP sections incorporating different levels of structural factors (**3.16**). These factors include drainage (presence or lack of it as provided by an open-graded permeable asphalt-treated drainage layer and edge drains), concrete thickness (8 or 11 in.), base type (dense-graded untreated aggregate or lean concrete), concrete flexural strength (550 or 900 psi at 14 days), and lane width (12 or 14 ft.). This experiment designed in a fractional factorial manner to enhance implementation practicality, is presented in Table 3.2 and includes 192 test sections located at 16 test sites.

Table 3.1 Experimental Design for SPS-1: Strategic Study of Structural Factors for Flexible Pavements

PAVEMENT STRUCTURE COMBINATIONS				FACTORS FOR MOISTURE, TEMPERATURE, SUBGRADE TYPE, AND LOCATION															
				WET								DRY							
				FREEZE				NO FREEZE				FREEZE				NO FREEZE			
DRAINAGE	BASE TYPE	TOTAL BASE THICK	SURFACE THICK	FINE		COARSE		FINE		COARSE		FINE		COARSE		FINE		COARSE	
				J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
NO	AGG	8"	4"		K1		M1		O1		Q1		S1		U1		W1		Y1
			7"	J1		L1		N1		P1		R1		T1		V1		X1	
		12"	4"	J2		L2		N2		P2		R2		T2		V2		X2	
			7"		K2		M2		O2		Q2		S2		U2		W2		Y2
	ATB	8"	4"	J3		L3		N3		P3		R3		T3		V3		X3	
			7"		K3		M3		O3		Q3		S3		U3		W3		Y3
		12"	4"		K4		M4		O4		Q4		S4		U4		W4		Y4
			7"	J4		L4		N4		P4		R4		T4		V4		X4	
	ATB / 4"AGG	8"	4"	J5		L5		N5		P5		R5		T5		V5		X5	
			7"		K5		M5		O5		Q5		S5		U5		W5		Y5
		12"	4"		K6		M6		O6		Q6		S6		U6		W6		Y6
			7"	J6		L6		N6		P6		R6		T6		V6		X6	
YES	PATB / AGG	8"	4"	J7		L7		N7		P7		R7		T7		V7		X7	
			7"		K7		M7		O7		Q7		S7		U7		W7		Y7
		12"	4"		K8		M8		O8		Q8		S8		U8		W8		Y8
			7"	J8		L8		N8		P8		R8		T8		V8		X8	
		16"	4"		K9		M9		O9		Q9		S9		U9		W9		Y9
			7"	J9		L9		N9		P9		R9		T9		V9		X9	
	ATB / PATB	8"	4"		K10		M10		O10		Q10		S10		U10		W10		Y10
			7"	J10		L10		N10		P10		R10		T10		V10		X10	
		12"	4"	J11		L11		N11		P11		R11		T11		V11		X11	
			7"		K11		M11		O11		Q11		S11		U11		W11		Y11
		16"	4"	J12		L12		N12		P12		R12		T12		V12		X12	
			7"		K12		M12		O12		Q12		S12		U12		W12		Y12

AGG = Dense-graded untreated aggregate base
ATB = Dense-graded asphalt-treated base
PATB = 4" thick open-graded permeable asphalt-treated drainage layer, underneath ATB or over AGG base
4" AGG = 4" thick dense-graded untreated aggregate base layer underneath ATB

Table 3.2 Experimental Design for SPS-2: Strategic Study of Structural Factors for Rigid Pavements

PAVEMENT STRUCTURE					CLIMATE ZONES, SUBGRADE, SITE															
DRAIN	BASE TYPE	PCC		LANE WIDTH	WET								DRY							
					FREEZE				NO FREEZE				FREEZE				NO FREEZE			
		THICK	STRENGTH		FINE		COARSE		FINE		COARSE		FINE		COARSE		FINE		COARSE	
		in.	psi	ft	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
NO	AGG	8	550	12	J1		L1		N1		P1		R1		T1		V1		X1	
				14		K1		M1		O1		Q1		S1		U1		W1		Y1
			900	12		K2		M2		O2		Q2		S2		U2		W2		Y2
				14	J2		L2		N2		P2		R2		T2		V2		X2	
		11	550	12		K3		M3		O3		Q3		S3		U3		W3		Y3
				14	J3		L3		N3		P3		R3		T3		V3		X3	
			900	12	J4		L4		N4		P4		R4		T4		V4		X4	
				14		K4		M4		O4		Q4		S4		U4		W4		Y4
NO	LCB	8	550	12	J5		L5		N5		P5		R5		T5		V5		X5	
				14		K5		M5		O5		Q5		S5		U5		W5		Y5
			900	12		K6		M6		O6		Q6		S6		U6		W6		Y6
				14	J6		L6		N6		P6		R6		T6		V6		X6	
		11	550	12		K7		M7		O7		Q7		S7		U7		W7		Y7
				14	J7		L7		N7		P7		R7		T7		V7		X7	
			900	12	J8		L8		N8		P8		R8		T8		V8		X8	
				14		K8		M8		O8		Q8		S8		U8		W8		Y8
YES	Perm. ATB	8	550	12	J9		L9		N9		P9		R9		T9		V9		X9	
				14		K9		M9		O9		Q9		S9		U9		W9		Y9
			900	12		K10		M10		O10		Q10		S10		U10		W10		Y10
				14	J10		L10		N10		P10		R10		T10		V10		X10	
		11	550	12		K11		M11		O11		Q11		S11		U11		W11		Y11
				14	J11		L11		N11		P11		R11		T11		V11		X11	
			900	12	J12		L12		N12		P12		R12		T12		V12		X12	
				14		K12		M12		O12		Q12		S12		U12		W12		Y12

AGG = Dense-graded untreated aggregate base
LCB = Lean concrete base
Perm. ATB = Permeable asphalt-treated base
All perpendicular doweled joints at 15 ft. spacing

SPS-3: Preventive Maintenance of AC Pavement

This experiment examined the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), subgrade type (fine- or coarse-grained), traffic rate, ratio of structural capacity, and condition of pavement (good, fair, or poor) on preventive maintenance of AC pavements. Table 3.3 presents the experimental design for SPS-3.

SPS-4: Preventive Maintenance of JCP

This experiment examined the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), subgrade type (fine- or coarse-grained), base type (dense granular or stabilized), and pavement type (plain or reinforced) on preventive maintenance of JCPs. Table 3.4 present the experimental design for SPS-4.

SPS-5: Rehabilitation of AC Pavement

This experiment (**3.15**) examined the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), condition of existing pavement (fair or poor), and traffic rate (as a covariant) on pavement sections incorporating different methods of rehabilitation with AC overlays. Rehabilitation methods used in this study included surface preparation (routine preventive maintenance or intensive preparation with cold milling and associated repairs), asphalt overlay type (virgin or recycled), and overlay thickness (2 or 5 in.). The experimental design for SPS-5 is presented in Table 3.5 and includes 128 test sections located at 16 test sites.

SPS-6: Rehabilitation of Jointed PCC Pavements

This experiment (**3.16**) examined the effects of environmental regions (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), type of pavement (plain or reinforced), condition of existing pavement (fair or poor), and traffic rate (as a covariant) on pavement sections incorporating different methods of rehabilitation with and without AC overlays. Rehabilitation methods used in this study included surface preparation (a limited preparation and full concrete pavement restoration) with a 4-in. thick asphalt concrete overlay or without an overlay, crack/break and seat with thin and thick AC overlays (4 and 8 in.), and limited surface preparation with a 4-in. thick AC overlay with sawed and sealed joints. The experimental design for SPS-6 is presented in Table 3.6 and includes 168 test sections located at 24 test sites.

SPS-7: Bonded Concrete Overlay of Concrete Pavements

This experiment examined the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze), type of pavement (JPCP or CRCP), and condition of existing

Table 3.3 Experimental Design for SPS-3: Preventive Maintenance of AC Pavements

MOISTURE		WET								DRY							
TEMPERATURE		FREEZE				NO-FREEZE				FREEZE				NO-FREEZE			
SUBGRADE		FINE		COARSE		FINE		COARSE		FINE		COARSE		FINE		COARSE	
TRAFFIC		LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
CONDITION	SN RATIO																
G	≤1	1	7	13	19	25	31	37	43	49	55	61	67	73	79	85	91
	>1	2	8	14	20	26	32	38	44	50	56	62	68	74	80	86	92
F	≤1	3	9	15	21	27	33	39	45	51	57	63	69	75	81	87	93
	>1	4	10	16	22	28	34	40	46	52	58	64	70	76	82	88	94
P	≤1	5	11	17	23	29	35	41	47	53	59	65	71	77	83	89	95
	>1	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96

Cell Number — 48

Table 3.4 Experimental Design for SPS-4: Preventive Maintenance of Jointed Concrete Pavements

PAVEMENT	MOISTURE	BASE TYPE \ TEMPERATURE	FREEZE		NO-FREEZE	
		SUBGRADE	FINE	COARSE	FINE	COARSE
PLAIN	WET	DENSE	1	3	5	7
PLAIN	WET	STAB	2	4	6	8
PLAIN	DRY	DENSE	9	11	13	15
PLAIN	DRY	STAB	10	12	14	16
REINFORCED	WET	DENSE	17	19	21	23
REINFORCED	WET	STAB	18	20	22	24

DENSE = Dense granular base
STAB = Stabilized base

Table 3.5. Experimental Design for SPS-5: Rehabilitation of AC Pavements

Rehabilitation Procedures		Factors for Moisture, Temperature, and Pavement Condition	Wet				Dry			
			Freeze		Nonfreeze		Freeze		Nonfreeze	
			Fair	Poor	Fair	Poor	Fair	Poor	Fair	Poor
Surface Prep.	Overlay Material	Overlay Thickness								
Routine Maint. (Control)		0	xx	xx	xx	xx	xx	xx	xx	xx
Minimum	Recycled AC	2 in.	xx	xx	xx	xx	xx	xx	xx	xx
		5 in.	xx	xx	xx	xx	xx	xx	xx	xx
	Virgin AC	2 in.	xx	xx	xx	xx	xx	xx	xx	xx
		5 in.	xx	xx	xx	xx	xx	xx	xx	xx
Intensive	Recycled AC	2 in.	xx	xx	xx	xx	xx	xx	xx	xx
		5 in.	xx	xx	xx	xx	xx	xx	xx	xx
	Virgin AC	2 in.	xx	xx	xx	xx	xx	xx	xx	xx
		5 in.	xx	xx	xx	xx	xx	xx	xx	xx

Each "x" designates a test section.
Subgrade Soil: Fine
Traffic: $\geq$ 100 KESALs/Yr

Table 3.6. Experimental Design for SPS-6: Rehabilitiation of Jointed PCC Pavements

Rehabilitation Procedure / Factors for Moisture, Temperature, Pavement Type, and Pavement Condition		Wet Freeze				Wet, Nonfreeze				Dry Freeze				Dry, Nonfreeze	
		JPCP		JRCP		JPCP		JRCP		JPCP		JRCP		JPCP	
		Fair	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair	Poor	Fair	Poor
PREPARATION	Overlay Thickness														
Routine Maintenance (Control)	0	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
Minimum Restoration	0	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
	4"	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
	4"	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
Maximum Restoration (CPR)	0	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
	4"	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
Crack/Break and Seat	4"	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x
	8"	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	x	x	x

* with saw AC overlay joints above JCP joints and seal
Subgrade Soil: Fine
Traffic $\geq$ 200 KESALs/Yr.
Each "x" designates a test section.

pavement and traffic (as covariants) on pavement sections incorporating different rehabilitation methods and concrete overlays (**3.17**). Rehabilitation techniques used in this study included different surface preparation methods (cold milling plus sandblasting or shotblasting), bonding agents (neat cement grout or none) and overlay thickness (3 or 5 in.). The experimental design for SPS-7 is presented in Table 3.7 and includes 96 test sections located at 12 test sites.

SPS-8: Study of Environmental Effects in the Absence of Heavy Loads

This experiment investigated the effects of environmental region (wet-freeze, wet-nonfreeze, dry-freeze, or dry-nonfreeze) and subgrade type (frost-susceptible, expansive, fine, or coarse) on pavement sections incorporating different flexible and rigid pavements subjected to very limited traffic. The target pavement structures included two levels (low/high) of highway design. For flexible pavements, these structural sections consisted of 4 or 7 in. AC surface layers resting on 8 or 12 in. thick dense-graded untreated granular base, respectively. For rigid pavements, the test sections consisted of pavement structures of 8 or 11 in. thick doweled jointed plain concrete pavements on 6 in. thick dense-graded granular base. The experimental design for SPS-8 is presented in Table 3.8 and includes 48 test sections at 12 test sites. A preliminary experimental design has been prepared (**3.14**).

Project Participation Requirements

Projects considered for inclusion in the SPS experiments must meet certain criteria to ensure that the relative performance between the test sections is due to the design parameters incorporated in the experiment and not to other associated factors such as changes in subgrade or traffic patterns.

The following basic criteria were considered in evaluating the suitability of projects for inclusion in the SPS experiments (**3.19**).

1. For the experiments on structural factors and environmental effects, the project must include new construction of all pavement layers along a new route, or as part of realignment, reconstruction, or construction of an experimental parallel roadway. The rehabilitation experiments must include restoration and/or overlay of pavements in their first performance cycle. The experiment on asphalt-aggregate mixture specifications may include new construction or resurfacing of an existing pavement. The test site for the experiments on pavement maintenance must include a GPS approved test section. Finally, projects in which the proposed experimental sections are to be constructed as added lanes or as a partial reconstruction (removal and replacement of surface layers only) are not considered suitable for an SPS project.

Table 3.7. Experimental Design for SPS-7: Bonded PCC Overlays

PCC Overlay Factors Within Projects			Factors for Moisture, Temperature, and PCC Pavement Type							
			Wet				Dry			
			Freeze		Nonfreeze		Freeze		Nonfreeze	
Overlay Preparation	Grout (Yes/No)	PCC Overlay Thickness	JCP	CRCP	JCP	CRCP	JCP	CRCP	JCP	CRCP
Cold Milling Plus Sand-blasting	No	3"	xx	x	xx	x	xx	x	xx	x
			xx	x	xx	x	xx	x	xx	x
	Yes	5"	xx	x	xx	x	xx	x	xx	x
			xx	x	xx	x	xx	x	xx	x
Shot-blasting	No	3"	xx	x	xx	x	xx	x	xx	x
			xx	x	xx	x	xx	x	xx	x
	Yes	5"	xx	x	xx	x	xx	x	xx	x
			xx	x	xx	x	xx	x	xx	x

Each "x" designates a test section.
Traffic: 200 KESALs/Yr

Table 3.8. Experimental Design for SPS-8: Study of Environmental Effects in the Absence of Heavy loads.

Pavement Structure[1,2]			Factors for Moisture, Temperature, and Subgrade Type[3]											
			Wet						Dry					
			Freeze			Nonfreeze			Freeze			Nonfreeze		
Type	Surface Thickness (in.)	Base Thickness (in.)	Active	Fine	Coarse	Active	Fine	Coarse	Active	Fine	Coarse	Active	Fine	Coarse
Flexible	4	8	X	X	X	X	X	X	X	X	X	X	X	X
	7	12	X	X	X	X	X	X	X	X	X	X	X	X
Rigid	8	6	X	X	X	X	X	X	X	X	X	X	X	X
	11	6	X	X	X	X	X	X	X	X	X	X	X	X

Notes

1. Dense-graded HMAC and JPC for flexible and rigid pavements, respectively.
2. Dense-graded aggregate base.
3. Active soil can be either frost-susceptible or swelling type relative to the climatic zone.

2. The construction project must include sufficient length of highway to provide an accommodation for all experiment test sections. In order to accommodate specific changes in layer thickness, materials, or other study parameters, the construction project must include appropriate transition lengths between the individual test sections.

3. Test site selection is based on presence of subgrade soils of similar classification and characteristics.

4. Test sections are located on portions of a project that are relatively straight, with less than 4% vertical grade and horizontal curves less than 3°. All test sections on a project must have the same transverse cross-section profile of the pavement surface to ensure similar surface drainage conditions.

5. Ideally, all test sections are to be located on shallow fills. The entire length of each test section, however, should be located completely in either a cut or a fill configuration. Cut-fill transitions and side-hill fills should be avoided.

6. It is highly desirable that the test sections be opened to traffic at the same time.

7. Each test section should be free of culverts, pipes, and other substructures beneath the pavement. If subsurface structures are required, they should be located in the transition zones between test sections.

8. The projects should be located on a route with an expected traffic level that conforms to the following criteria: $\geq$ 100 KESALs/yr. for SPS-1 and SPS-5; $\geq$ 200 KESALs/yr. for SPS-2, SPS-6, and SPS-7; and $\leq$ 10 KESALs/yr. for SPS-8.

9. Traffic flow should be uniformly applied over all the test sections on a project. All sections should carry essentially the same traffic stream. Minor variations in traffic rates between test sections at the site due to intersections, on-off ramps, etc., are allowed. However, these variations should not occur within any of the test sections. As a result, intersections, rest stops, on-off ramps, weaving areas, quarry entrances, etc., should be avoided on and between test sections on a project.

10. Pavement sections that are obviously excessively under- or over-designed for existing site conditions should be avoided for rehabilitation experiments.

11. For rehabilitation projects, distress type, extent, and severity should be reasonably uniform over the project and representative of the type of distress observed within the SHA's jurisdiction.

Candidate projects are evaluated individually to determine the extent of compliance with these criteria. The impact of deviations from these criteria on test section performance and the suitability of the test site for inclusion in the experiment are assessed in determining project acceptance. Variation in traffic level on the test sections at a specific site due to intermediate intersections and/or interchanges and deviation from the desired geometrical requirements have been assessed in some cases as part of the SPS project acceptance process.

Project Requirements

The participating SHAs agreed to perform several activities in order to ensure uniformity in construction and obtain needed data on materials characteristics, traffic rates, climatic conditions, and other factors at each test site. Agencies participating in SPS were expected to comply with the following conditions.

1. All test sections required by a given experimental design must be constructed during the same construction season, and the treatments within the length of the test sections must be applied across all lanes in the direction of travel. For the experiments, the SHA is responsible for developing appropriate asphalt or concrete mixture designs and for testing the materials and mixtures used for the test sections in accordance with the specified procedures.

2. A traffic data collection station shall be installed at or near the site to monitor traffic that passes over the test sections. For the experiments on rehabilitation and asphalt-aggregate mixture specifications (SPS-5, SPS-6, and SPS-7), this station must be operated to obtain, as a minimum, continuous automated vehicle classification and provide for four 1-week sessions of seasonal weigh-in-motion each year. For the experiments on structural factors (SPS-1 and SPS-2), the station must provide continuous weigh-in-motion. For the experiment on environmental effects (SPS-8), the station must provide continuous automated vehicle classification supported by portable weigh-in-motion on an as-needed basis. For the experiments on pavement maintenance (SPS-3 and SPS-4), traffic data collected for the on-site GPS test section are considered applicable to the SPS test site.

3. A weather station shall be installed and operated at SPS-1, SPS-2, and SPS-8 test sites if sites are not located in proximity to an existing station.

4. Except for test sites on pavement maintenance (SPS-3 and SPS-4), the SHA will perform and/or provide for drilling, coring, sampling, and testing of in-place pavement materials and materials used in construction or rehabilitation. The sampling and testing plans must be tailored to the site and must conform to SHRP operational memorandums and guides.

5. The SHA shall prepare plans, specifications, quantities, and all other documents necessary as a part of contracting procedures. The SHA must also provide construction control, inspection, and management in accordance with its standard quality control and quality assurance procedures.

6. If an existing pavement is to become part of the test sections, the SHA will provide historical information on pavement inventory features, traffic levels and loads, and maintenance data similar to that required for the GPS test sections.

7. Periodic traffic control will be provided by the SHA for on-site data collection activities such as materials drilling and sampling, deflection measurements, and other monitoring activities.

8. Maintenance activities on the test sections shall be coordinated to prevent premature application of treatments that alter the characteristics of the test sections and limit their use in the study.

9. The SHA shall provide and maintain signing and marking of test sites.

10. Finally, the SHA will notify SHRP when any of the test sections reach an unsafe condition or become candidates for rehabilitation to allow recording of the condition of the test sections prior to rehabilitation.

To aid the participating SHAs in performing these functions, SHRP prepared a series of reports that outline guidelines for the different facets of participation, such as procedures for evaluating candidate projects, sampling and testing needs, and construction requirements.

Test Site Requirements

The SPS experiments were developed to study the effects of certain important factors on pavement performance. To accomplish this objective, a number of test sites with specific characteristics are sought in each climatic region. Table 3.9 lists the number of test sites required in each climatic region for each site-specific condition for the experiments on structural factors, rehabilitation, and environmental effects. A total of 106 sites are required for these experiments. These include 56 test sites of new pavement construction or reconstruction and 50 sites of pavement rehabilitation. The new construction projects include 28 sites of flexible pavements and 28 sites of rigid pavements. The rehabilitation projects include 16 sites of flexible pavement rehabilitation and 34 sites of rigid pavement rehabilitation. Thus, these SPS experiments include 44 test sites of flexible pavement and 62 test sites of rigid pavements.

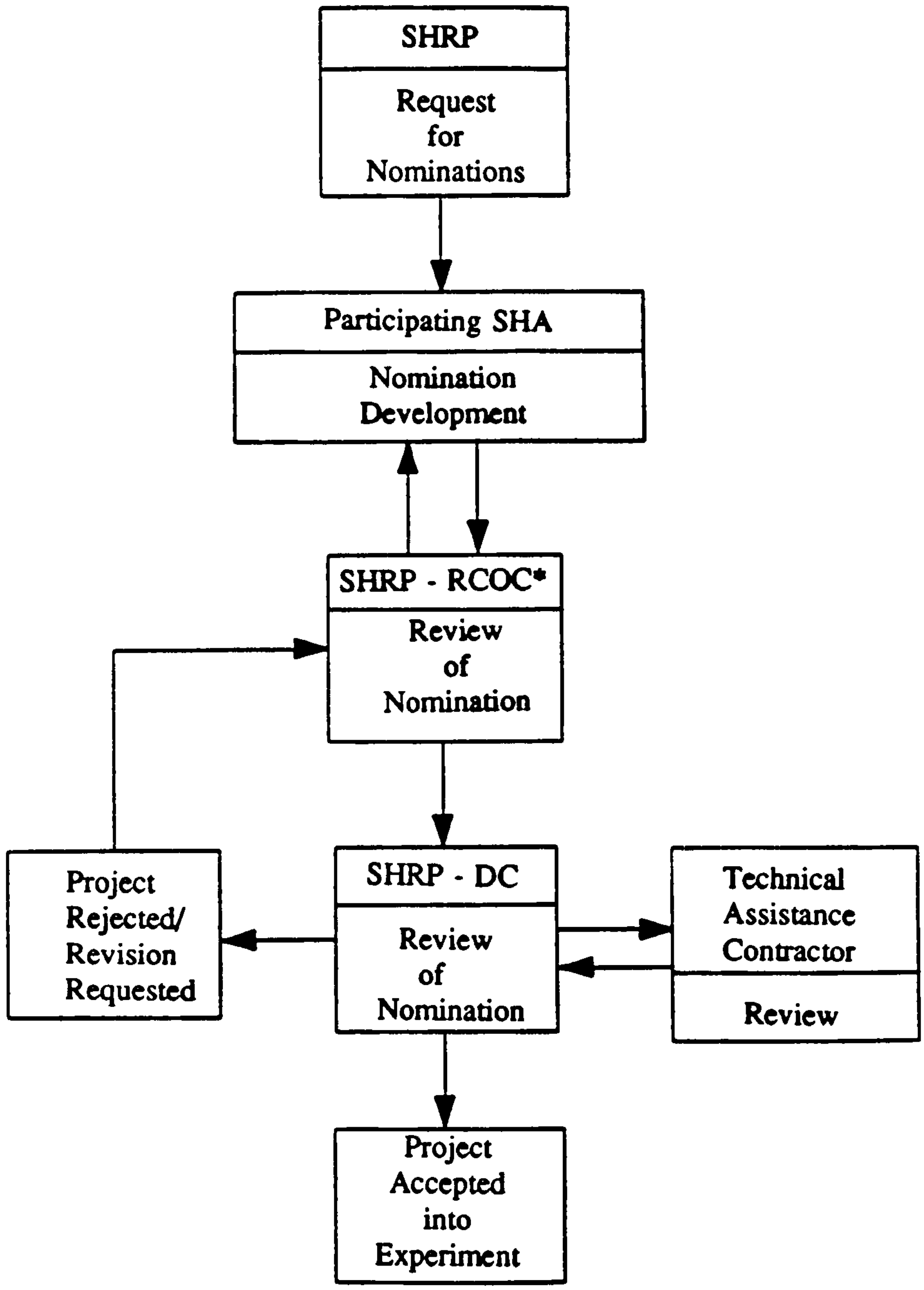
The experiments on pavement maintenance include 128 test sites. These include 81 sites of flexible pavement maintenance and 47 sites of rigid pavement maintenance. Thus, the entire SPS program (SPS-1 through SPS-8) includes 234 test sites distributed throughout the United States and Canada.

Project Recruitment and Approval Process

A systematic procedure was followed in selecting the test sites for the experiments on structural factors, rehabilitation, environmental effects, and asphalt-aggregate mixture specifications. This procedure involved a request for nomination of test sites, evaluation of candidate projects, and approval of selected test sites. Figure 3.6 illustrates this process.

Table 3.9. Number of Test Sites Required in Each Climatic Region.

Experiment	Wet Freeze	Dry Freeze	Wet Nonfreeze	Dry Nonfreeze	Total
SPS-1	4	4	4	4	16
SPS-2	4	4	4	4	16
SPS-5	4	4	4	4	16
SPS-6	8	4	8	2	22
SPS-7	3	3	3	3	12
SPS-8	3 to 6	3 to 6	3 to 6	3 to 6	12 to 24
Total	26 to 26	22 to 25	26 to 29	20 to 23	94 to 106



* RCOC = Regional Coordination Office Contractor

Figure 3.6. Project Recruitment and Approval Process

Project Solicitation and Nomination

Guidelines for nomination and evaluation of candidate projects were developed for each experiment to assist the SHAs in nominating test sites for the SPS experiments. These guidelines outlined project selection criteria and participation requirements and included project nomination forms and instructions. The project selection criteria detailed the specific requirements for the test site and its desired characteristics. Participation requirements outlined the responsibilities of the participating SHA concerning construction, testing, monitoring, and other related activities. The nomination forms were completed by the participating SHA to provide detailed information on the proposed project to help assess its suitability for the experiment.

An SHA desiring to participate in SPS completed the nomination forms for the experiment in which participation was sought. A sample of these nomination forms, for the SPS-1 experiment on structural factors for flexible pavements, is shown in Figure 3.7. These forms provide information on project location, traffic rate, project layout and geometry, and SHA construction plans. In addition, these forms provide information on anticipated contract and construction schedule as well as the SHA's deadline for SHRP's decision concerning the approval of the proposed test site.

The nomination forms were generally submitted to the appropriate SHRP regional office. Based on a review of the nomination form, the regional staff determined the suitability of the proposed test site for the intended experiment. If the proposed project was deemed a potential candidate for the study, a project verification followed. Otherwise, the participating SHA was notified of the unsuitability of the nominated project for inclusion in the study.

Project Verification (3.19)

Project verification consisted of two parts: a project record review, conducted in the participating SHA office, and a field site visit. These two verification steps were performed by the Regional Coordination Office Contractor's (RCOC) staff together with representatives from the participating SHA office and, when possible, the SHRP Regional Engineer.

The project record review allowed the RCOC staff to become familiar with the project prior to the site visit and thus expedite the field verification process. During this review, the RCOC staff performed the following activities:

- Review of project records, including as-built plans, cross-sections, profiles, and specifications for maintenance and rehabilitation projects
- Review of available information on soil borings and materials along the project to evaluate subgrade uniformity at the test site
- Confirmation candidate project data by comparison of as-built plans and data furnished on the nomination forms

SHEET A. SPS-1 CANDIDATE PROJECT NOMINATION AND INFORMATION FORM

STATE ______________ SHRP SECTION NO ______________

GENERAL PROJECT INFORMATION

PROJECT LOCATION

ROUTE NUMBER ______________

ROUTE SIGNING [ ] Interstate [ ] State [ ] County

Other ____

PROJECT LOCATION Start Milepost ___________ End Milepost ___________

Start Station ___________ End Station ___________

DIRECTION OF TRAVEL [ ] North B. [ ] South B. [ ] West B. [ ] East B.

PROJECT LOCATION DESCRIPTION ____

____

____

COUNTY

HIGHWAY AGENCY DISTRICT NUMBER ______________

SHRP ENVIRONMENTAL ZONE ______________

[ ] WET FREEZE [ ] WET NONFREEZE [ ] DRY FREEZE [ ] DRY NONFREEZE

SIGNIFICANT DATES

LATEST DATE OF APPROVAL NOTIFICATION FROM SHRP ______________

CONTRACT LETTING DATA ______________

ESTIMATED CONSTRUCTION START DATE ______________

ESTIMATED DATE TEST SECTIONS OPENED TO TRAFFIC ______________

ESTIMATED CONSTRUCTION COMPLETION DATE ______________

PROJECT DESCRIPTION

PROJECT TYPE [ ] New Route [ ] Removal and Reconstruction [ ] Parallel Roadway

Other ____

____

____

FACILITY [ ] Divided [ ] Undivided NUMBER OF LANES (One Way) ______________

DESIGN TRAFFIC DATA

ANNUAL AVERAGE DAILY TRAFFIC (TWO DIRECTIONS) ______________

% HEAVY TRUCKS AND COMBINATIONS (OF AADT) ______________

ESTIMATED 18K ESAL APPLICATIONS IN DESIGN LANE ______________

TOTAL DESIGN 18K ESAL APPLICATIONS IN DESIGN LANE ______________

DESIGN PERIOD (Years) ______________

Figure 3.7. Sample SPS Nomination Form

SHEET B. SPS-1 CANDIDATE PROJECT NOMINATION AND INFORMATION FORM

STATE ______________ SHRP SECTION NO ______________

AGENCY'S PAVEMENT STRUCTURE DESIGN FOR SITE

LAYER[1] NO.	LAYER[2] DESCRIPTION CODE	MATERIAL TYPE[3] CLASS CODE	THICKNESS[4] (INCHES)	STRUCTURAL[5] COEFFICIENT
1	SUBGRADE (7)	__ __	__ __ __	________
2	__ __	__ __	__ __.__	0.__ __
3	__ __	__ __	__ __.__	0.__ __
4	__ __	__ __	__ __.__	0.__ __
5	__ __	__ __	__ __.__	0.__ __
6	__ __	__ __	__ __.__	0.__ __
7	__ __	__ __	__ __.__	0.__ __
8	__ __	__ __	__ __.__	0.__ __
9	__ __	__ __	__ __.__	0.__ __

STRUCTURAL DESIGN METHOD [ ] 1972 AASHTO [ ] 1986 AASHTO [ ] MODIFIED AASHTO

Other ________________________________

AASHTO DESIGN RELIABILITY FACTORS R% ______________ S_o ______________

OUTSIDE SHOULDER TYPE

[ ] Turf [ ] Granular [ ] Asphalt Concrete [ ] Surface Treatment

[ ] PCC [ ] Curb and Gutter Other ______________

OUTSIDE SHOULDER TYPE (Feet) ______________

SUBSURFACE EDGE DRAINS [ ] Yes [ ] No

NOTES

1. Layer 1 is the natural occurring subgrade soil. The pavement surface will have the largest assigned layer number.
2. Layer description codes;
   Surface Layer ....03 Base Layer .... 05 Subgrade 07
   Subsurface HMAC ..04 Subbase Layer .... 06 Embankment (Fill) 11
3. Refer to Table 1 through 4 for material class codes.
4. If subgrade depth to a rigid layer is known, enter this depth for subgrade thickness, otherwise leave subgrade layer thickness blank.
5. Enter AASHTO structural layer coefficient value, as appropriately modified, used in pavement design or typical coefficient used by agency for this material. For the subgrade, enter either AASHTO soil support value or resilient modules value (psi) used in design.

Figure 3.7. (Continued)

SHEET C. SPS-1 CANDIDATE PROJECT NOMINATION AND INFORMATION FORM

STATE ______________ SHRP SECTION NO ______________

TEST SECTION LAYOUT

NUMBER OF TEST SECTIONS ENTIRELY ON: FILL ____________ CUT ____________
SHORTEST TRANSITION BETWEEN CONSECUTIVE TEST SECTIONS (Feet) ____________
VERTICAL GRADE (Avg %) (+ upgrade; - downgrade) ____________
HORIZONTAL CURVATURE (Degree) [ ] Tangent ____________°
COMMENTS ON DEVIATIONS FROM DESIRED SITE LOCATION CRITERIA ____________

OTHER SHRP TEST SECTIONS

DOES AGENCY DESIGN CONFORM TO GPS-1 OR GPS-2 PROJECT CRITERIA? [ ] Yes [ ] No
DISTANCE TO NEAREST GPS TEST SECTION ON SAME ROUTE (Miles) ____________
TEST SECTION NUMBER OF NEAREST GPS SECTION ____________

SUPPLEMENTAL TEST SECTIONS

IF SUPPLEMENTAL EXPERIMENTAL TEST SECTIONS ARE PROPOSED, COMPLETE THE FOLLOWING
TOTAL NUMBER OF SUPPLEMENTAL TEST SECTIONS ____________
FACTORS TO BE INVESTIGATES ____________

Figure 3.7 (Continued)

- Identification of potential test section locations within the project by inspection of geometric, drainage, and other relevant factors

- Review of traffic and safety considerations

- Review of photologs or other site-specific data, if available, to help identify suitable test section locations

- Identification of any planned maintenance, rehabilitation, or other construction that might affect the suitability of the project for inclusion in the study

- Review of available information on traffic rates and patterns to confirm suitability of the test site for the intended experiment

Also during the office review, the potential locations of the test sections at the site were identified. The suitability of these locations was then confirmed during the field visit.

During the field visit, the actual test sections were located after a review of the potential locations identified as part of the project record review. For rehabilitation experiments, a survey of pavement condition and distress was made to assess the uniformity and similarity of these test sections. Also during the field visit, the previously identified locations of the subsurface structures and intersections were confirmed.

Project Approval

Following the office record review and the field verification visit, the SHRP regional office staff furnished SHRP headquarters with copies of project plans, cross-sections, profiles, and other details indicating the proposed locations of the test sections. SHRP staff, in consultation with the LTPP technical assistance contractor's staff, reviewed the furnished details to assess the suitability of the proposed test site for inclusion in the experiment. In this assessment, consideration was given to factors that could affect the usefulness of the test site in achieving the experiment's objectives. These include

- Suitability of the project to accommodate all of the test sections
- Traffic rate and possible change in traffic flow along the test site
- Subgrade material and variation along the test site
- Alignment and geometry of test sections
- Locations of culverts, pipes, and subsurface structures within the limits of test sections
- For rehabilitation projects, variation in pavement condition and distress along the test site
- For rehabilitation projects, structural design of the existing pavement and whether it is over- or underdesigned for the prevailing traffic levels

Based on the results of this evaluation, the proposed project was assessed and classified in one of three categories: approved, tentatively approved, or unacceptable. Projects classified as "approved" met all of the requirements stipulated for the experiment or require minor modifications. Projects classified as "tentatively approved" met the essential requirements for the experiment, but required some adjustments to conform to other criteria. Projects classified as "unacceptable" did not meet the essential requirements for the experiment.

Following this review, SHRP headquarters informed the SHRP regional office of the review findings and the decision concerning the approval of the proposed project. Because the experiments on structural factors for flexible and rigid pavements (SPS-1 and SPS-2) required the construction of 12 of the 24 possible test sections at each site, the approval of test sites for these experiments identified the specific experimental set that had to be constructed at the evaluated test site. The SHRP regional office then notified the nominating SHA of the results of the review and approval process. For projects classified as "tentatively approved," the regional office coordinated with the nominating SHA to revise test site locations and/or details to conform to the experiment requirements. The revised plans were then submitted to SHRP headquarters for review and final approval.

Following the approval of a test for inclusion in SPS, the RCOC staff, together with the SHRP Regional Engineer, coordinated with the participating SHA in the completion of the different activities required for project implementation. This ensured that the test site was constructed in accordance with the guidelines stipulated for the experiment and thus would provide the information needed to achieve the objectives of the experiment.

Construction Guidelines

Construction guidelines were developed in cooperation with SHAs and the Federal Highway Administration to ensure practical and implementable procedures for constructing the test sections. The construction guidelines addressed items that should be considered by the participating SHAs when preparing plans, technical provisions, bid documents, and other related information to ensure adherence to the study requirements. Specifically, the guidelines addressed the following items:

- The experimental levels that must be included in the test site
- The primary construction features and details that must be incorporated in the test sections
- Specifications for the construction materials and details required for the test sections
- Typical cross-sections and details for the different test sections
- Construction operations and as-built requirements
- Special considerations and limitations that should be observed

The final construction guidelines for each experiment were distributed to all SHAs. In addition, SHRP, the technical assistance contractors, and the RCOCs provided clarification of items included in the guidelines when requested by a participating SHA.

Status as of May 1992

As of May 6, 1992, a total of 205 test sites have been identified in SHRP-LTPP for the SPS test sites (Table 3.10). Of these, 127 test sites have been constructed and 48 have been nominated and/or approved. In addition, nominations for 35 test sites were anticipated. If all potential candidate test sites are nominated and approved, 40 test sites will still be needed to complete the experiments on structural factors (SPS-1 and SPS-2), on rehabilitation (SPS-5, SPS-6, and SPS-7), and on environmental effects (SPS-8). No additional sites are being sought for the experiment on maintenance treatment of flexible and rigid pavements (SPS-3 and SPS-4).

Table 3.10. Distribution of Approved SHRP SPS Sections

Experiment	Constructed	Nominated/Approved	Potential	Total
SPS-1: Structural Factors for Flexible Pavements	-	7	10	17
SPS-2: Structural Factors for Rigid Pavements	-	6	8	14
SPS-3: Preventive Maintenance of Flexible Pavements	81	-	-	81
SPS-4: Preventive Maintenance of Rigid Pavements	28	19	-	47
SPS-5: Rehabilitation of AC Pavements	10	4	2	16
SPS-6: Rehabilitation of Jointed PCC Pavements	5	7	2	14
SPS-7: Bonded Concrete Overlays of Concrete Pavements	3	1	1	5
SPS-8: Environmental Effects	-	3	10	13
Total	127	47	33	207

References

3.1 *Strategic Highway Research Program Research Plans, Final Report.* Transportation Research Board, National Research Council, Washington, D.C., May 1986.

3.2 Strategic Highway Research Program. "Development of Specific Pavement Studies." Washington, D.C., September 1988.

3.3 High, R. "Strategic Pavement Design Initiatives for SPS-1 and SPS-2." (TRDF Technical Memorandum AU-35). Texas Research and Development Foundation, Austin, Texas, February 1989.

3.4 Anderson, V. and R. High. "Value of Fractional Factorials for SPS-1 and SPS-2 Experimental Designs." (TRDF Technical Memorandum AU-56). Texas Research and Development Foundation, Austin, Texas, March 1989.

3.5 Strategic Highway Research Program. "Specific Pavement Studies. Experimental Design and Research Plan for Experiment SPS-1: Strategic Study of Structural Factors for Flexible Pavements." Washington, D.C., February 1990.

3.6 Strategic Highway Research Program. "Specific Pavement Studies. Experimental Design and Research Plan for Experiment SPS-2: Strategic Study of Structural Factors for Rigid Pavements." Washington, D.C., April 1990.

3.7 High, R. "SPS-2 Experimental Design Development" (TRDF Technical Memorandum AU-90). Texas Research and Development Foundation, Austin, Texas, May 1990.

3.8 Anderson, V. "Crucial Analyses for SPS-1" (TRDF Technical Memorandum AU-162). Texas Research and Development Foundation, Austin, Texas, September 1990.

3.9 Anderson, V. "Recommendations" (Addendum to TRDF Technical Memorandum AU-162). Texas Research and Development Foundation, Austin, Texas, October 25, 1990.

3.10 Hudson, W.R. and P. Irick. "Draft Report on Further Development of SPS-6" (TRDF Technical Memorandum AU-45). Texas Research and Development Foundation, Austin, Texas, January 24, 1989.

3.11 Strategic Highway Research Program. "Specific Pavement Studies Guidelines for Nomination and Evaluation of Candidate Projects for Experiment SPS-6: Rehabilitation of JPCC Pavements." Washington, D.C., November 1989.

3.12 Strategic Highway Research Program. "Specific Pavement Studies Guidelines for Nomination and Evaluation of Candidate Projects for Experiment SPS-7: Bonded PCC Overlays." Washington, D.C., June 1990.

3.13 Anderson, V. "Error Variation for GPS and SPS." (TRDF Technical Memorandum AU-171). Texas Research and Development Foundation, Austin, Texas, November 25, 1990.

3.14 Strategic Highway Research Program. "Specific Pavement Studies. Experimental Design and Participation Requirements." (SHRP Operational Memorandum SHRP-LTPP-OM-005R), Washington, D.C., July 1990.

3.15 Strategic Highway Research Program. "Specific Pavement Studies. Experimental Design and Research Plan for SPS-5: Rehabilitation of Asphalt Concrete Pavements." Washington, D.C., November 1989.

3.16 Strategic Highway Research Program. "Specific Pavement Studies. Experimental Design and Research Plan for SPS-6: Rehabilitation of Jointed Portland Cement Concrete Pavements." Washington, D.C., November 1987.

3.17 Strategic Highway Research Program. "Specific Pavement Studies. Experimental Design and Research Plan for SPS-7: Bonded Portland Cement Concrete Overlays." Washington, D.C., February 1990.

3.19 Hanna, A. N., and S. D. Tayabji. *The Specific Pavement Studies: A Status Report* (SHRP-LTPP Report 5). Washington, D.C., October 1993.

Section 4
Pavement Materials Characterization

Introduction

Background

The Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) program was structured to include General Pavement Studies (GPS) of existing pavement sections and Specific Pavement Studies (SPS) of new or rehabilitated pavement sections (**4.1, 4.2**). The basic parameters and variables used in the selection process for the GPS and SPS studies included climate, traffic, pavement age, and subgrade type. In the SHRP-LTPP program, many basic materials properties (i.e., resilient modulus) were considered essential data requirements. Therefore, all GPS and SPS sites were subjected to detailed materials characterization evaluations. The *SHRP-LTPP Pavement Materials Characterization: Five-Year Report* (**4.3**) should be consulted if the reader desires additional information concerning this facet of LTPP.

Characterization of materials properties and knowledge of the variations in these properties between and within test sections are required to evaluate causes of performance differences between test sections and to provide a basis for improving/defining models for use in pavement design methods. Materials characterization includes parameters used in current pavement design models and mechanistic analysis models, as well as the engineering properties generally required to assess the characteristics and behavior of materials.

During SHRP-LTPP it was necessary, indeed critical, to have site-specific materials information. GPS and SPS pavement performance depend on many interrelated factors, not the least of which is the thickness and quality of the materials constituting the pavements at the monitored sites. SHRP sought to acquire samples for materials characterization and provide site-specific, detailed, and accurate information regarding thickness, quality, strength, modulus, and other attributes of the pavement layers from the GPS and SPS sites. SHRP, therefore, set out to develop a two-tiered materials characterization program consisting of field materials sampling and laboratory materials testing. This information is imperative in subsequent verification of project experiment cells and other detailed data analysis functions (**4.4**).

Field Materials Sampling and Testing

As part of the overall SHRP-LTPP objectives, the field materials sampling and field testing portion of this study provided important information to the National Pavement Performance Database (NPPDB). A primary source of the information to be included in the NPPDB was the field data collected on the GPS in-service pavements and the SPS test sections built and instrumented for more intensive evaluation of selected factors. The SHRP field materials sampling and field testing program encompasses all fifty U.S. states, ten Canadian provinces, and Puerto Rico.

GPS Field Materials Sampling and Field Testing

The GPS field sampling program contained 777 test sections located throughout the North American continent. Each of these sections was drilled and sampled to obtain in situ information and testable core specimens. This program was conducted in strict conformance to a SHRP-prepared drilling and sampling guide (**4.5**).

The SHRP GPS drilling and sampling operations were conducted in the vicinity of the test section <u>but not within</u> the test section. This approach was adopted because samples retrieved from within the test sections could have induced abnormal distress manifesting over time with cracking emanating from the core locations within the test section. The patched core holes and abnormal distress development could have resulted in spurious measurements from monitoring devices such as falling weight deflectometers (FWDs) and profilometers (**4.4**).

Organizational Structure

A number of agencies were involved in the LTPP GPS operations (Figure 4.1). Efficient and timely conduct of field materials sampling and field testing activities required a clear understanding of the administrative, supervisory, and operational responsibilities of the various agency personnel.

The SHRP Regional Engineer was responsible for administration and management of all SHRP contracts in the region, including the contract for drilling and sampling. The SHRP Regional Engineer also provided coordination between the various regional contractors and state highway agencies (SHAs) and resolved questions and concerns that arose during the day-to-day operations of the field sampling and testing program.

The SHRP Regional Engineer also was responsible for supervision and approval of the SHRP Regional Coordination Office Contractor (RCOC) staff. The RCOC staff provided coordination between the activities of all contractors in their respective regions.

The RCOC designated a drilling supervisor (SHRP Authorized Representative) to provide primary on-site supervision during the drilling and sampling operations. The SHRP Authorized Representative was responsible for the direction of field operations and worked

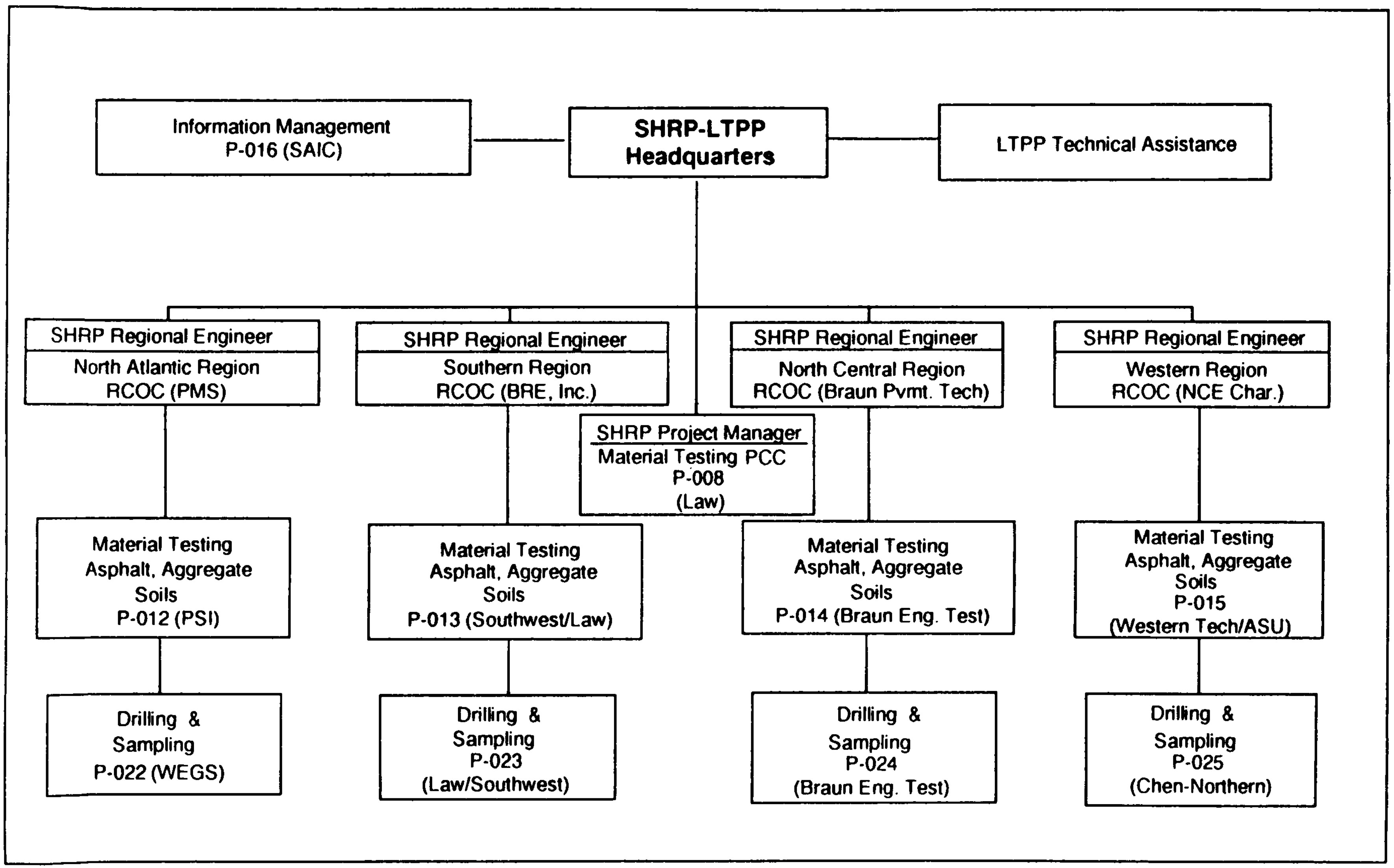


Figure 4.1. Agencies Involved in LTPP GPS Field Drilling and Sampling Operations

with the drilling and sampling contractor to ensure effective, efficient, and safe operations at the work site. The SHRP Authorized Representative performed all day-to-day coordination between SHRP central staff, the SHRP Regional Engineer, the RCOC, the field materials sampling contractor, and the laboratory materials testing contractor.

Field Materials Sampling Guide

A critical element of the drilling and sampling program was the development and evolution of the "SHRP-LTPP Guide for Field Materials Sampling, Handling, and Testing" (**4.5**). The outline for later revisions of the Field Guide was begun in October 1987 with the issuance of the "Materials Sampling and Testing Guide for Long-Term Pavement Performance Studies" (**4.6**). Subsequent to this guide, a field sampling guide designated SHRP Operational Guide OG-006 (**4.5**) was developed that identified the requirements of the GPS sampling operations and provided explicit directions to the drilling and sampling contractors, SHRP Authorized Representatives, and RCOCs. The primary objective of the LTPP field materials sampling guide was to achieve consistency and high quality in the field activities of the regional drilling and sampling contractors.

Conduct of Field Materials Sampling

Each SHRP region conducted its field drilling and sampling operations under different schedules and with different drilling and sampling contractors. However, adherence to the guidelines defined in the "SHRP-LTPP Guide for Field Materials Sampling, Handling, and Testing" (**4.5**) ensured that the quality of specimens and field testing remained consistent and that similar results were obtained. The number of test sections to be sampled ranged from approximately 135 in the North Atlantic region to 260 in the Southern region. The Western and North Central regions drilled and sampled approximately 180 and 200 test sections, respectively. Figure 4.2 shows the approximate locations of the SHRP test sections. These test sections were located throughout the continental United States, Canada, Alaska, Hawaii, and Puerto Rico.

Typical layouts for materials sampling points and field testing points are shown in Figures 4.3 and 4.4. More detailed sampling and testing plans for each type of test section are shown in Appendix B of the "SHRP-LTPP Guide for Field Materials Sampling, Handling, and Testing" (**4.5**).

Coring of asphalt concrete (AC) and portland cement concrete (PCC) was conducted using 4, 6, and 12 in. diamond drill bits with water as a coolant. Special care was taken to ensure minimum use of water so as not to contaminate lower unbound layers of the pavement structure during this operation. Coring was often performed with a truck-mounted drill rig or a tractor-mounted drill rig for smaller diameter core holes. Prior to extraction from the pavement, all cores were marked with an arrow to indicate the direction of traffic. This arrow was subsequently used in the laboratory to align the cores for certain

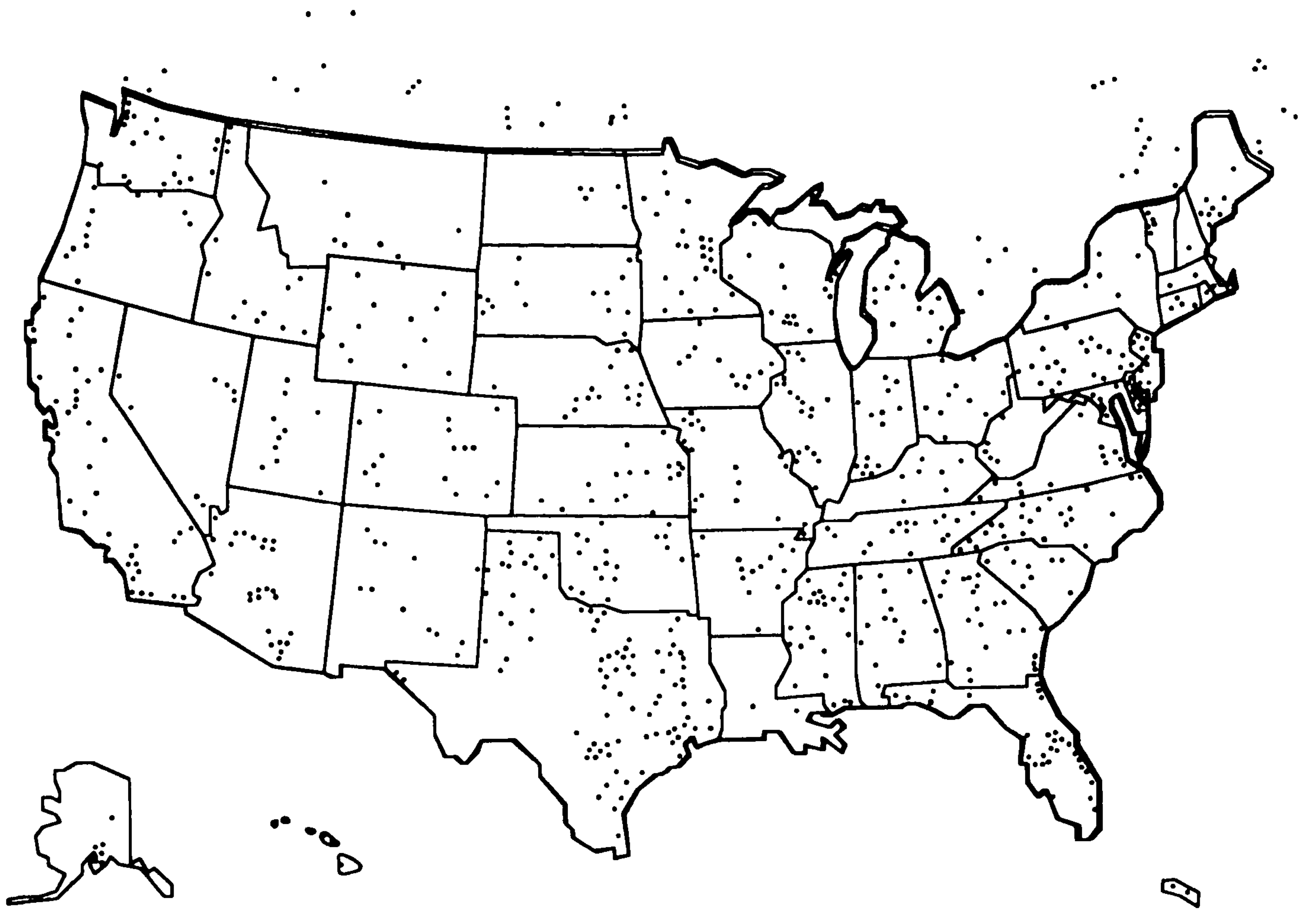


Figure 4.2. Locations of Approved GPS Sites

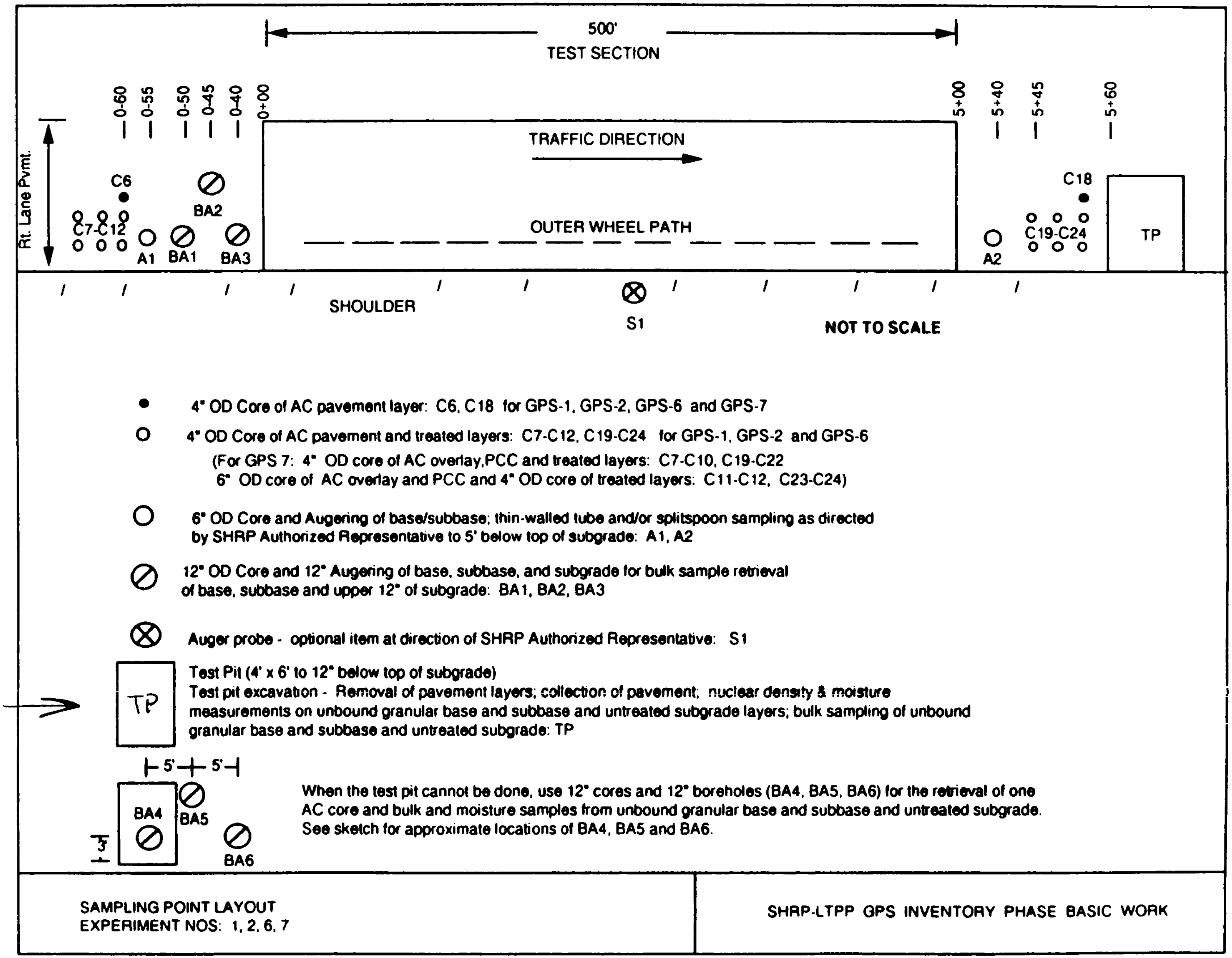


Figure 4.3. Typical Sampling Point Locations for GPS-1, GPS-2, GPS-6, and GPS-7 (Flexible) Pavements

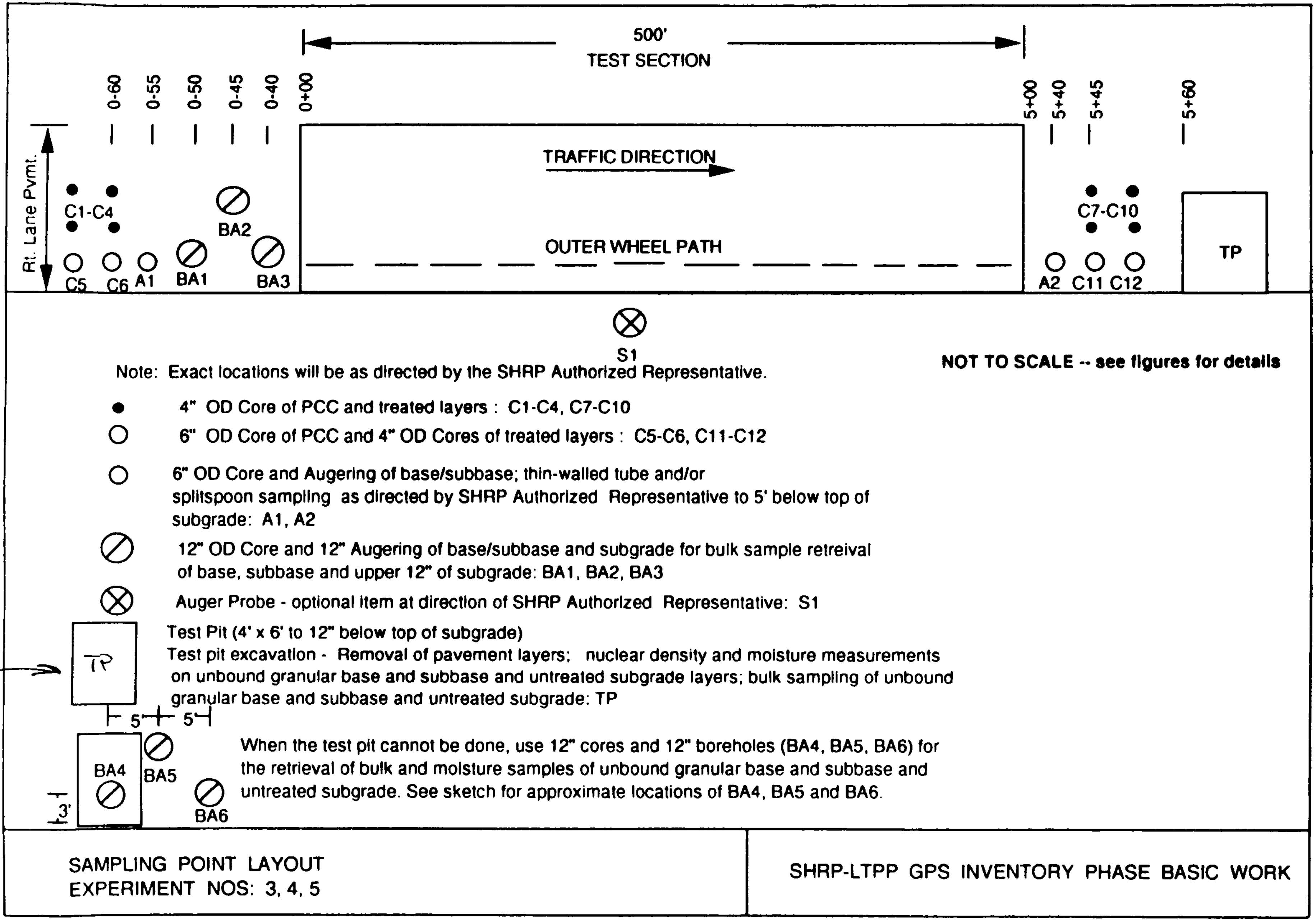


Figure 4.4. Typical Sampling Point Locations for GPS-3, GPS-4, GPS-5, and GPS-9 (Rigid) Pavements

test procedures. Layer thicknesses and the condition of extracted cores were recorded on the appropriate data sheet.

After removal of the bound layers for the 6 in. and 12 in. diameter core holes, the remaining layers were augered. This activity was conducted using American Association of State Highway and Transportation Officials standards, AASHTO T203-82(86), "Soil Investigation and Sampling by Auger Borings," and AASHTO M146-70(80), "Terms Relating to Subgrade Soil-Aggregate and Fill Materials."

Undisturbed samples of the natural subgrade or fill material were obtained to a depth of 4 ft. below the top of the subgrade, using (if appropriate) thin-walled shelby tube sampling.

When thin-wall shelby tubes were not appropriate due to soil conditions, splitspoon samples were recovered. Blow counts were recorded, and splitspoon samples were opened, examined, and logged as to the length of recovery and description of the soil.

The inclusion of a test pit in the field drilling and sampling plan provided the best opportunity to obtain site-specific data and information that was not available from any other source. The SHRP drilling and sampling contractors used an excavation machine (usually a backhoe), a pneumatic pavement breaker, a chisel, and a dump truck to perform the test pit excavations.

The pavement was sawn, along with treated layers if present, to the specified overall dimensions. These pavement components were cut into smaller pieces as necessary for removal. One 12 in. by 12 in. sample of an AC pavement surface was recovered intact for packaging and shipment to the laboratory. No samples of PCC pavement surface or treated layers were retained, except for when cores of such layers suitable for testing were not obtained elsewhere from the test section.

After removal of the surface and treated layers, the untreated layers (including the subgrade) were tested using the nuclear density gauge. Bulk samples of all unbound layers were obtained. Excavations of the subgrade continued to 12 in. below the top of the subgrade. Also, one 12 in. by 12 in. sample of AC pavement was recovered and retained for shipment to the laboratory.

Upon completion of test pit operations, the test pit was restored to as near original condition as possible by SHA personnel and/or drilling and sampling contractor personnel. Test pits for asphalt sections and non-continuously reinforced concrete pavements were usually completed the same day as the drilling and sampling operations.

A shoulder auger probe was employed in the field drilling and sampling operations to determine whether bedrock or other significantly dense layers existed within 20 ft. of the pavement surface. Augering was performed with a 6 in., continuous flight, solid, helical auger by a drill rig mounted on the truck. Augering was performed to a depth of 20 ft. or refusal, whichever came first. In some cases, when refusal occurred prior to 20 ft., another probe was initiated at a nearby location to confirm that a hard layer was present. If refusal occurred at the second location, the auger probe activity was terminated and refusal was reported.

Sample Numbering, Packaging, and Shipment

After cleaning, drying, wrapping, and packaging, all samples were marked separately with a sample number prior to shipment to the laboratory. Every sample was identified in accordance with the directions in the drilling and sampling guide. Samples were shipped to the appropriate laboratory within 5 days of sampling using wooden boxes of standard construction.

Data Collection Guidelines

The primary objective of the drilling and sampling program was to provide a comprehensive evaluation of the pavement layer structure and layer thicknesses of the GPS pavement layer materials, as well as to provide high-quality samples/specimens for further laboratory materials characterization. To facilitate the collection of these data, standard data entry sheets and standard materials codes were developed to record all data collected in the field (**4.7**).

The guidelines for recording data collected from the field materials sampling program are contained in Appendix C of SHRP-LTPP-OG-006, "SHRP-LTPP Guide for Field Materials Sampling, Handling, and Testing" (May 1990). Data collection sheets were completed primarily by the drilling and sampling contractor's crew chief and were subsequently reviewed by the SHRP RCOC for completeness and accuracy prior to entry in the NPPDB.

Detailed descriptions of field materials sampling and field testing operations and data collection are available in Reference **4.5**. This document, along with the *IMS Researchers Guide* (**4.8**), should be used to comprehend fully the data collection activities for the field materials characterization program.

Quality Assurance/Quality Control in the Field

The field materials sampling and field testing work conducted for GPS was unprecedented in terms of geographic coverage, specificity of requirements, and magnitude of work. Throughout this effort, SHRP required consistent, high-quality field materials sampling and field testing from all drilling and sampling contractors. To achieve this goal, SHRP implemented uniform quality assurance (QA) and quality control (QC) procedures in each region (**4.9**).

The QA/QC procedures instituted requirements related to the quality of field materials sampling and field testing and were followed to an extent consistent with the production of an acceptable quality of coring, boring, augering, disturbed and undisturbed sampling, bulk sampling from the test pits, and in situ field testing. The first step in the QA/QC process was the adherence to the SHRP guidelines for field materials handling and testing (**4.5**).

SHRP RCOC personnel were responsible for checking the field data packets for completeness and reasonableness. This included checks of the documentation regarding sample receipt by the laboratories. These documents were cross-checked with the field shipping forms to ensure that the number, type, and condition of the specimens shipped from the field matched those that reached the laboratory. In addition, the RCOC personnel coordinated activities between the SHRP drilling and sampling contractor and the appropriate SHRP laboratory. All of these activities helped to avoid sampling error and added to the consistency and accuracy of the field sampling and testing data.

As part of the QA/QC process, the drilling and sampling contractor's equipment was adequately maintained and calibrated so that quality samples and test data could be obtained. A preventive maintenance program was implemented to reduce the downtime of the equipment on the project. Other equipment was inspected on a frequent basis to ensure efficient operation. Additionally, the SHRP Quality Assurance Consultant visited several drilling operations to ensure that appropriate QA/QC procedures were followed.

Periodically, nuclear moisture-density equipment was calibrated using standard materials of known density and moisture. A verification/calibration program was established to ensure the accuracy and consistency of the data obtained by these devices (**4.10**). This was essential because the in situ moisture and density data were collected by four different contractors using different nuclear equipment on different material types in four geographic regions. Materials of known density (traceable to the National Institute of Standards and Technology (NIST)) were used to verify that the device was recording measurements within an acceptable range of the known density and moisture. The nuclear density gauges were calibrated based on the results of this verification procedure.

Status of GPS Materials Sampling and Testing

All of the GPS sites that were scheduled for initial drilling and sampling were completed during SHRP-LTPP. Additional GPS sections that may be added as the program continues will have to be drilled and sampled, probably by SHA personnel according to SHRP guidelines. Drilling and sampling of GPS-6B (planned AC overlay of AC) and GPS-7B (planned AC overlay of PCC) test sections that have been overlaid after the initial round of drilling and sampling will have to be drilled and sampled to obtain the cores of the pavement overlay.

Most of the GPS drilling and sampling program has been completed, and a major effort is not expected in this portion of the materials characterization program for the remainder of the LTPP program.

SPS Field Materials Sampling and Field Testing

The SPS experiments were developed to investigate the performance of selected flexible and rigid pavement structures, maintenance treatments of flexible and rigid pavements, rehabilitation treatments for flexible and rigid pavements, environmental effects in the absence of heavy loads, and asphalt mix performance, generally within a factorial design that included different subgrade types and environmental conditions. The structural factors included surface layer and base layer thicknesses. Rehabilitation and maintenance treatments ranged from crack sealing and minor repair to extensive surface preparation followed by asphalt or concrete overlay.

The SPS experiments consist of individual sites composed of multiple test sections, with each site having similar details and materials according to the various experiment requirements. These sites are distributed among climatic regions as well as subgrade soil types. The experimental designs and construction considerations for the experiments are described in the experimental design and research plan documents published for each experiment (**4.11, 4.12, 4.13, 4.14, 4.15, 4.16**). Construction features and details of the experiments are described in the construction guidelines documents published for each experiment (**4.17, 4.18, 4.19, 4.20, 4.21, 4.22**).

Special Considerations for SPS Field Sampling and Field Testing

SPS experiments include both existing pavements and new construction. As a consequence, field sampling and testing plans must address the need to minimize destructive sampling and testing activities in both existing and finished pavements. Constraints on access caused by construction schedules must also be addressed. The GPS sampling and testing program sought to maximize the information obtained while limiting the number of destructive test locations near the test section to prevent influences on performance resulting from these activities. This same policy applied in SPS but is complicated by the number of sections at a site, the number of different pavement structures at a site after completion of the construction, and the desired objectives of sampling and testing during construction activities.

Experiments dealing with rehabilitation of existing pavements require the same type of sampling as in GPS. An adequate number of core locations, a test pit, and shoulder probes were distributed throughout the project site, based on the assumed subgrade variability. This is termed preconstruction sampling. Experiments involving new pavement construction required that a program of sampling and testing be conducted throughout the construction process. As layers were completed, sampling and testing were performed.

The materials sampling and testing plan had to be tailored to the specific features encountered on each project; therefore, the sampling and testing plan was site-specific. An example of materials sampling and testing procedures and a conceptual site plan for an SPS-8 project site (with flexible pavement sections) is presented in the *Pavement Materials Characterization: Five-Year Report* (**4.3**).

Field Materials Sampling and Testing Guidelines

Field materials sampling and testing guidelines have been published by SHRP for the SPS-1, -2, -5, -6, -7, and -8 experiments (**4.23, 4.24, 4.25, 4.26, 4.27, 4.28**). These documents combine the sampling plans and instructions with the laboratory testing requirements for each experiment. The sampling procedures are based on the "SHRP-LTPP Guide for Field Materials Sampling, Handling, and Testing" (**4.5**).

Data Collection Guidelines for SPS Field Materials Sampling

Data elements obtained as part of the field materials sampling and testing activities for SPS experiments are classified into the following groups:

- Test Section Location Reference Table
- Construction Data
- Field Materials Sampling and Testing Data
- Laboratory Materials Testing Data

The data collection and reporting process for SPS test sites required the completion of specific data sheets from the "Data Collection Guide for LTPP Studies" (**4.7**) developed for GPS and additional data sheets developed specifically for SPS. The SPS project-specific data sheets address construction data and other aspects of the materials sampling and testing activities. Data collection guideline documents have been published for SPS-1, -2, -5, -6, -7, and -8 (**4.29, 4.30, 4.31, 4.32, 4.33, 4.34**).

Conduct of Field Materials Sampling

The field materials sampling and field testing activities provided pavement material samples for laboratory testing and yielded in-situ moisture and density data for each test site, density data for new AC, and measurements of air content of fresh concrete, depth to rigid layer, and modulus of subgrade reaction. Field sampling and field testing operations were performed during the different phases of pavement construction to fully characterize the pavement structure in each test section. This information was used in evaluating the service life and long-term performance of the different pavement structures and design procedures used in the various experiments.

SPS-3 and SPS-4 Field Sampling and Field Testing Plans

The purpose of the SPS-3 and SPS-4 studies was to develop a database that will permit increased understanding of selected maintenance treatments in extending pavement service life or reducing the evidence of pavement distress. This included an evaluation of the effectiveness of the pavement maintenance treatments and establishment of a study methodology that can be followed by SHAs to evaluate other maintenance treatments.

The study includes six specific preventive treatments:

- Chip seals, thin overlays, slurry seals, and crack sealing for flexible pavements
- Undersealing and joint and crack sealing for rigid pavements

The study of the treatments applied to flexible pavements was designated SPS-3, and the study of the treatments applied to rigid pavements was designated SPS-4.

Field Sampling, Testing, and Data Collection

There were four phases of field data sampling, testing, and data collection in addition to the standard condition monitoring. In the first phase, the initial conditions prior to treatment application were defined. This was part of the site verification process. In the second, the materials to be used in the treatments were sampled. In the third, information was collected during the treatment application to determine the quality of the treatment process, including the materials being used at each site. In the fourth, tests determined how the pavements change over time after treatment application.

SPS-3 Construction Monitoring, Sampling, and Field Tests

The RCOC collected the samples of the materials during construction. These samples were then marked, packaged, and shipped to the regional testing lab in accordance with the SHRP-LTPP field materials sampling and field testing guide (4.5). The samples were identified with the section identification number from which they were taken. When samples were taken other than in a section, they were identified with the section number of the next section to which they were to be applied.

The RCOC was responsible for monitoring the application process and for conducting several checks, including equipment calibration checks, temperature checks, distance measurements, area measurements, and similar checks.

The physical measurements for crack sealing included the temperature of the air, temperature of the sealant, and width of cracks and sealant. Relative humidity was based on local weather information. Temperature of the sealant was based on the temperature gauge on the sealant heating equipment.

The physical measurements for slurry seals included moisture content of the aggregate, ambient temperature, and relative humidity. Relative humidity was based on local weather information. The application rate measurement was based on the equipment readings, which varied with the type of machine.

The physical measurements for chip seals included moisture content of the aggregate, ambient temperature, and relative humidity. Relative humidity was based on local weather information. The emulsion application rate was based on measurements of the emulsified asphalt quantity in the distributor.

All data were recorded on the data collection sheets described below. All data were then entered into the NPPDB by RCOC personnel.

SPS-3 Materials Sampling After Construction

The final materials sampling will occur approximately 2 years after construction and will be repeated biennially until the section is removed from the study. A single asphalt core will be obtained from each site. The hole will then be filled in accordance with SHA requirements. The cores will be marked, wrapped, packaged, and shipped in accordance with the SHRP-LTPP field materials sampling guide requirements.

SPS-4 Materials Sampling Prior to Construction

Assurance coring was included in the site verification process. Construction records were also reviewed to ensure that there was no change in surface thickness. At least one 6 in. diameter core was obtained from the paved shoulder adjacent to each test section and extended to the subgrade. Each layer material, thickness, and subgrade type was identified. No laboratory testing of cores or materials obtained during verification sampling was conducted.

A distress survey was conducted within 90 days prior to application of the treatments. This and subsequent distress surveys were to include a measurement of faulting and edge dropoff. FWD deflection and roughness testing was also conducted on all SPS-4 sections prior to treatment applications and biennially thereafter. Standard loss-of-support testing for underseal sections was conducted using the benkelman beam (Field Protocol H32F) to determine which joints and cracks to underseal.

SPS-4 Materials Acceptance Sampling

Joint and crack sealant material samples were conducted in accordance with ASTM D 3405. Joint and crack sealant material samples were obtained, marked, packaged, and shipped in accordance with the SHRP-LTPP field materials sampling and field testing guide (4,5). Sample material was identified with the section identification number when section identification numbers were required.

SPS-4 Construction Monitoring Sampling and Field Tests

The monitoring QA/QC program included initial deflection tests, stability tests, equipment calibration, material volumes, locations, temperatures, and other similar tasks and measurements.

Specific data required for joint and crack sealing activities included air temperature, relative humidity, temperature of the sealant, width of joint and cracks, depth of sealant below pavement surface, depth of backer rod, application pressure, and thickness of sealant. Relative humidity was based on local weather information. Temperature of the American Society for Testing and Materials (ASTM) D3405 sealant was based on the calibrated temperature gauge on the sealant heating equipment.

SPS-4 Special Testing After Construction

A distress survey will be conducted 6 months after application, 1 year after application, and on an annual basis thereafter. Initial and subsequent condition surveys are to include measurements of faulting and edge drop off. Deflection testing of the underseal section should include benkelman beam testing (Field Protocol H32F) in addition to FWD testing (Field Protocol H30F) using the SPS-4 testing plan for these devices.

Laboratory Materials Handling and Testing

Organizational Structure

A number of people were involved in the LTPP GPS laboratory materials operations (Figure 4.5). Efficient and timely conduct of the laboratory materials testing operation required a clear understanding of the administrative, supervisory, and operational responsibilities of the various personnel. The organizational structure is similar to that of the GPS field materials sampling and testing program.

The SHRP Regional Engineer was responsible for administration and management of all SHRP contracts within the region (including the contract for the laboratory materials testing) and provided coordination among the various regional contractors, SHAs, and technical assistance contractors. The SHRP Regional Engineer was also responsible for supervision and approval of the SHRP RCOC staff.

The SHRP Regional Engineer and the RCOC provided coordination between the regional laboratory materials testing contractor and the regional drilling and sampling contractor. The SHRP Regional Engineer and the designated RCOC staff worked with the regional laboratory materials testing contractor to assure effective, efficient, and safe operations in the materials laboratory at all times. The RCOC also worked jointly with the SHRP Regional Engineer to ensure data integrity and quality assurance throughout the laboratory testing program.

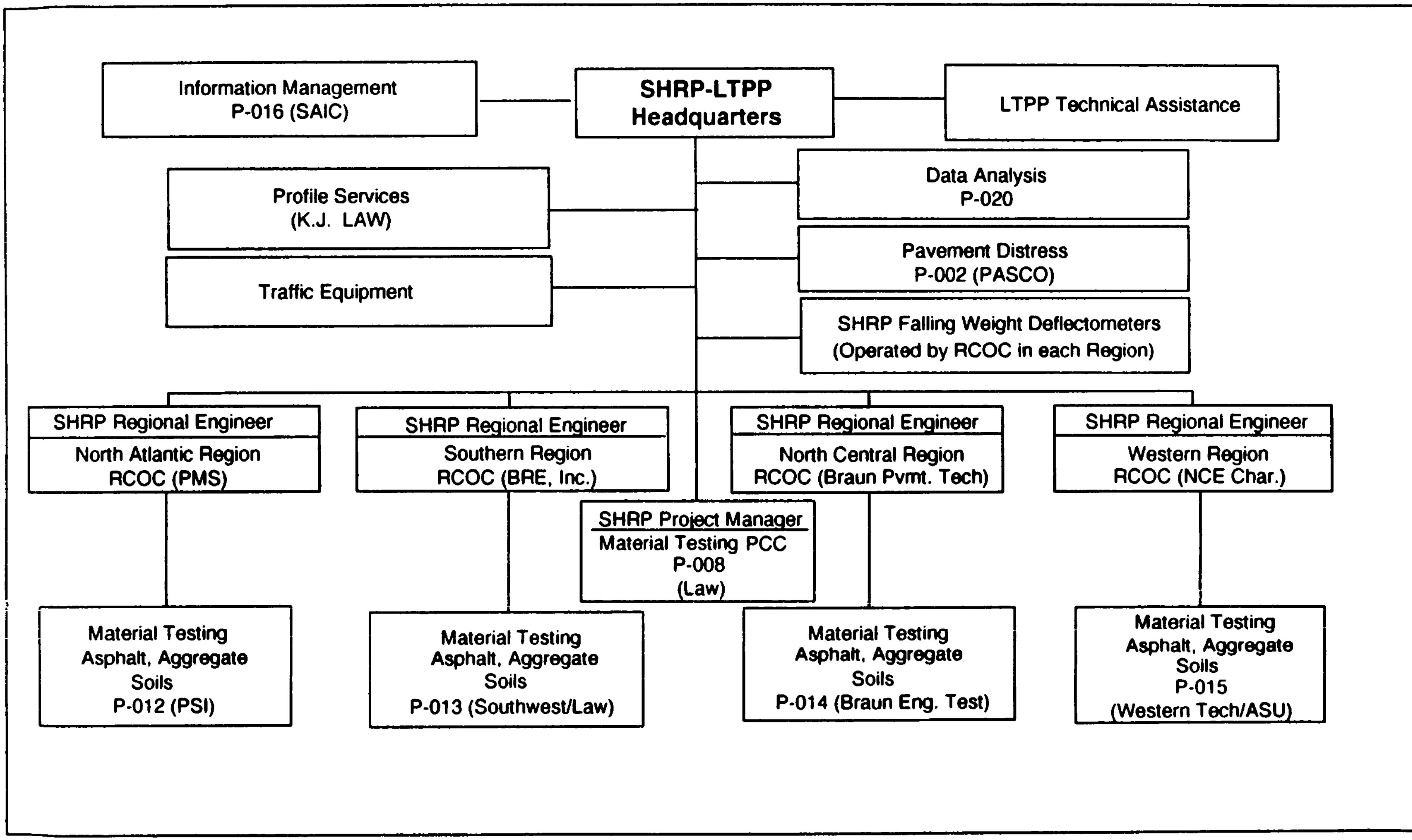


Figure 4.5. Agencies Involved in LTPP GPS Laboratory Operations

Laboratory Materials Testing Guide

SHRP developed a comprehensive, detailed guide for materials testing. The guide, entitled "SHRP-LTPP Interim Guide for Laboratory Materials Handling and Testing (PCC, Bituminous Materials, Aggregates, and Soils)" (**4.35**), was first issued in November 1989, revised in February 1991, and finalized in August 1992. The guide provides specific instructions regarding sample handling, storage, testing, reporting, and discarding. The 1,200-page guide is organized as follows:

Section 1	Introduction
Section 2	Field Sampling and Laboratory Testing Operations
Section 3	Lab Testing of Bituminous Materials, Aggregates, and Soils
Section 4	Lab Testing of Portland Cement Concrete
Section 5	Verification and Payment
Section 6	Laboratory Test Data Quality
Appendix A	Organizations and Personnel Contact Names
Appendix B.1	Lab Testing Program by GPS Experiment Type
Appendix B.2	Lab Testing Program by SPS Experiment Type
Appendix C.1	SHRP Standard Forms for GPS Laboratory Testing
Appendix C.2	SHRP Standard Forms for SPS-1, -2, -5, -6, -7, and -8 Laboratory Testing
Appendix C.3	SHRP Standard Forms for SPS-3 and SPS-4 Laboratory Testing
Appendix D	SHRP Terminology for Pavement Materials and Soils
Appendix E.1	SHRP Protocols for GPS Laboratory Testing
Appendix E.2	SHRP Protocols for SPS-1, -2, -5, -6, -7, and -8 Laboratory Testing
Appendix E.3	SHRP Protocols for SPS-3 and SPS-4 Laboratory Testing
Appendix F	GPS Field Sampling Plans
Appendix G	Laboratory Tracking Tables for the GPS Experiments

Each of these sections and appendices is necessary to understand and complete the laboratory materials testing operations.

One of the most important facets of the guide is the standardization of the procedures used to conduct each laboratory test. These protocols outline step-by-step instructions for each test procedure and include sections concerning sample handling, data reporting, and other information related to SHRP needs (e.g., sample identification and location). This type of standardization was of paramount importance in obtaining accurate, usable test data.

The guide was initially and primarily developed for the GPS testing program, and sections concerning the SPS materials testing program were added at a later date. However, the materials testing program for the SPS experiments uses the same principles as the GPS program, and the guide is very useful for SPS laboratory materials testing purposes.

Protocol Development

All of the protocols used in the GPS testing program were developed by an expert in the field of materials or by a group of experts for the more complicated test procedures (i.e., resilient modulus). Development began in late 1988 and continued throughout SHRP-LTPP. The bulk of the guide was completed in November 1989. After that time, SHRP instituted a series of Materials Directives that were used to update the testing protocols between revisions to the guide. Final development of all protocols was completed in October 1992 with the issuance of the latest version of the guide.

Future Use

The guide is an instrumental tool in the materials characterization testing program for the GPS and SPS experiments. In the future, this guide can be used by other organizations that wish to perform a similar laboratory testing program. Additionally, this guide will be used extensively in the SPS program for many years to come.

The guide was provided to SHRP Regional Engineers, RCOCs, the laboratory materials testing contractors, and others. In effect, the guide served as the control for the laboratory materials testing program. This guide is the definitive source of information on the methodology used by SHRP in conducting laboratory materials testing operations (**4.4**).

Conduct of Laboratory Materials Testing

Each SHRP region conducted its laboratory materials handling and testing operations under different schedules and with different contractors. However, due to the use of the "Guide for Laboratory Materials Handling and Testing," the quality of testing and specimen handling was consistent and provided similar results. Laboratory materials testing operations began in late 1989 and continued through the end of 1991. Currently, only the resilient modulus testing (Protocols P07, P33, and P46) remains to be completed for the GPS program. Approximately half of all GPS testing was completed in mid-1993. The remainder of the GPS testing will be completed in U.S. Department of Transportation Federal Highway Administration (FHWA) continuation of the LTPP program.

PCC Laboratory Material Testing

The National Laboratory PCC Testing Contractor worked under the supervision of the SHRP contract manager in Washington, D.C. This laboratory conducted the testing for all PCC pavement layers. All other cement-treated materials (including econocrete, lean concrete, cement-aggregate, etc.) were tested by the SHRP Regional Bituminous Laboratory.

Table 4.1 contains a list of the laboratory tests required on PCC pavement cores by the Laboratory PCC Testing Contractor.

Table 4.1. PCC Laboratory Tests Required for GPS Pavements

Tests Per PCC Layer	Protocols
PC01. Compressive Strength	P61
PC02. Splitting Tensile Strength	P62
PC04. Static Elastic Modulus	P64
PC06. Visual Examination and Thickness	P66

Bituminous, Treated, and Unbound Materials Testing

The remaining laboratory materials testing for the GPS program dealt with AC, extracted aggregate from the AC bound (stabilized) base, subbase, subgrade, and unbound granular base/subbase/subgrade materials.

To ensure consistency and QC in the laboratory materials testing process, each regional laboratory conformed to the set of SHRP laboratory testing protocols and all procedures in the laboratory testing guide (4.35). The regional laboratories were required to maintain close coordination with the SHRP Regional Engineers and RCOCs, starting when samples were received from the field and continuing until final disposal of the materials.

Pavement Layering

One of the more critical goals of the SHRP materials characterization program was the establishment of pavement structure layering for each test section. The pavement structure was preliminarily determined by the laboratory after the sample receipt process. Pavement structures, layer descriptions, and layer types were established early in the laboratory testing process and adjusted (if necessary) at the completion of the laboratory testing activities. After the completion of this process, the appropriate forms were submitted to the SHRP Regional Engineer for review and approval. After this step, the laboratory began testing the pavement materials. Figures 4.6 and 4.7 illustrate a typical pavement structure and testing program for flexible and rigid pavements, respectively.

General Laboratory Testing

The regional soils and bituminous laboratory materials testing contractors completed testing on the following materials:

1. AC (for each layer including hot-mix, hot-laid, and bituminous surface layers and other HMAC layers). These materials include AC mixtures and extracted aggregates.

2. Treated (bound or stabilized) materials (for each layer). These include asphalt-treated base (ATB) materials and other than asphalt-treated base (OTB) materials. OTB materials include cement-treated materials, econocrete, lean concrete, lime-treated materials and materials treated or stabilized with chemicals.

3. Unbound granular materials (for each layer). These include soil-aggregate mixtures and naturally occurring materials used in base or subbase layers.

4. Subgrade soils. These include all cohesive, non-cohesive, and granular soils present in the top 5 ft. of subgrade. Typically these are <u>untreated</u> soils.

Material Type and Code Based on Inventory Data	GPS-2 Selection Criteria	Example of LTPP Field Material Sample Data: Field Layer No.	Example of LTPP Field Material Sample Data: Material Code	Example of LTPP Laboratory Layering Information: Lab Layer No.	Example of LTPP Laboratory Layering Information: Material Code	Regional Laboratory Material Tests
Thin seal layer (71,72,73)	With or Without Seal Coat or Porous Friction Course	4	AC(700)	6 *	AC (700)	AC01, AC02, AC03, AC04, AC07, AG04
Dense-graded HMAC surface (01)	Dense-graded HMAC surface			5 *	AC (700)	AC01, AC02, AC03, AC04, AC07, AG04
Dense-graded HMAC (28)	None, one or more Dense-graded HMAC Layers			4 *	AC (700)	AC01, AC07
Bound Base (27 to 39, 42, 43, 44, 46)	Bound Base (Two or more lifts of same mixture considered as one layer)	3	Cement Aggregate Mixture (331)	3	Cement Treated Base (331)	TB01, TB02
Subbase (22 to 26, 42, or 43)	With or Without Subbase (Unbound or Treated)	2	Lime-Treated Soil (338)	2 **	Lime-Treated Subbase **(338)	TB01, TB02 **
Subgrade Soil (51 to 65)	+ Subgrade	1	Clay Subgrade (101)	1	Silty Clay (134)	SS01, SS02, SS03, SS04, SS05, SS07, SS09

NOTES: + A treated subgrade is considered a treated subbase layer.

* All specified asphaltic concrete tests to be done on cores from the top two maximum testable HMAC layers only. Only AC01 and AC07 tests to be done on other testable HMAC layers.

** Assign layer material code 321 and perform TB03 instead of TB02 test if this layer is asphalt treated layer.

Figure 4.6. Example of Laboratory Testing Plan for a Flexible GPS Test Section

Material Type and Code Based on Inventory Data	GPS-3, GPS-4, GPS-5 Selection Criteria	Example of LTPP Field Material Sample Data: Field Layer No.	Example of LTPP Field Material Sample Data: Material Code	Example of LTPP Laboratory Layering Information: Lab Layer No.	Example of LTPP Laboratory Layering Information: Material Code	Laboratory Material Tests
PCC Pavement JPCP(04), JPCP(05), CRCP(06)	PCC Pavement	4	PCC(730)	4	PCC(730)	PC06, PC01, PC02, PC04
Unbound or # Treated Base (21 to 24, 26 to 44, 46)	Bound Base	3	Asphalt Treated Base (321)	3 ++	Asphalt Treated Base (321) ++	TB01, TB03 ++
Subbase (21 to 44, 46)	With or Without Subbase (Unbound or Treated)	2	Lime-Treated Soil (338)	2 **	Lime-Treated Subbase (338) **	TB01, TB02 **
Subgrade Soil (51 to 65)	+ Subgrade	1	Clay Subgrade (101)	1	Silty Clay (134)	SS01, SS02, SS03, SS04, SS05, SS07, SS09

NOTES: + A treated subgrade is considered a treated subbase layer.

\# A seal coat and interlayers are permitted above an unbound granular base layer.

++ Exception - Perform AC01, AC07 tests instead of TB01, TB03; (a) if HMAC base (material code 319) is sampled and if the inventory data shows material code 28 and (b) if sand asphalt base (material code 320) is sampled.

** Assign layer material code 321 and perform TB03 instead of TB02 test if this layer is asphalt treated layer.

Figure 4.7. Example of Laboratory Testing Plan for a Rigid GPS Test Section

Laboratory Test Procedures for AC

AC testing was conducted on core specimens and block samples retrieved from the pavement test section. Table 4.2 lists AC core locations and the required test procedures for each specimen. Testing (except for core examination and thickness) was conducted on each AC layer. Cores that contained more than one AC layer were sawed in the laboratory. The AC Core Examination and Thickness Test was the first test performed on all AC core specimens. It identifies and determines the thickness of the individual layers within a core.

The Bulk Specific Gravity Test (test AC02) and Maximum Specific Gravity Test (test AC03) were conducted on 6 in. AC cores. Asphalt content tests (test AC04) were performed on block samples and 12 in. core specimens. The aggregate obtained from the AC04 test was used for sieve analysis using SHRP Protocol P14. Additionally, the fine portion of the aggregate specimen was used to perform a particle shape test using SHRP Protocol P14A. This testing (P14A) was performed by the National Aggregate Association's Joint Research Laboratory (NAA-JRL). No testing was performed on extracted asphalt cement.

The Resilient Modulus and Tensile Strength Test, SHRP Designation AC07, was conducted on 4 in. core specimens from the pavement test section using SHRP Protocol P07. Appendices 1 and 2 of the *Materials Characterization: Five-Year Report* (**4.3**) documents the entire process undertaken for the resilient modulus testing program.

Laboratory Testing of Treated Materials

The testing of treated materials was conducted on core specimens, chunks, and pieces of pavement materials. SHRP Protocol P31, "Identification and Description of Treated Base and Subbase Materials, and Determination of Type of Treatment," was used for preliminary identification and detailed description of treated materials and treatment types. The thickness of these materials was also determined using this test procedure. Based on the results of the P31 test, laboratory tests using SHRP Protocol P32 or P33 (depending on material type) were required.

Protocol P32, "Compressive Strength of OTB Material," was used to test treated materials other than asphalt-treated base materials (lean concrete, econocrete, soil cement, lime-treated soils, and chemical stabilized soils). The asphalt-treated materials were tested using Protocol P33, "Resilient Modulus of Asphalt-treated Materials."

TABLE 4.2. Summary of AC Core Locations and Required Tests

Sample/Core Locations	Sample Size	Tests Per Each 1.5 in. or Thicker Layer	SHRP Protocol
All C-type A1, A2 cores	4 in. diam.	AC01. AC Core Examination and thickness	P01
C8, C9, C10, and C20, C21, C22 Cores (C7, C19 if needed)	4 in. diam.	AC07. AC Resilient Modulus	P07
A1, A2 Cores (C12, C24 if needed)	6 in. diam.	AC02. AC Bulk Specific Gravity	P02
A1, A2 Cores	6 in. diam.	AC03. AC Maximum Specific Gravity	P03
BA1 or other BA type core	12 in. diam.	AC03. AC Maximum Specific Gravity	P04
Block from Test Pit or BA type core, if no test pit	12 in. x 12 in.	AC04. AC Asphalt Extraction	P04

Laboratory Testing of Unbound Granular Base, Subbase, and Untreated Subgrade Soils

The testing of unbound materials was conducted on bulk samples of the material. These samples were taken from 12 in. diameter bore holes or from the test pit location at the test section and were sent to the laboratory in bags. In the laboratory, these bulk samples were combined, prepared, and reduced to a representative test size in accordance with procedures contained in the laboratory materials testing guide.

Layer thicknesses for these layers were determined by the laboratory from the field drilling and sampling logs provided by the drilling and sampling contractor. The thickness of the layer was then averaged from this information. The laboratory assigned a detailed classification for the soil after performing all designated tests on the samples. Table 4.3 lists the laboratory tests required for the unbound materials in the GPS program.

For subgrade soils, thin-walled tube samples were retrieved from sections containing cohesive subgrade soils. These extracted tube samples were then used for resilient modulus testing using protocol P46. If tube samples were not available from a pavement test section, bulk samples were reconstituted and used for this testing.

Quality Assurance/Quality Control in the Laboratory

Because high-quality, accurate materials testing data were critical to the attainment of the objectives of LTPP, SHRP required that the testing contractors maintain their own in-house QA programs. Another important requirement in the QA/QC process was the accreditation of each laboratory through the AASHTO Accreditation Program (AAP). All SHRP contract laboratories were accredited by AAP, thereby providing SHRP with important external QA checks (**4.4**).

The laboratory materials testing guide was the first stage of the QA/QC process. Strict adherence to the use of the guide was intended to ensure regional data quality and interregional data consistency. The guide contains all laboratory test data forms, protocols, and other laboratory instructions. Strict conformance to the SHRP protocols and sample handling and storage requirements was essential to the success of the laboratory materials testing process.

A commitment to QA/QC was required throughout all levels of SHRP-LTPP, including the SHRP Regional Engineer, SHRP Project Manager, RCOC staff, laboratory materials testing contractors, and SHRP technical assistance contractors.

TABLE 4.3. Laboratory Tests for Unbound Granular Base and Subbase Materials and for Untreated Subgrade Soils

Laboratory Tests Per Layer *			SHRP Protocol
(a)	Unbound Granular Base Material		
	UG10.	Natural Moisture Content	P49
	UG01. and UG02.	Gradation	P41
	UG04.	Atterberg Limits	P43
	UG08.	Classification and Description	P47
	UG05.	Moisture-Density Relations	P44
	UG07.	Resilient Modulus	P46
(b)	Unbound Granular Subbase Material		
	UG10.	Natural Moisture Content	P49
	UG01. and UG02.	Gradation	P41
	UG04.	Atterberg Limits	P43
	UG08.	Classification and Description	P47
	UG05.	Moisture-Density Relations	P44
	UG07.	Resilient Modulus	P46
(c)	Subgrade Soils		
	SS09.	Natural Moisture Content	P49
	SS01.	Sieve Analysis	P51
	SS02.	Hydrometer Analysis	P42
	SS03.	Atterberg Limits	P43
	SS04.	Classification and Description	P52
	SS05.	Moisture-Density Relations	P55
	SS07.	Resilient Modulus	P46

* Recommended sequence of testing for each layer.

SHRP Proficiency Testing Program

After extensive consultation and careful study of the AAP and of SHRP's QA/QC needs, supplemental proficiency testing programs were identified and designed. Six programs, were approved for implementation:

1. Type 1 (Granular) Soil Proficiency Sample Program - Resilient Modulus (Protocol P46)

2. Type 2 (Cohesive) Proficiency Sample Program - Resilient Modulus (Protocol P46)

3. Soil Moisture Proficiency Sample Program (Protocol P49)

4. PCC Core Proficiency Sample Program - Static Modulus of Elasticity, Poisson's Ratio, Splitting Tensile Strength, and Compressive Strength (Protocols P61, P62, and P64)

5. AC Core Proficiency Sample Program - Resilient Modulus (Protocol P07)

6. Laboratory Molded AC Core Proficiency Sample Program - Resilient Modulus (Protocol P07)

Data Collection Guidelines

The guidelines for recording data generated from the laboratory materials testing work are contained in Appendix C of SHRP-LTPP-OG-004, "SHRP-LTPP Interim Guide for Laboratory Materials Handling and Testing" (**4.35**). The data forms identified in this document are primarily completed by the laboratory material testing contractor and are subsequently reviewed by the RCOC for completeness and accuracy prior to entry in the Information Management System (IMS).

Summary Statistics and Information

At the conclusion of the GPS laboratory materials testing program, the estimated number of tests performed will be as follows:

1.	PCC	6,600 tests
2.	AC	18,700 tests
3.	Extracted Aggregate	2,100 tests
4.	Treated Base/Subbase	1,800 tests
5.	Unbound Base/Subbase	17,000 tests
6.	Subgrade	13,000 tests
	Total:	59,200 tests

All of this materials characterization information will be recorded in the NPPDB and will, in itself, be an important and unique storehouse of information for highway pavement researchers (**4.4**).

Status of GPS Laboratory Materials Testing

All laboratory tests of samples shipped from GPS sites were completed by mid-1993. The main effort in this area is the transfer of the data from the laboratories into the NPPDB so that the data can be used by researchers.

SPS-1, -2, -5, -6, -7, and -8 Laboratory Materials Handling and Testing

Materials property data needs for SPS experiments have been developed over time through a process of proposal and review by different agencies and contractors. Much of the work conducted for GPS was incorporated into SPS, with additional needs provided in the form of new "SPS only" protocols. Each experiment contains many elements that are similar but also contain unique items. The individual laboratory test plans provide the minimum number of results required for the specified protocols. These plans are the culmination of the data needs process.

As stated in Section 3, SPS laboratory testing plans were developed individually for each project. This was necessitated by the inherent variability in pavement cross-sections and subgrade properties. Guidelines for design of laboratory testing plans are contained in several SHRP Operational Memoranda (**4.23, 4.24, 4.25, 4.26, 4.27, 4.28**).

The guidelines include tabular summaries that specify the test protocols, the numbers of tests to be conducted, and the specific source of the test specimen from within the project site for a generic project. The principles contained in these guidelines were then used to develop site-specific laboratory testing plans.

The laboratory protocols in the guide address testing of subgrade soils, unbound aggregate materials, asphalt-stabilized materials, hardened PCC, and AC. Each of these areas contains numerous protocols that refer to AASHTO and ASTM testing standards with modifications specifically for use in SHRP. Laboratory testing protocols were developed as data needs were identified.

Conduct of Laboratory Materials Testing

Most SPS testing is the responsibility of the participating SHA. The SHA may choose to contract this work to a consultant or may perform the work using its own resources. In any case, the test plans and standard laboratory protocols are used. Most SPS testing, including resilient modulus, creep, and interface bond testing, is conducted under separate contract by the FHWA to ensure regional consistency.

Requirements for Individual SPS Experiments

Guidelines for each SPS experiment contain many similarities as well as significant, unique requirements. Subgrade soils, unbound aggregate materials, cementitious/pozzolanic treated bases, and asphalt-treated bases are all tested in essentially the same way for each SPS experiment, as shown in Table 4.4. The additional testing requirements for each experiment are explained in detail in several SHRP reports (**4.23, 4.24, 4.25, 4.26, 4.27, 4.28**).

QA/QC in the Laboratories

As in the GPS laboratory testing program, the accuracy of materials testing data was of critical importance to attainment of the objectives of LTPP. For SPS, laboratories are required to undergo AASHTO Materials Reference Laboratory (AMRL) inspection and perform a reasonable amount of QA/QC on their own initiative.

The implementation of the procedures contained in the laboratory materials testing guide is another important part of the QA/QC program. Strict adherence to the guide was intended to ensure regional data quality and interregional data consistency. A program similar to that used in GPS ensures accurate materials testing data.

Summary Statistics and Information

At the conclusion of the SPS-1, -2, -5, -6, -7, and -8 laboratory materials testing program, an estimated 40,000 individual laboratory test results will have been generated.

SPS-3 and SPS-4 Laboratory Materials Handling and Testing

The objective of the SPS-3 and SPS-4 research effort was to compare the effectiveness of mechanisms by which the selected maintenance treatments preserve and extend pavement service life, safety, and ride quality. This was done over a range of environmental conditions, traffic volume, and other factors that were incorporated into the analysis. An important part of this project was the laboratory materials characterization plan for these studies. Table 4.5 lists the protocols and tests used for completion of the SPS-3 and SPS-4 studies. These tests were all conducted by one laboratory under contract to SHRP.

TABLE 4.4. Laboratory Materials Testing Common to the SPS Experiments

Subgrade Soils	Sieve Analysis Hydrometer to 0.001 mm Atterberg Limits Classification Moisture-Density Relations Resilient Modulus Unit Weight Natural Moisture Content Unconfined Compressive Strength
Unbound Granular Base	Particle Size Analysis Sieve Analysis (washed) Atterberg Limits Moisture-Density Relations Resilient Modulus Classification Permeability Natural Moisture Content
Permeable Asphalt-Treated Base	Core Examination/Thickness Bulk Specific Gravity Maximum Specific Gravity Asphalt Content (Extraction) Moisture Susceptibility Resilient Modulus
Asphalt-Treated Base	Core Examination/Thickness Bulk Specific Gravity Maximum Specific Gravity Asphalt Content (Extraction) Moisture Susceptibility Resilient Modulus
Cementitious/Pozzolanic Treated Base	Core Examination/Thickness Compressive Strength

TABLE 4.5. List of Lab Protocols Used for SPS-3 and SPS-4 Testing

SHRP Test Number	Protocol Number	Name
AC08	H01L	Preparation of Asphalt Cores for Aging Tests
AE01	H02L	Recovery of Asphalt from Solution by Abson Method
AE02	H03L	Penetration of Bituminous Material
AE06	H04L	Viscosity of Asphalts
SC01	H05L	Standard Methods of Testing Emulsified Asphalts
SC02	H06L	Sand Equivalent Values of Soils and Fine Aggregates
SC03	H07L	Crushed Stone, Crushed Slag, and Gravel for Single or Multiple Bituminous Surface Treatments
SC04	H08L	Determination of Flakiness Index of Aggregates
SC05	H09L	Design, Testing, and Construction of Slurry Seal
SC06	H10L	Test Method for Measurement of Excess Asphalt in Bituminous Mixtures by Use of a Loaded Wheel Tester and Sand Cohesion
SC07	H11L	Wet Stripping for Cured Slurry Seal Mixes
SC08	H12L	Determination of Slurry System Compatibility
SC09	H13L	Mixing, Setting, and Water Resistance Test to Identify "Quick Set" Emulsified Asphalts
SC10	H14L	Sieve Analysis of Seal Coat Aggregates
SC11	H15L	Chip Seal Mix Design
SC12	H19L	Quantitative Extraction from Slurry Seal Sample
SC13	H20L	Accelerated Polishing of Aggregate
CS01	H16L	Joint Sealants, Hot-Poured, for Cement and Asphalt Pavements
CS02	H17L	Joint Sealants, Silicone
US01	H18L	Compressive Strength of Hydraulic Cement Mortar Blocks

Summary

All materials characterization information will be recorded in the NPPDB and will, in itself, be an important and unique storehouse of information for highway pavement researchers. Perhaps most important of all, SHRP will have met its goal and provided present and future pavement researchers with high-quality, detailed, accurate materials characterization information regarding thickness, quality, strength, and other attributes of the pavement layers from the LTPP GPS and SPS sites (**4.4**).

References

4.1 Strategic Highway Research Program. *SHRP-LTPP General Pavement Studies: Five-Year Report* (Report No. SHRP-P-387). National Research Council, Washington, D.C., 1994.

4.2 Strategic Highway Research Program. *SHRP-LTPP Specific Pavement Studies: Five-Year Report* (Report No. SHRP-P-395). National Research Council, Washington, D.C., 1994.

4.3 Strategic Highway Research Program. *SHRP-LTPP Materials Characterization: Five-Year Report*. National Research Council, Washington, D.C., Forthcoming.

4.4 Pelzner, A. *SHRP-LTPP Pavement Materials Characterization, Interim Report* (unpublished). Strategic Highway Research Program, National Research Council, Washington, D.C., April 1990.

4.5 Strategic Highway Research Program. "SHRP-LTPP Guide for Field Materials Sampling, Handling, and Testing." (Operational Guide SHRP-LTPP-OG-006). Washington, D.C., May 1990.

4.6 Gardner, M. and B. Rauhut. "Materials Sampling and Testing Guide for Long-Term Pavement Performance Studies" (Draft). Brent Rauhut Engineering Inc., Austin, Texas, October 1987.

4.7 Strategic Highway Research Program. "Data Collection Guide for Long-Term Pavement Performance Studies." (Operational Guide SHRP-LTPP-OG-001). National Research Council, Washington, D.C., Revised January 1990.

4.8 Strategic Highway Research Program. "Long-Term Pavement Performance Information Management System Researchers Guide." National Research Council, Washington, D.C., January 1991.

4.9 Groeger, J. "Quality Assurance/Quality Control of SHRP-LTPP Field Drilling and Sampling" (Technical Memorandum EC-45). Texas Research and Development Foundation, Austin, Texas, April 16, 1990.

4.10 Strategic Highway Research Program. "National Verification of Nuclear Moisture Density Equipment Used by SHRP Drilling and Sampling Contractors" (SHRP-LTPP Materials Directive No. 15). National Research Council, Washington, D.C., October 5, 1989.

4.11 Strategic Highway Research Program. "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-1: Strategic Study of Structural Factors for Flexible Pavements." National Research Council, Washington, D.C., February 1990.

4.12 Strategic Highway Research Program. "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-2: Strategic Study of Structural Factors for Rigid Pavements." National Research Council, Washington, D.C., April 1990.

4.13 Strategic Highway Research Program. "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-5: Rehabilitation of Asphalt Concrete Pavements." National Research Council, Washington, D.C., April 1989.

4.14 Strategic Highway Research Program. "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-6: Rehabilitation of Jointed Portland Cement Concrete Pavements." National Research Council, Washington, D.C., April 1989.

4.15 Strategic Highway Research Program. "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-7: Bonded Portland Cement Concrete Overlays." National Research Council, Washington, D.C., February 1990.

4.16 Strategic Highway Research Program. "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-8: Study of Environmental Effects in the Absence of Heavy Loads." National Research Council, Washington, D.C., February 1992.

4.17 Strategic Highway Research Program. "Specific Pavement Studies Construction Guidelines for Experiment SPS-1: Strategic Study of Structural Factors for Flexible Pavements" (Operational Memorandum SHRP-LTPP-OM-017). National Research Council, Washington, D.C., December 1990.

4.18 Strategic Highway Research Program. "Specific Pavement Studies Construction Guidelines for Experiment SPS-2: Strategic Studies of Structural Factors for Rigid Pavements" (Operational Memorandum SHRP-LTPP-OM-018). National Research Council, Washington, D.C., December 1990.

4.19 Strategic Highway Research Program. "Specific Pavement Studies Construction Guidelines for Experiment SPS-5: Rehabilitation of Asphalt Concrete Pavements" (Operational Memorandum SHRP-LTPP-OM-012). National Research Council, Washington, D.C., June 1990.

4.20 Strategic Highway Research Program. "Specific Pavement Studies Construction Guidelines for Experiment SPS-6: Rehabilitation of Jointed Portland Cement Concrete Pavements" (Operational Memorandum SHRP-LTPP-OM-013). National Research Council, Washington, D.C., July 1990.

4.21 Strategic Highway Research Program. "Specific Pavement Studies Construction Guidelines for Experiment SPS-7: Bonded Portland Cement Concrete Overlays" (Operational Memorandum SHRP-LTPP-OM-016). National Research Council, Washington, D.C., December 1990.

4.22 Strategic Highway Research Program. "Specific Pavement Studies Construction Guidelines for Experiment SPS-8: Study of Environmental Effects in the Absence of Heavy Loads" (Operational Memorandum SHRP-LTPP-OM-029). National Research Council, Washington, D.C., March 1992.

4.23 Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-1: Strategic Study of Structural Factors for Flexible Pavements" (Operational Memorandum SHRP-LTPP-OM-021). National Research Council, Washington, D.C., February 1991.

4.24 Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-2: Strategic Study of Structural Factors for Rigid Pavements" (Operational Memorandum SHRP-LTPP-OM-022). National Research Council, Washington, D.C., April 1991.

4.25 Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-5: Rehabilitation of Asphalt Concrete Pavements" (Operational Memorandum SHRP-LTPP-OM-014). National Research Council, Washington, D.C., October 1990.

4.26 Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-6: Rehabilitation of Jointed Portland Cement Concrete Pavements" (Operation Memorandum SHRP-LTPP-OM-019). National Research Council, Washington, D.C., January 1991.

4.27 Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-7: Bonded Portland Cement Concrete Overlays" (Operational Memorandum SHRP-LTPP-OM-020). National Research Council, Washington, D.C., January 1991.

4.28 Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-8: Study of Environmental Effects in the Absence of Heavy Loads" (Operational Memorandum SHRP-LTPP-OM-030). National Research Council, Washington, D.C., March 1992.

4.29 Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-1: Strategic Study of Structural Factors for Flexible

Pavements" (Operational Memorandum SHRP-LTPP-OM-026). National Research Council, Washington, D.C., December 1991.

4.30. Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-2: Strategic Studies of Structural Factors for Rigid Pavements" (Operational Memorandum SHRP-LTPP-OM-028). National Research Council, Washington, D.C., February 1992.

4.31 Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-5: Rehabilitation of Asphalt Concrete Pavements" (Operational Memorandum SHRP-LTPP-OM-015). National Research Council, Washington, D.C., October 1990.

4.32 Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-6: Rehabilitation of Jointed Portland Cement Concrete Pavements" (Operational Memorandum SHRP-LTPP-OM-023). National Research Council, Washington, D.C., May 1991.

4.33 Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-7: Bonded Portland Cement Concrete Overlays" (Operational Memorandum SHRP-LTPP-OM-024). National Research Council, Washington, D.C., July 1991.

4.34 Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-8: Study of Environmental Effects in the Absence of Heavy Loads" (Operational Memorandum SHRP-LTPP-OM-031). National Research Council, Washington, D.C., September 1992.

4.35 Strategic Highway Research Program. "SHRP-LTPP Interim Guide for Laboratory Materials Handling and Testing (PCC, Bituminous Materials, Aggregates, and Soils)" (Operational Guidelines SHRP-LTPP-OG-004). National Research Council, Washington, D.C., September 1992.

Section 5
Monitoring Activities

Introduction

A goal of the Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) project was to develop and implement a plan to uniformly and thoroughly monitor the performance of pavements identified in the General Pavement Studies (GPS) and Specific Pavement Studies (SPS). The Pavement Monitoring Task was established to provide guidelines and procedures for SHRP personnel and contractors to ensure that data collection efforts yielded consistent, comprehensive, high-quality data for the SHRP National Pavement Performance Database (NPPDB).

Specific areas of interest in pavement monitoring include pavement distress, deflection, profile, friction, instrumentation (for temperature, moisture, and deflection), and seasonal monitoring.

Distress

Distress surveys have always been one of the more problematic areas of pavement data collection. Difficulties include the length of time over which distress must be observed, determination of the time at which various distresses are initiated, the difficulty of capturing the data, the repeatability of results, and the various ways in which data are collected. These problems have traditionally hindered development of good predictive models from distress data.

The primary focus of the Pavement Distress activity was to document the long-term performance of the pavement through distress histories developed by monitoring pavement distresses. The distresses that are observed will eventually be used to confirm or calibrate existing models and to develop new predictive models of pavement performance (or pavement life).

Distress Interpretation Procedure

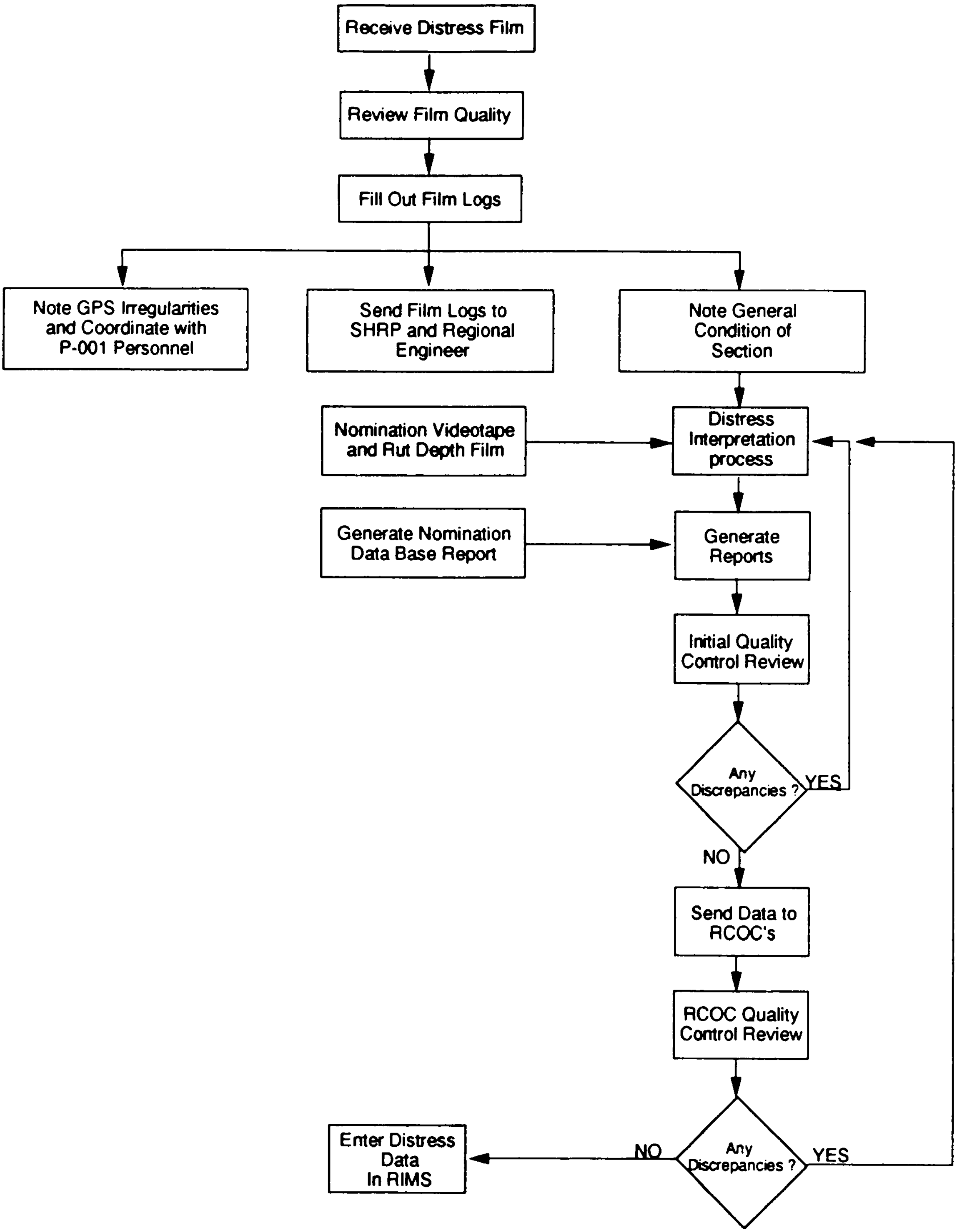
Pavement distress observations were collected photographically on 35 mm movie film, thereby providing a time-related "snapshot" of distress. The eventual accumulation of a series of distress snapshots will provide a documented historical record of pavement performance over a long period. The type, severity, and amount of distress for each pavement section is quantified through computer-assisted interpretation of the film.

PASCO Distress Interpretation

Early activities included preparation of the initial *PASCO Distress Identification Manual* (**5.1**), review of the initial PASCO distress film, formulation of the PASCO film acceptance review process (**5.2**) and development of certification criteria for the PASCO Film Motion Analyzer (FMA) technician (**5.3**). In addition, PASCO Distress Interpretation Procedures (**5.4**) were developed that incorporated the distress interpretation flow diagram shown in Figure 5.1.

To evaluate the FMA process and to further define interpretive procedures, a pilot study was conducted on 30 SHRP-LTPP sections (**5.5**) to finalize the interpretive procedures prior to initiation of production distress interpretation. In the pilot study the following interpretive findings were identified:

> Experience is a critical factor in accurate distress interpretation. Surface distresses such as raveling and weathering, bleeding, and scaling are particularly subject to misinterpretation.
>
> The texture and nature of the pavement surfaces can be a hindrance in identifying both the presence and extent of different types of low-severity cracking. Continuously reinforced concrete pavement (CRCP) and jointed concrete pavement (JCP) are particularly subject to problems because they often have tined or broomed surfaces, while the light color of these pavements can lead to film overexposure or washout in the middle of the frame. Both these factors can make crack interpretation a difficult or even impossible task with the Pavement Distress Analysis System (PADIAS) Film Motion Analyzer (FMA) method.
>
> In order to determine if some cracks were actually indistinguishable on the FMA screen, the film was projected on a large screen using a slide projector fitted with a film strip viewing attachment. The clarity and detail obtained from the projector was much higher than with the FMA. Cracks that were barely perceptible on the FMA were clearly visible through the projector.
>
> In addition to the projector, video tapes recorded by regional personnel in the initial section verification process were found to be extremely useful to the FMA operator. This represents a valuable enhancement to FMA since video film should be available for every GPS test section. In some instances, the video commentary implied even more distress existed in asphalt concrete (AC) pavements than was revealed by review of the film with the slide projector. In addition, the review process utilizing the projector displayed cracks that were not visible in the FMA review.
>
> In the distress interpretation system there were limitations that must be taken into account to insure that a truly accurate picture of pavement distress is obtained. These limitations are:



* RIMS = Regional Information Management System

Figure 5.1. Distress Interpretation Procedure

- Difficulty in perceiving low-severity cracking due to pavement texture, color, or film exposure.
- Surface distresses such as bleeding, raveling, and weathering and scaling require extensive viewing experience to make valid comparative evaluations.
- Joint seal damage cannot be perceived from distress film.

These limitations can be overcome through operator experience, the use of a slide projector adaptor to enhance film resolution, and supplemental information gained from video tapes and manual distress surveys when possible (5.5).

During production interpretation of the PASCO distress film, the list of distress manifestations that could not be consistently defined was extended to include shoving for the flexible pavements and polished aggregate, water bleeding and pumping, lane-to-shoulder dropoff, and lane-to-shoulder separation for both flexible and rigid pavements (5.6).

Manual Distress Interpretation

Manual distress surveys using the *Distress Identification Manual* (5.7) were conducted in situations for which the photographic equipment was not available. To facilitate interpretation, recommendations for quality control of manual distress data (5.8) and certification procedures for manual distress survey personnel (5.9) were developed.

Certification Requirements

A series of training and evaluation materials were developed for manual and automated survey techniques that lead to certification of people performing distress surveys. The certification process is an important element in ensuring high-quality, repeatable distress data collection.

Rater Accreditation

The accreditation process is administered in a workshop situation. The raters are brought to a single location for 1 week of classroom and field work. Classroom training is limited in scope due to the level of experience required for attendance; the primary emphasis is on changes or revisions to the *Distress Identification Manual* along with any changes in field procedures. A general review of distress types is also conducted using slides and video to reinforce the attendees' knowledge of these changes and revisions. Field survey exercises are conducted to "calibrate" the raters. Sections in the early portion of the field exercises contain only a few distresses, while more complex sections are used in later exercises. The objective of these surveys is to determine the individual rater's biases and to ameliorate or correct those biases as necessary.

Status of Distress Activities

During SHRP-LTPP, two rounds of distress surveys were conducted on all current SHRP GPS test sections and most of the existing SPS test sections. In addition, a third round of distress surveys on all SHRP GPS and SPS sections was nearly complete (October 1992). Manual (visual) distress surveys were required on a few test sections due to their remote nature or to time constraints that made photographic surveys impossible.

Interpretation of the distress photographs has been completed for the initial round of GPS and SPS surveys, including all quality assurance checks, corrections where necessary, and report generation. Interpretation has also been completed for the second round of GPS and most SPS surveys, but quality checks have been conducted on only a subset of these sections. It is anticipated that all second-round interpretation activities for GPS and SPS sections will be completed within the SHRP-LTPP timeframe; however, interpretation of the third round of surveys be completed in the Federal Highway Administration (FHWA) LTPP continuation effort.

Deflection

Deflection testing with the falling weight deflectometer (FWD) represents a primary source for assessing structural capacity and variations within the various elements of the pavement. The FWD testing activity was undertaken in two distinct phases. The first phase was linked to the original drilling and sampling scheme for the LTPP sections, while the second phase was concerned with the seasonal monitoring program. The phases involved deflection basin testing for flexible pavements and basin and load transfer tests for rigid pavements.

Devices/Storage

The Dynatest FWD was selected as the standard SHRP deflection testing equipment. Four devices were purchased and were used to collect deflection data in each region. Because of increased data collection demands due to SPS, state highway agency (SHA) FWDs were sometimes used to supplement the SHRP devices. Calibration centers were established to help ensure interregional calibration and calibration of the non-SHRP devices. SHRP has developed generic calibration procedures for FWDs to allow devices from different manufacturers to be calibrated.

Standard procedures for FWD testing were developed for GPS sites (**5.10**), and supplemental guidelines have been developed for use in tests of SPS sites (**5.10**). The standards also include considerations for supplemental data collection (temperature, joint/crack widths, etc.).

The FWD data acquisition system can store the full history of the applied load pulse and resulting deflection response. However, because of database storage limitations, 25% of the load-deflection historical data are stored off-line on optical disks, while the peak magnitudes of the impulse load and deflection responses are stored in the NPPDB.

Quality Assurance/Quality Control (QA/QC) Procedures

A uniform drop sequence is used for all test points throughout the test section. The sequence is initiated with three drops of a seating load followed by four repeat drops at each drop height (or load level) used. Four drop heights are used for flexible pavements, while three drop heights are used for rigid pavement test sections.

QA checks on the SHRP-LTPP FWD data are conducted at three levels:

1. Data Collection Software (**5.10**)
2. FWD Scan (**5.11**)
3. FWD Check (**5.12**)

The field data collection software automatically performs five validity checks (**5.10**):

1. A check to verify that sensor signals attenuate with time
2. A check that sensor deflections are lower at locations further from the load
3. A check to verify that sensor deflections are less than 80 mils or 2000 microns
4. A check at a specific location that the load for a particular drop is within 200 pounds (or 12 KPa contact pressure) of the average load for that drop height
5. A check at a specific location that the normalized deflection (based on load) for a particular drop is within 0.24 mils (6 microns) of the average normalized deflection for that drop height

The FWDSCAN program is "intended to check FWD data files for completeness and readability, and generates an output file summarizing the results of the checking process" (**5.11**). The objective of this program is to flag potential errors or problems and not to eliminate data.

The FWDCHECK program is "intended to check FWD data files for:

- Section homogeneity
- Nonrepresentative test pit and section data
- General reasonableness of structural capacity." (**5.12**)

As a rule, the checks included in the FWDCHECK program do not eliminate data but provide reasons for flagging potential problems. During SHRP-LTPP, there was no standardized set of rules or procedures by which regional FWD QA/QC personnel could assess the quality of any questionable deflection data.

The present QA/QC checks included in the FWD software programs include verifications that the deflections are within sensor limits (i.e., 80 mils or 2000 microns), that the deflections decrease with distance from the load, and that the load falls within acceptable ranges. Although these checks identify possible data anomalies, there are no formalized rules for assessing the quality of the data. The FWD data are generally transferred to the

NPPDB, regardless of the results of QA/QC checks, unless regional personnel make a determination to exclude the data.

The present FWD QA/QC software program uses normalized deflections based on the applied load (i.e., deflections per unit load) to assess section homogeneity and to conduct comparisons between test pit FWD results (i.e., outside the LTPP section) and FWD results within the section. This approach should be augmented with normalized deflections based on the sixth sensor (i.e., D_0/D_{36}, D_8/D_{36}, ..., 1.0, D_{60}/D_{36}). This approach would not only ameliorate the problems associated with "noise" in the load pulse (which would yield improper deflection/load values), but also is believed to provide a more fundamental approach to assessment of deflection basin data (**5.14**).

Status of Deflection Activities

Since the initiation of SHRP, significant progress has been made in the deflection testing arena. Actual field testing of GPS sections was initiated in the early months of 1989. Over the past 3 years, the first round of testing on the GPS test sites identified to date has been completed, and second-round testing is progressing rapidly. Also, most of the required deflection testing of SPS sections has been completed. The focus of deflection testing is shifting from the initial inventory-type testing of GPS sections to the more intensive testing for the evaluation of moisture- and temperature-related variations in pavement response, testing of SPS sections as they are constructed, and long-term monitoring of GPS sections through testing at 5-year intervals.

Initial FWD Data Analysis

Like the rest of the LTPP data, the raw deflection data are stored in the NPPDB and will ultimately be available to all researchers. SHRP undertook a back-calculation exercise as an initial analysis of the LTPP data. The endeavor was undertaken with the full expectation that it would be a preliminary analysis of these deflection data. The layer moduli derived from this endeavor were used to supplement the raw deflection data stored in the NPPDB.

In order to estimate in-situ layer moduli, SHRP developed a back-calculation procedure consisting of an existing back-calculation program and a series of application rules (**5.13**). The term "back-calculation program" or "software" means just that—computer programs used in back-calculation. However, the manner in which a back-calculation program is used is in some cases more important than which program is used. Hence "back-calculation procedure" refers not only to the software but also to the "rules" by which that software is applied. Too much, however, remains to be learned about the art and science of back-calculation for this program to be regarded as anything more than a first step.

Deflection Measurement Program Issues

At this stage of the LTPP, FWD hardware has been obtained and large amounts of FWD data have been acquired. Hardware, software, and procedural problems have been identified and most have been addressed; data collection processes have been developed and data collected. However, some important issues remain to be addressed, including noise in the FWD load pulse, calibration "consistency" between the SHRP FWDs, and between SHRP FWDs and SHA FWDs, and QA/QC interpretation of the FWD data for inclusion in the NPPDB.

The occasional "noise" issue has complicated the deflection testing program. High-frequency noise can introduce an occasional "glitch" in the pulse, which is not necessarily transmitted to the pavement structure. When this phenomenon coincides with the peak load magnitude, an erroneously high peak load is obtained. Such erroneous data, if transferred to the NPPDB, would represent a data anomaly that could significantly affect back-calculated values.

Calibration consistency can be addressed through use of the calibration centers and standardized periodic checks of FWD operation. Furthermore, the QA/QC issue can be addressed with the development of detailed guidelines for assessing the quality of FWD data.

Recommended FWD Activities

An analysis and assessment of FWD data collection requirements should be undertaken to determine if a reduction in the number of FWD test points could be allowed (e.g., from 25 ft. spacing to 50 ft. [15.2 m] or 100 ft [30.5 m] spacing). A similar analysis could be conducted to directly assess the need for the present number of drop heights (or load levels) and/or the present number of drops at a specific drop height (or load level). Reduced testing requirements could lead to savings in time, effort, and money, with the concomitant advantage that site scheduling conflicts could be reduced.

Profile

The general serviceability concept developed during the AASHO Road Test (**5.15**), in which the performance of a pavement was defined by its ability to serve traffic over time, has been maintained in SHRP-LTPP. Because AASHO serviceability was influenced by both longitudinal and transverse profile, as well as by the amount of cracking and patching, it is apparent that SHRP-LTPP can likewise provide an opportunity for serviceability assessments by combining profilometer data (longitudinal profile), PASCO cross-profile data (lateral profile), and distress data from FMA film interpretation (cracking and patching).

The principal factor in the AASHO Present Serviceability Index (PSI) equation is slope variance, which represents a measure of variation in longitudinal profile or roughness (**5.15**). SHRP selected the K.J. Law profilometer to monitor longitudinal profile or roughness variation within each GPS and SPS section (**5.16, 5.17**).

Theory of Operation

The Law road profilometer uses a non-contact light sensor system to measure the distance between the vehicle frame and the road surface. The profilometer is equipped with two sensors, one in each wheel path. The sensor consists of a light source, a light receiver, and an electronic enclosure. The light receiver uses a rotating scanning mirror assembly for detecting signals in measuring the road profile.

The relative displacement between the vehicle and the road measured by the non-contact light sensor is one input to the profile equation. The other input, vertical vehicle motion is provided by a precision servo-balanced accelerometer. The difference between the vehicle displacement and the relative motion between the vehicle and the road surface provides the actual raw road profile output.

Law Profilometer Evaluations

Acceptance-type testing was completed and comparative analyses were completed for the three identical SHRP profilometers as well as for the fourth SHRP-FHWA profilometer (**5.18, 5.19, 5.20**). In addition, the first "rough-off" comparative testing program for all four SHRP profilometers was conducted at Austin, Texas in February 1990 (**5.21, 5.22**). A second profilometer rough-off was conducted at Ann Arbor, Michigan in June 1991 (**5.23**). The first rough-off included six flexible pavement sections, while the second rough-off was conducted on four flexible and four rigid pavement sections.

QA/QC recommendations for profile data collection (**5.24, 5.25, 5.26**) and data processing (**5.27, 5.28, 5.29**) have been developed based on the results of the first rough-off. Recommendations for identifying influential effects of "saturation spikes" and "lost lock" on profile roughness (**5.30, 5.31, 5.32**) were developed.

Saturation Data Anomaly

Distortion in the non-contact light sensor output caused by application of an external light source to the detectors will cause the signals to saturate. This "fools" the non-contact sensor electronics into interpreting the road profile as being closer to the vehicle than it actually is. This saturated non-contact signal is then combined with the accelerometer signal and distorts the output of the raw road profile as illustrated at stations 250 and 450 in Figure 5.2. Note that this example of a saturation spike was extracted from a profilometer run on an Austin test site during the first rough-off. A second run on the same site resulted in a profile relatively free of large spikes (Figure 5.3). There are, however, apparent small spikes at stations 3+00 and 4+25.

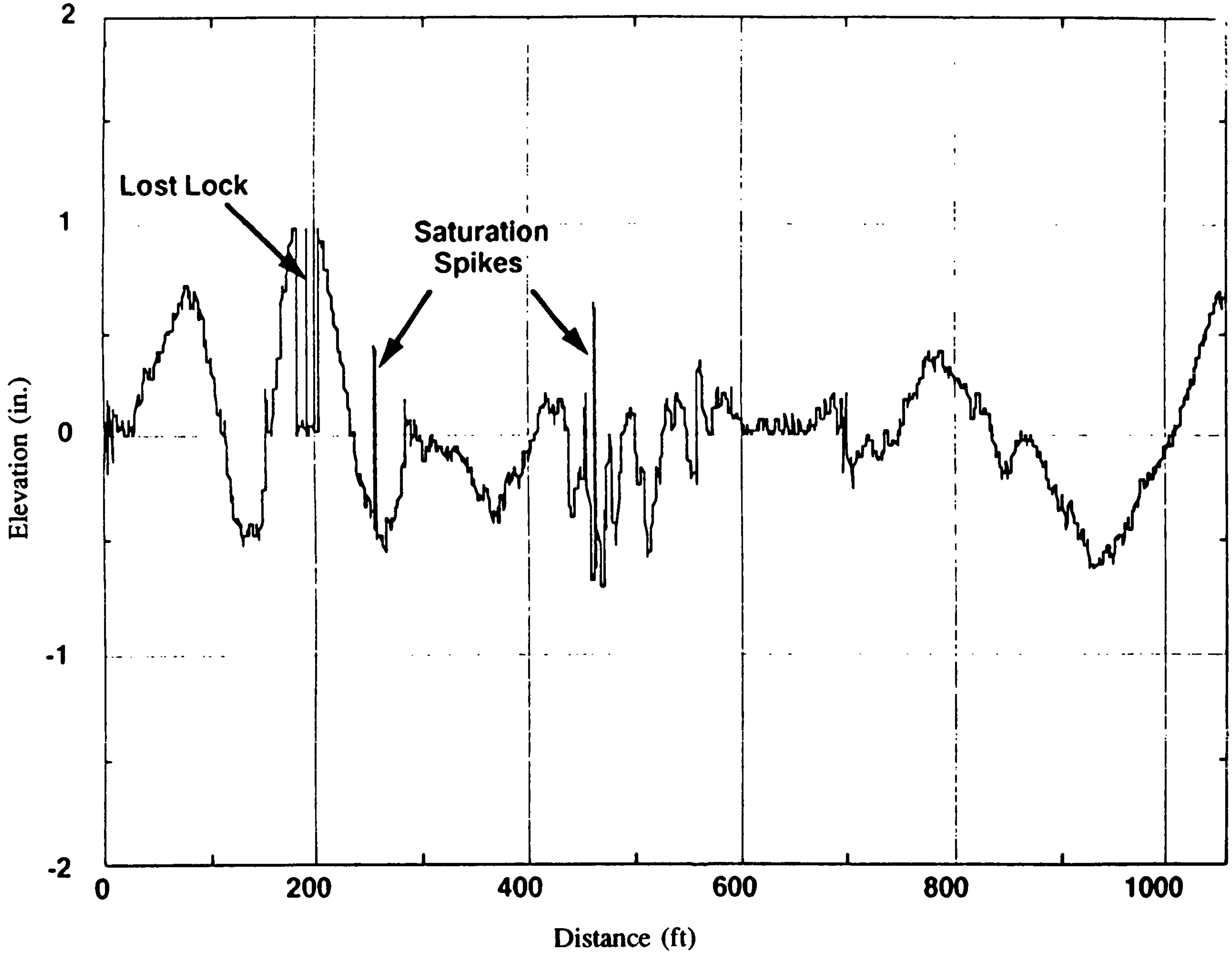


Figure 5.2. Example of Randomly Generated Data Anomalies in a Profilometer Run

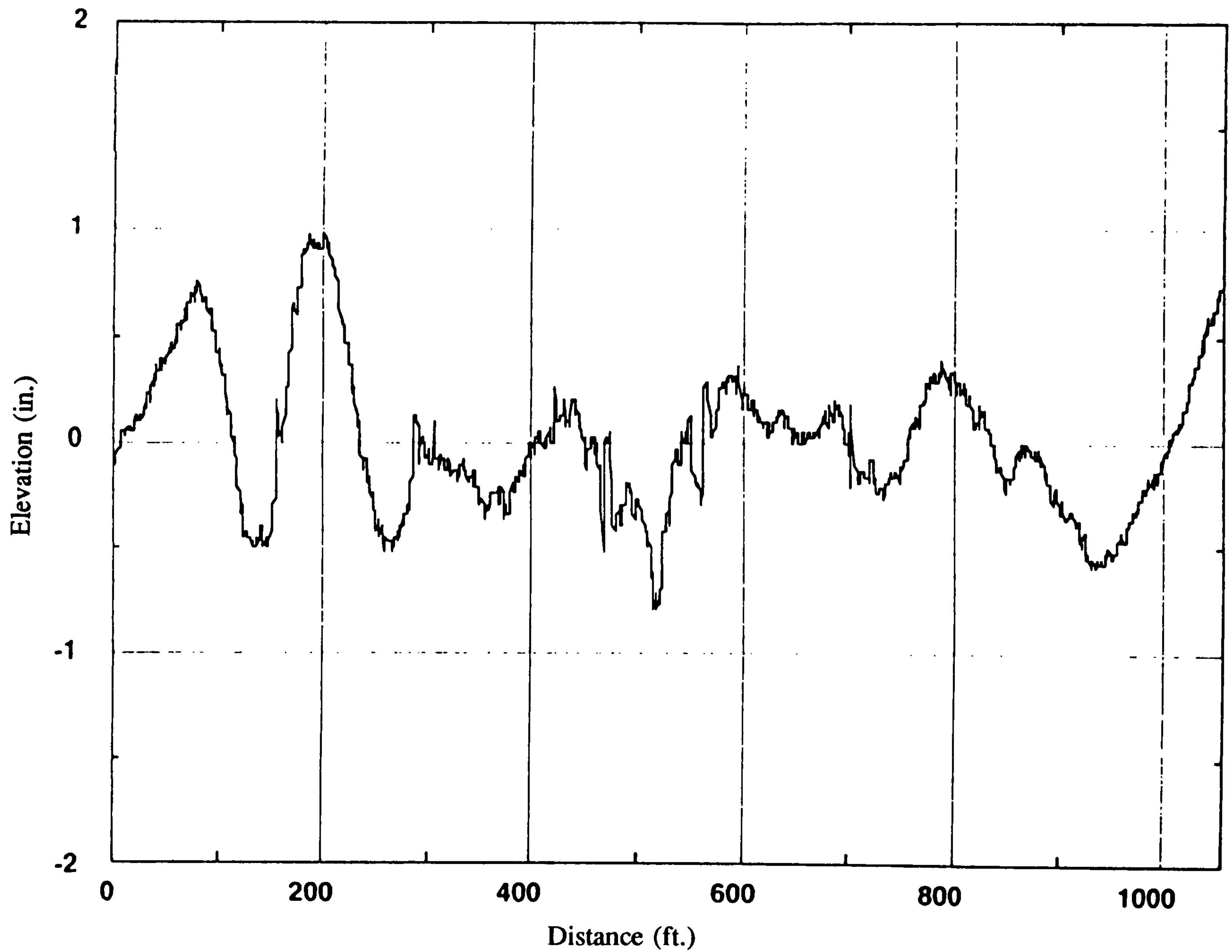


Figure 5.3. Example of Profilometer Run Free of Data Anomalies

Lost Lock Data Anomaly

Another distortion of the raw road profile output is created when the road pulse signal is lost due to changes in road surface reflectivity. As the vehicle proceeds down the lane and the road surface changes from a high light-reflective surface to a high light-absorbing surface, the road signal pulse is greatly attenuated. In this instance, the non-contact sensor output then reduces to a zero or flat output, and the resulting raw road profile output consists only of the accelerometer output. An example of this type of data anomaly was observed during the same profilometer run at station 2+00 (Figure 5.2). It is interesting to note that a saturation data anomaly also developed within about 50 ft. (15.2 m) of the location of the lost lock anomaly. A second run on the same site (Figure 5.3) resulted in a dynamic profile free of "lost locks."

Face DIPstick® Device

Although the Law inertial profilometer was the primary device selected for use in measurement of longitudinal profile variations, the profilometer was sometimes unavailable due to scheduling, equipment difficulties, or inaccessibility (e.g., Puerto Rico and Hawaii). In these instances the Digital Increment Profiler (DIPstick®) manufactured by Face Construction Technologies, Inc. was selected as the backup device for profile measurements (**5.33**).

For proper use of the DIPstick device, a data handling plan (**5.34**) was developed and acceptance testing was conducted for the devices (**5.35, 5.36**). In addition, an evaluation of roughness indices developed from DIPstick profile data (**5.37**) was completed. This enabled direct comparisons between the roughness indices generated by the Law profilometer and by the DIPstick (**5.33**).

Profilometer-DIPstick Profile Comparisons

The present SHRP policy, in which the Dipstick profile data are substituted for Law profilometer profile data, implies in its application that the two profiles are compatible. This implication is not necessarily true, as indicated in Figure 5.4, for a flexible pavement site in Austin, Texas (from rough-off #1) or in Figure 5.5 for a rigid pavement site in Ann Arbor, Michigan (from rough-off #2). In addition, profile data for the Law profilometer are generated every 6 in. while the DIPstick data can only be developed at 12 in. spacings.

The calculation of roughness indices such as International Roughness Index (IRI), slope variance (SV), and root-mean-square vertical acceleration (RMSVA) will no doubt yield different results for these indices if the profiles do not match and the data point spacings are different. There is a need to identify, characterize, and/or calibrate the relationship between the profilometer and DIPstick data.

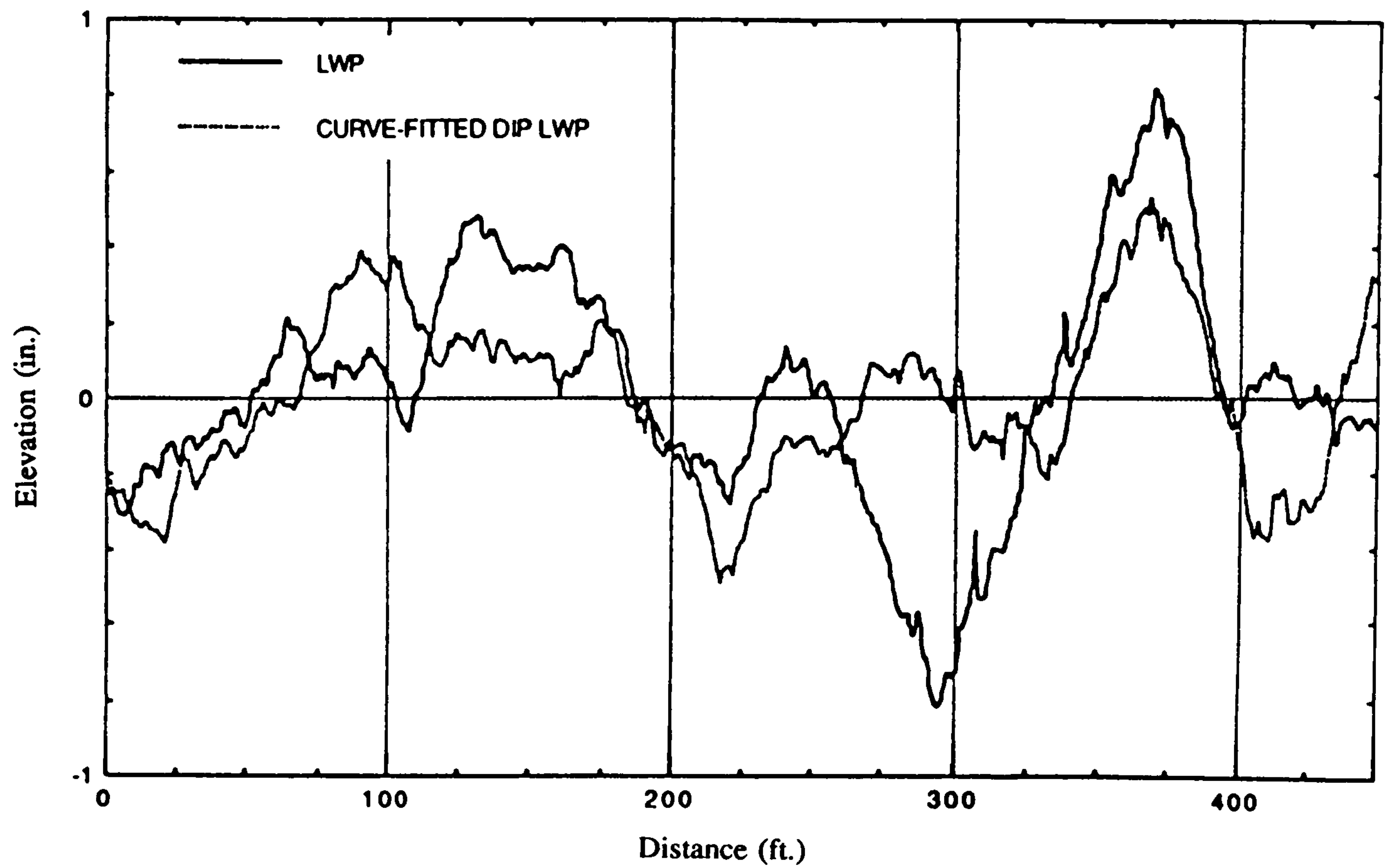
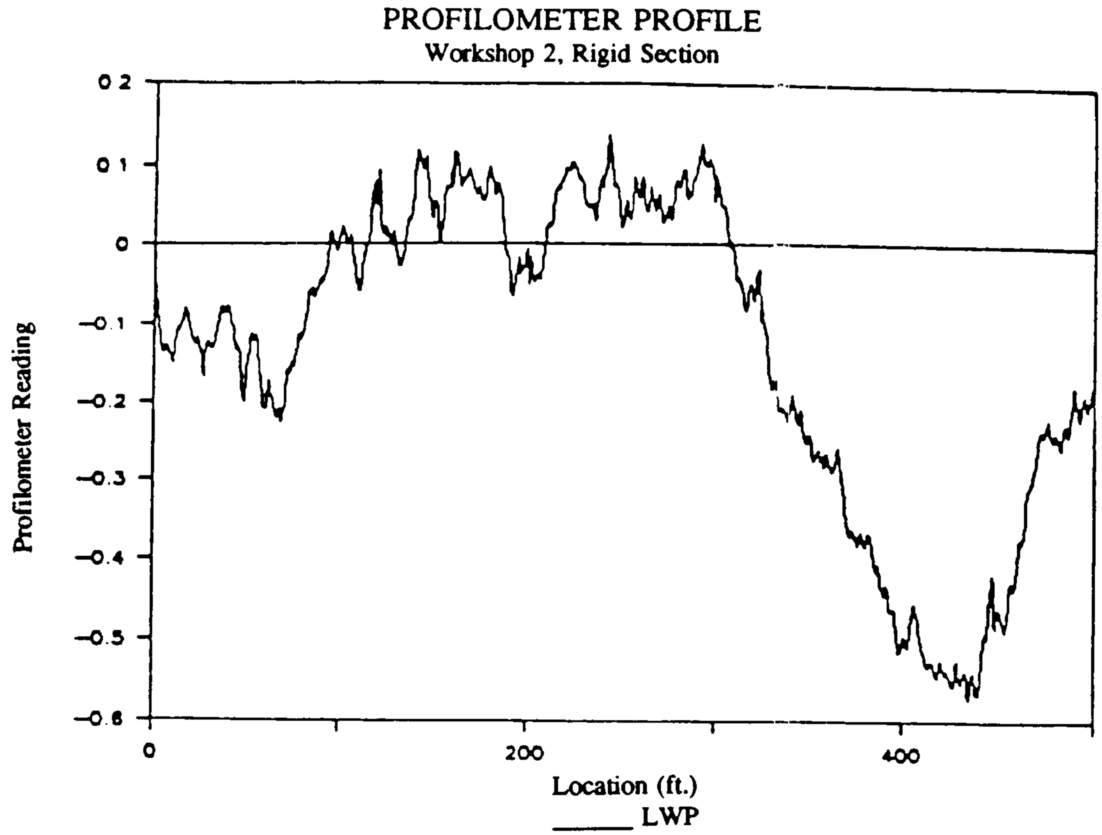


Figure 5.4. Comparison of Law Profilometer and Face DIPstick Profiles—Flexible Pavement



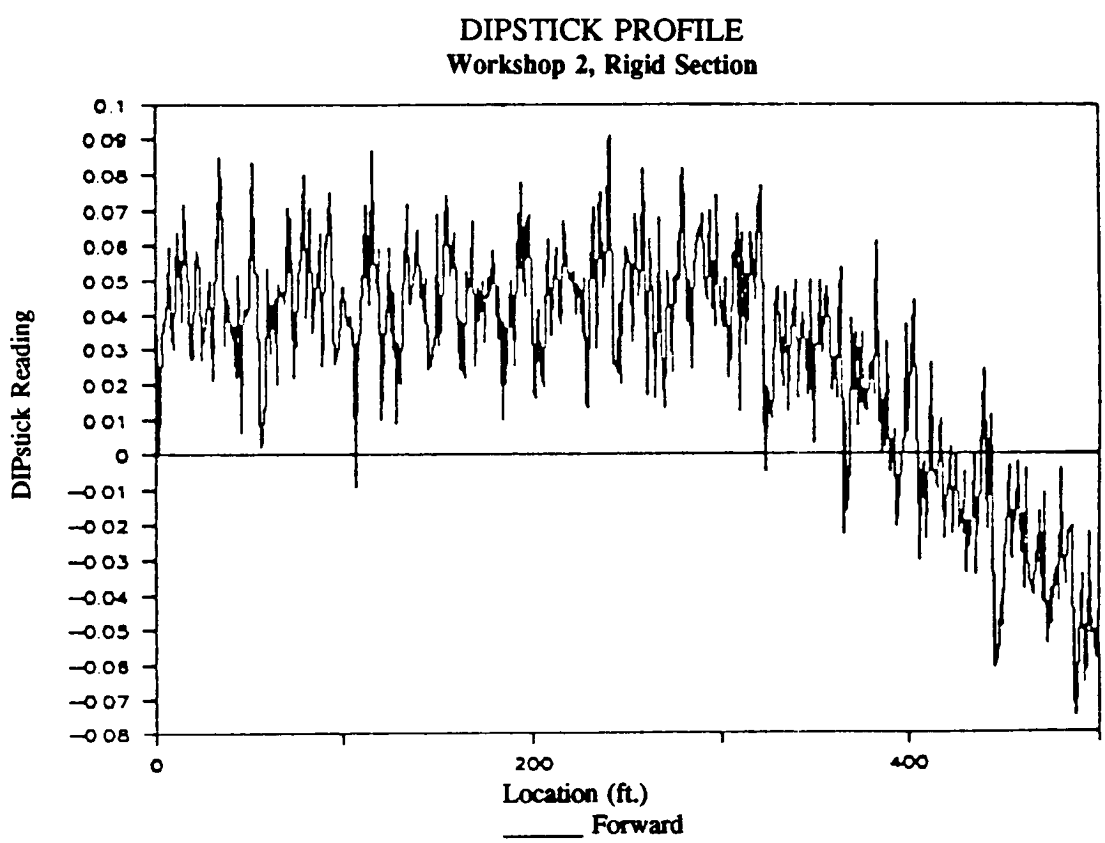


Figure 5.5. Comparison of Law Profilometer and Face DIPstick Profiles—Rigid Pavement

In addition, the slope variance estimates developed for the Law profilometer are calculated from Equation 5.1, which is based on slope values established from a horizontal baseline:

$$SV_p = \frac{\Sigma Y^2 - (1/n)(\Sigma Y)^2}{n - 1} \tag{5.1}$$

where

SV_p	=	profilometer slope variance,
Y	=	difference in elevation of two points 1 ft. apart,

and

n	=	number of readings.

This is at variance with the classical AASHO baseline for slope calculations, which was defined by a line connecting the back tire of the pulling vehicle and the wheel of the longitudinal profilometer—a distance of 25.5 ft. The AASHO slope variance was calculated using Equation 5.2:

$$SV_a = \frac{\sum_{i=1}^{n} X_i^2 - (1/n)(\sum_{i=1}^{n} X_i)^2}{n - 1} \tag{5.2}$$

where

SV_a	=	AASHTO slope variance,
X_i	=	the i^{th} slope measurement,

and

n	=	total number of measurements.

Comments on Status

There is a need to ensure that quality data are obtained in measuring the longitudinal profile with either the Law profilometer, the Face DIPstick, or any other devices adopted by FHWA. In addition, it is essential to ensure compatibility of profile data among the four SHRP profilometers, with particular attention to the FHWA profilometer (located in the North Central region), which has a shorter sensor spacing. The quality assurance activity could be accomplished in annual profile workshops, reviews of quality assurance procedures, and on-site observations of profilometer operations.

Traffic Monitoring

Traffic Data Collection Requirements

After considering initial traffic needs (**5.38**) and available options (**5.39**), the traffic data collection plan eventually adopted by SHRP-LTPP involved three levels (**5.40**):

1. A preferred approach that relied upon continuously operated weigh-in-motion (WIM) equipment
2. A desirable level that substituted automated vehicle classifiers (AVCs) for WIM equipment and added portable WIM measurements for a week each quarter
3. A minimum response that was similar to the desirable level but reduced the length of time for the portable WIM counts

As noted in Table 5.1, the SHAs preferred the option that allows for the installation of AVCs at GPS test sites, with portable WIM measurements on a quarterly basis to collect weight data. With SHRP-LTPP impetus and a desire for better traffic data, the SHAs significantly increased the number of WIM sites (**5.41**) at LTPP sites.

The three alternatives for monitoring traffic data were further defined as follows:

- Preferred traffic data collection: permanent, year-round WIM equipment installed at each site and operated continuously

- Desirable traffic data collection: a permanent, year-round site-specific AVC supplemented by 1-week of WIM measurements for each season of the year at each study site

- Minimum traffic data collection: a year-round AVC counting a minimum of 1 full year during each 5-year period, supplemented by one 48-hour weekend and one 48-hour weekday WIM session conducted during each season of the year

Site-Specific Versus Site-Related Data Collection

As envisioned in the SHRP-LTPP plan, all traffic data collection would take place immediately upstream or downstream of the LTPP pavement test sections (**5.42**). Thus, a given traffic loading estimate for a particular LTPP section would be site-specific because it would be based on traffic data collected from the particular test location. The traffic data collection equipment was placed to ensure that no interruption or interference would develop. In instances where the traffic counting and weighing station is separated from the test location

TABLE 5.1. Traffic Data Collection Equipment Preferences

Region	WIM	AVC	Other or Unknown	Total Sites
N. Atlantic	58	59	18	135
Southern	53	209	0	262
Western	54	129	0	183
N. Central	108	88	2	198
Totals:	273	485	20	778
Percentage:	35%	62%	3%	100%

and truck traffic varies between the two sites, additional traffic data must be collected at each site to document the relative difference in traffic loading at the two sites.

Traffic Data in the LTPP NPPDB

The specific traffic data elements included in the LTPP NPPDB consist of the Level 1 Primary Loading Estimates (Figure 5.6) from the LTPP Central Traffic Database (**5.43**). These Level 1 records represent the "best estimate" of the traffic loads experienced at each LTPP site for each calendar year since the particular LTPP site was opened to traffic. The loading estimates are presented as the number of axles by weight range and axle type (singles, tandems, tridems, and quadrems) to which the LTPP pavement test section was exposed that year. The FHWA 13-Class vehicle classification system and the standard FHWA formats are used in reporting traffic volume, classification, and weight data (**5.44**).

Equivalent single axle load (ESAL) estimates based on the traffic data and the pavement structure identified in the NPPDB are stored in the two databases (**5.45**).

International Traffic Data Requirements

The traffic data requirements for international GPS test locations are to be the same as those set for U.S. and Canadian sites. To help coordinators from the various countries to understand these requirements, an "International Traffic Data Collection Handbook" (**5.46**) was compiled incorporating the most important technical memoranda, reports, and documents. The handbook was initially distributed at the International Coordinators Meeting in England in November 1990.

Surface Friction

The LTPP pavement condition monitoring program included periodic surface friction data collection on GPS and SPS test sections. This is accomplished through friction measurements of LTPP sections conducted by the SHAs.

Friction Data Collection Frequency and Timing

Routine Monitoring Frequency

Routine monitoring was performed on GPS and SPS test sections during normal monitoring cycles if no major maintenance or rehabilitation action (e.g., an overlay, seal coat, or porous friction course) had been undertaken on the test section. Routine friction measurements were taken <u>once every 2 years</u>, or more frequently if desired by the participating agency.

Study site location	________		
Year	________		
Data Availability Index (3 digits)	________		
Study site lane volume	________	Standard Dev. Of Volume Est.	________
		Sample Size (N) for Vol. Est.	________
Single axle weight distribution			
Single axles counted	________	Single axles weighed	________
Single axles estimated for the year	________		
weight category 1: Definition _____		Number of Axles	________
weight category 2: Definition _____		Number of Axles	________
etc.			
Tandem axle weight distribution			
Tandem axles counted	________	Tandem axles weighed	________
Tandem axles estimated for the year	________		
weight category 1: Definition _____		Number of Axles	________
weight category 2: Definition _____		Number of Axles	________
etc.			
Triple axle weight distribution			
Triple axles counted	________	Triple axles weighed	________
Triple axles estimated for the year	________		
weight category 1: Definition _____		Number of Axles	________
weight category 2: Definition _____		Number of Axles	________
etc.			
Quad + axle weight distribution			
Quad + axles counted	________	Quad + axles weighed	________
Quad + axles estimated for the year	________		
weight category 1: Definition _____		Number of Axles	________
weight category 2: Definition _____		Number of Axles	________
etc.			
Total Number of Truck & Combinations	________		
Std Dev. of Truck Vol. Est.	________	Sample Size for Truck Vol.Est.	________
Annual ESAL for study site this year	________	Std Dev. of ESAL Est.	________
		Weighted N for ESAL Est.	________
SN (structural number) for study site this year	________		
D (Depth of concrete pavement)	________		
Number of historical modifications (version number)	________		
Code for method used to estimate AADT	________		
Date this update was created	________		
Comments			

Repeat this record once for each year since the pavement section was opened for traffic. The entire set of records is then repeated for each study site.

Figure 5.6. LTPP Central Traffic Database Primary Loading Estimates

Timing of Friction Measurements and Seasonal Variation

Each SHA selected the most appropriate time of year for conducting friction measurements in its area, based on the local experience and consideration of seasonal variation. Friction data were collected for the same time of year with each round of routine monitoring cycles.

Monitoring Before and After Rehabilitation/Maintenance Treatment

Additional friction measurements were performed on the GPS and SPS test sections before and after a major maintenance or rehabilitation action (e.g., overlay, seal coat, or porous friction course) had been completed. Guidelines for timing of friction measurements was provided by SHRP.

Friction Measurement Procedure/Equipment

Equipment

The locked-wheel friction tester (used in accordance with AASHTO T242, American Society for Testing Materials [ASTM] E274, supplemented with Appendix B of FHWA Technical Advisory T 5040.17) was the preferred method for obtaining friction measurements.

Operating Speed and Air Temperature

The friction data and air temperature were collected with a calibrated locked-wheel friction tester at 40 mph. Tests could be conducted at a lower speed if the legal maximum posted speed was less than 40 mph. For QA/QC restrictions, friction measurements were not conducted when the air temperature fell outside the range of 32°F to 110°F.

Friction Data Collection on 500 ft. GPS Test Sections

Friction data were collected on 500 ft. GPS test sections at two locations. Because the SHRP sections were marked at 100 ft. stations, the first friction measurement was completed on the first half of the section between stations 0 and 2, while the second friction measurement was obtained near the end of the section between stations 3 and 5. All measurements were obtained from the center of the inner wheel path. Skid Data Sheet 1 (5.47) was used to record the friction data for the 500 ft. GPS sections.

Friction Data Collection on 1000 ft. SPS Test Sections

Friction measurements were conducted at four locations within the 1000 ft. SPS sections:

1. First measurement (at the beginning) between stations 0 and 2
2. Second measurement (interior) between stations 3 and 5
3. Third measurement (interior) between stations 5 and 7
4. Fourth measurement (near the end) between stations 8 and 11

All measurements were conducted in the center of the inner wheel path. Skid Data Sheet 2 (5.47) was used to record the friction data for 1000 ft. SPS sections.

Data Reporting

Skid Number

The surface friction data were reported as a Skid Number (SN), which is the ratio of the frictional force to the test wheel load multiplied by 100.

Other Data Elements

The following data elements were also recorded on the skid data sheets: section identification and operator data, date and time of measurements, equipment brand and model, SHA equipment number, date of last calibration, pavement surface type, air temperature, and comments.

Other Monitoring: Maintenance

The maintenance activities undertaken on the LTPP sections will no doubt influence or affect the results of the pavement studies. Within SHRP-LTPP, maintenance performed on a test section was limited to that which would maintain the pavement in a safe and serviceable condition (5.48). Because any previous maintenance performed on an LTPP section could affect the pavement performance, both ongoing and historical maintenance data were considered essential to pavement performance evaluation of SHRP-LTPP data. Revisions in the type and level of maintenance or specific deferment or elimination of maintenance strategies could bias pavement performance results (5.48). To minimize the impact of such action, it was necessary to establish maintenance guidelines for SHRP-LTPP.

Maintenance Policy

A maintenance policy was developed for the GPS test sections to establish a set of rules that permit a "reasonable" level of maintenance to be performed on the monitoring sections. The policy was based on representative SHA preventive or routine maintenance procedures (**5.49**). The monitored sections were not to receive an artificially high amount of maintenance attention simply because of designation as a national pavement test site. Maintenance treatments were to be applied to a section in response to an observed pavement need, not in response to edicts to expend apportioned maintenance funds.

Scope and Objective

Maintenance guidelines were developed to ensure application of the same routine maintenance action to a SHRP-LTPP section as would be initiated at any similar site not included in SHRP. Specific guidelines were developed to ensure that maintenance actions were limited to those that would not influence the structural response of the pavement. In particular, limitations were placed on activities that would reduce, limit, or mask the type and amount of pavement performance information that could be obtained from the test site. Non–pavement–related maintenance activities for guard rails, lighting, and signs were not to be restricted by the guidelines (**5.49**).

Maintenance Control Zone

A maintenance control zone (Figure 5.7) was established for each SHRP-LTPP monitored test section to coordinate maintenance activities at the site and to reduce the influence of other types of maintenance activities on the performance of the pavement sections (**5.48, 5.49**). The zone was delineated to restrict maintenance within the confines of the zone to specifically designated activities. The SHRP-LTPP maintenance guidelines were, therefore, only to be applicable to maintenance activities performed within the maintenance control zone (**5.48**).

Safety-related maintenance could be performed at any time in accordance with the governing SHA standards. Safety-related maintenance activities included in this category are

- Spot patching of potholes
- Punchouts
- Blowups
- Other surface defects and restoration of skid resistance

Maintenance Requirements

The SHRP Regional Coordination Office Contractors (RCOCs) were to be advised, prior to commencement of a maintenance operation in the control zone, of any actions that would cover the pavement surface and "hide" distresses or change the structural characteristics (**5.48**). Maintenance treatments within the control zone were to be completed using the

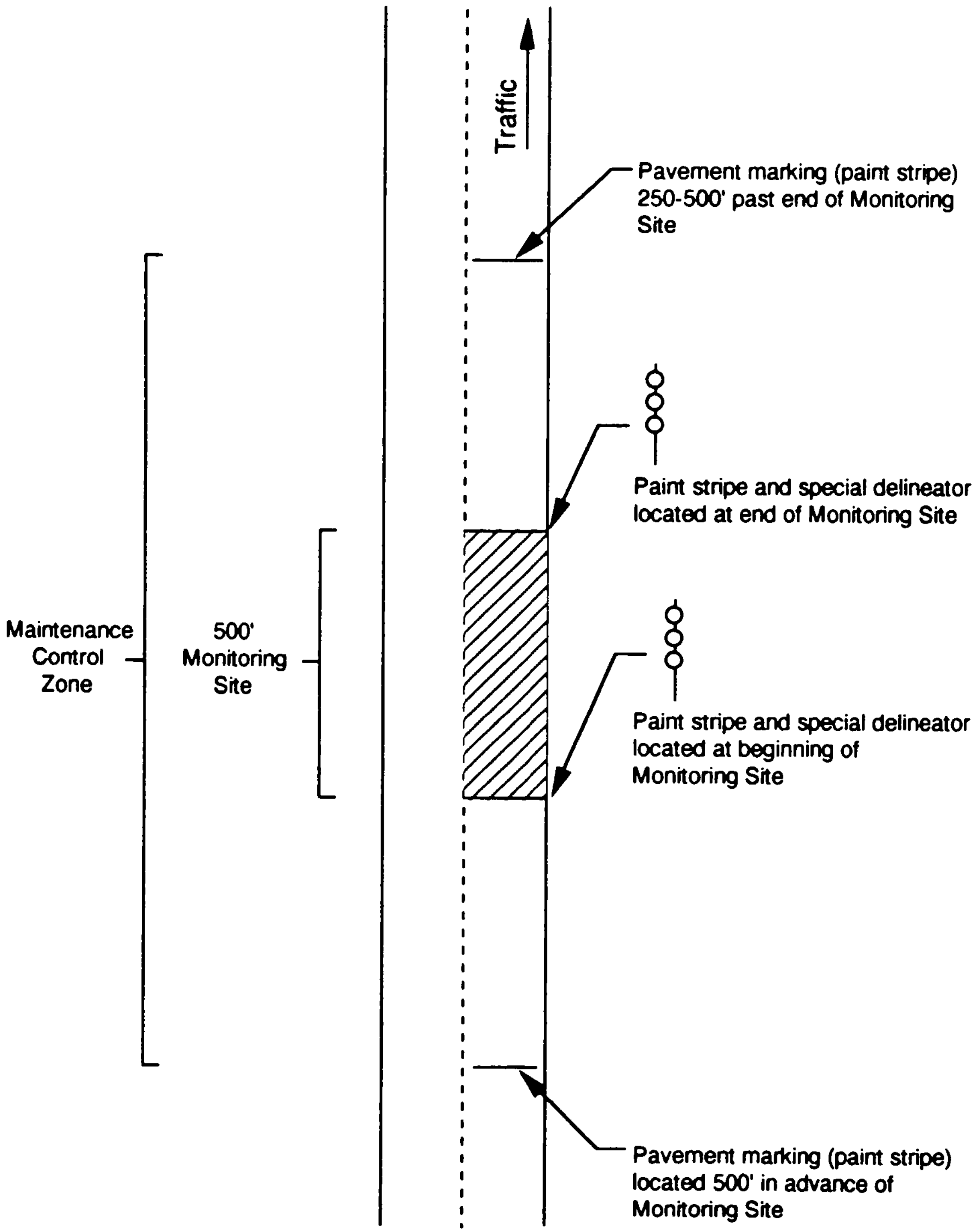


Figure 5.7 Illustration of Maintenance Control Zone

SHA's standard procedures and materials. Details concerning all maintenance activities for the LTPP-monitored sites were to be recorded on appropriate SHRP maintenance data forms.

For slowly deteriorating safety conditions, it was desirable that the SHA notify the SHRP RCOC in advance of any corrective action so that an assessment of the pavement condition could be made prior to application of the treatment. To ensure the attainment of the greatest amount of structural performance information from a test section, use of hot-mix asphalt concrete (HMAC) overlays to restore skid resistance in the control zone was discouraged.

Routine or Preventive Maintenance

The types of "routine" or "preventive" maintenance activities that were allowed on a SHRP-monitored section without RCOC notification included

- Crack sealing
- Joint cleaning/sealing
- Isolated spot pavement repairs

Other types of maintenance activities that were allowed on the SHRP-monitored sections but required coordination with the RCOC included application of the following types of seal coats:

- Sand seal
- Chip seal
- Aggregate seal
- Slurry seal
- Fog seal

Restoration or Rehabilitation Treatments

Maintenance, restoration, or rehabilitation treatments that should not be applied at the SHRP-monitored pavement sections in their first performance period (non-overlaid) include

- Milling, grinding, or use of heater-planer
- Undersealing
- HMAC or portland cement concrete (PCC) overlays
- Slab jacking
- Retrofitted underdrains or edge drains
- Other specialized types of maintenance activities that affect the structural response or performance of the test section

Maintenance Data Collection

The maintenance data collection plan addresses two separate time periods referred to as (1) historical data and (2) SHRP accumulated data. Historical data consist of information collected on or near the monitoring site prior to initiation of the site-specific SHRP maintenance data collection program. SHRP accumulated data is defined as the information collected anytime after the initiation of SHRP monitoring of the site. The SHRP maintenance data are accumulated using the collection system described in the remainder of this document. Historical data are recorded on a single maintenance data sheet, while the SHRP accumulated data are recorded on a series of maintenance data sheets.

The maintenance sheets were intended to record data items concerning maintenance activities that reasonably identify

- Existing pavement conditions prior to treatment
- Properties and quantities of materials used
- Construction techniques applied during treatment

Maintenance Data for SPS Test Sections

The data collection and reporting process for SPS test sites required the completion of specific data sheets, including some extracted from the "Data Collection Guide for Long-Term Pavement Performance Studies" (**5.50**), and other data sheets developed specifically for SPS. The SPS project-specific data sheets address construction data and special aspects of the materials sampling and testing activities.

In general, data obtained from monitoring activities performed after construction will be reported on data forms similar to those used for GPS test sections (**5.51, 5.52, 5.53, 5.54**). In contrast to the GPS test sections, each SPS site is composed of several test sections. Monitoring data on SPS sections, however, are recorded as section-specific data. Therefore, all maintenance activities performed on these SPS test sections, after completion of construction, should be recorded on a test section basis using appropriate data sheets contained in Chapter 6 of the "SHRP-LTPP Data Collection Guide" (**5.50**).

Other Monitoring: Rehabilitation

The collection of rehabilitation data for SHRP test sections is separated into distinct "before" and "after" time periods. Rehabilitation data for the pre-SHRP period were gleaned from historical data on existing pavement sections. The data accumulated during SHRP-LTPP studies were obtained through real-time data collection activities. The entry of both historical and current data in the LTPP National Pavement Performance Database (or in the National Information Management System) is essential because rehabilitation actions can significantly affect pavement performance of the test sections and hence monitoring data results.

Historical Rehabilitation Data

Historical rehabilitation data consisted of the information collected on the test section from original construction until initiation of site-specific SHRP rehabilitation data collection activities. The historical data for GPS and SPS sections are recorded on a single Inventory Data Sheet (Figure 5.8) which is described in Chapter 2 of the "Data Collection Guide" for LTPP studies (**5.55**). The maintenance and work activities to be reported as historical data are presented in Table 5.2.

SHRP Accumulated Rehabilitation Data for GPS Test Sections

Rehabilitation of the approved GPS test sections was not permitted during the SHRP monitoring performance period, except when the condition of the test section dropped to a level that required a rehabilitative measure. In this event, the RCOC was to coordinate the last round of evaluation measurements with the scheduled rehabilitation action. Examples of such rehabilitation actions are

- Extensive milling, grinding, grooving, or use of heater planer
- Undersealing
- Overlays (HMAC/PCC)
- Slab jacking
- Retrofitting underdrains or edge drains
- Other specific types of activities that affect the structural response of the monitoring site

For SHRP-LTPP these measures should have been applied to the pavement within a minimum of the designated 1250 ft. maintenance control zone (i.e., 500 ft. prior to the test section, 500 ft. within the test section, and 250 ft. beyond the test section), as described in Chapter 7 of the SHRP-LTPP "Data Collection Guide" (**5.56**).

If an activity is planned for the area outside of but not included within the maintenance control zone, a transition zone between the treatment and the control zone should be of sufficient length to ensure that the monitoring site is not influenced by the rehabilitative activity. The recommended transition zone length is 200 ft.

Rehabilitation Data for SPS Test Sections

The data collection and reporting process for SPS test sites requires the completion of specific data sheets, including some—extracted from the "Data Collection Guide for Long-Term Pavement Performance Studies" (**5.56**)—which were developed for the GPS and other data sheets developed specifically for SPS. The SPS project-specific data sheets address construction data and special aspects of the materials sampling and testing activities. Data obtained from monitoring activities performed after construction will be reported on data forms similar to those used for the GPS test sections. In contrast to the GPS test sections,

*STATE ASSIGNED ID [_ _ _ _]

SHEET 4

INVENTORY DATA

LTPP PROGRAM

*STATE CODE [_ _]

*SHRP SECTION ID [_ _ _ _]

AGE AND MAJOR PAVEMENT IMPROVEMENTS

* 1.DATE OF LATEST (RE)CONSTRUCTION (MONTH/YEAR) [_ _/_ _]

* 2.DATE SUBSEQUENTLY OPENED TO TRAFFIC (MONTH/YEAR) [_ _/_ _]

3.LATEST (RE)CONSTRUCTION COST PER LANE MILE (IN THOUSANDS OF DOLLARS)[1] _ _ _ _ _ _.

MAJOR IMPROVEMENTS SINCE LATEST (RE)CONSTRUCTION

* 4. YEAR	* 5. WORK TYPE CODE (TABLE A.17)	* 6. WORK QUANTITY (TABLE A.17 for units)	7. TOTAL COST[1] (THOUSANDS OF THICKNESS (INCHES)	8. DOLLARS PER LANE-MILE)
[_ _]	[_ _]	[_ _ _ _ _ _.]	_ _._	_ _ _.
[_ _]	[_ _]	[_ _ _ _ _ _.]	_ _._	_ _ _.
[_ _]	[_ _]	[_ _ _ _ _ _.]	_ _._	_ _ _.
[_ _]	[_ _]	[_ _ _ _ _ _.]	_ _._	_ _ _.
[_ _]	[_ _]	[_ _ _ _ _ _.]	_ _._	_ _ _.
[_ _]	[_ _]	[_ _ _ _ _ _.]	_ _._	_ _ _.

* 9.YEAR WHEN ROADWAY WIDENED [_ _]

*10.ORIGINAL NUMBER OF LANES (ONE DIRECTION) [_]

*11.FINAL NUMBER OF LANES (ONE DIRECTION) [_]

*12.LANE NUMBER OF LANE ADDED[2] [_]

NOTES:
1. Cost is to represent pavement structure cost. Non-pavement costs such as cut and fill work, work on bridges, culverts, lighting, and guard rails are to be excluded.
2. A lane created by roadway widening should not be used for SHRP LTPP unless the pavement structure under the entire lane was constructed at the same time and is uniform.

Figure 5.8. Inventory Data Sheet

Table 5.2. Maintenance and Rehabilitation Work Type Codes

	Code
Crack Sealing (linear ft)	01
Transverse Joint Sealing (linear ft)	02
Lane-Shoulder, Longitudinal Joint Sealing (linear ft)	03
Full Depth Joint Repair Patching of PCC (sq yd)	04
Full Depth Patching of PCC Pavement Other than at Joint (sq yd)	05
Partial Depth Patching of PCC Pavement Other than at Joint (sq yd)	06
PCC Slab Replacement (sq yd)	07
PCC Shoulder Restoration (sq yd)	08
PCC Shoulder Replacement (sq yd)	09
AC Shoulder Restoration (sq yd)	10
AC Shoulder Replacement (sq yd)	11
Grinding/Milling Surface (sq yd)	12
Grooving Surface (sq yd)	13
Pressure Grout Subsealing (no. of holes)	14
Slab Jacking Depressions (no. of depressions)	15
Asphalt Subsealing (no. of holes)	16
Spreading of Sand or Aggregate (sq yd)	17
Reconstruction (Removal and Replacement) (sq yd)	18
AC Overlay (sq yd)	19
PCC Overlay (sq yd)	20
Mechanical Premix Patch (using motor grader and roller) (sq yd)	21
Manual Premix Spot Patch (hand spreading and compacting with roller) (sq yd)	22
Machine Premix Patch (placing premix with paver, compacting with roller) (sq yd)	23
Full Depth Patch of AC Pavement (removing damaged material, repairing supporting material, and repairing) (sq yd)	24
Patch Pot Holes - Hand Spread, Compacted with Truck (no. of holes)	25
Skin Patching (hand tools/hot pot to apply liquid asphalt and aggregate) (sq yd)	26
Strip Patching (using spreader and distributor to apply hot liquid asphalt and aggregate) (sq yd)	27
Surface Treatment, single layer (sq yd)	28
Surface Treatment, double layer (sq yd)	29
Surface Treatment, three or more layers (sq yd)	30
Aggregate Seal Coat (sq yd)	31
Sand Seal Coat (sq yd)	32
Slurry Seal Coat (sq yd)	33
Fog Seal Coat (sq yd)	34
Prime Coat (sq yd)	35
Tack Coat (sq yd)	36
Dust Layering (sq yd)	37
Longitudinal Subdrains (linear ft)	38
Transverse Subdrainage (linear ft)	39
Drainage Blankets (sq yd)	40
Well System	41
Drainage Blankets with Longitudinal Drains	42

Table 5.2 (Continued)

	Code
Hot-Mix Recycled AC (sq yd)	43
Cold-Mix Recycled AC (sq yd)	44
Heater Scarification, Surface Recycled AC (sq yds)	45
Crack and Seat PCC Pavement as Base for New AC Surface (sq yd)	46
Crack and Seat PCC Pavement as Base for New PCC Surface (sq yd)	47
Recycled PCC (sq yd)	48
Pressure Relief Joints in PCC Pavements (linear ft)	49
Joint Load Transfer Restoration in PCC Pavements (linear ft)	50
Mill Off Existing Pavement and Overlay with AC (sq yd)	51
Mill Off Existing Pavement and Overlay with PCC (sq yd)	52
Other	53
Partial Depth Patching of PCC Pavement at Joints (sq yd)	54

each SPS site includes several test sections. Monitoring data on SPS sections will be recorded as section-specific data.

Instrumentation

The deterioration of the nation's highways during the past 15 years was the catalyst for the initiation and implementation of SHRP-LTPP (**5.57**). The LTPP effort was undertaken in part to develop a better understanding of the impact of a number of environmental and structural factors on pavement performance (**5.38**). The performance and behavior of the various GPS and SPS sections were scheduled for monitoring over time and across diverse environments, traffic loads, materials, pavement designs, maintenance strategies, and other influential factors (**5.58**).

Because of the combined number of GPS and SPS sites within LTPP, data acquisition for most monitoring activities was an annual affair. During SHRP-LTPP there have been two or three rounds of FWD, profile, and distress data acquisition. In the normal data acquisition program, there is no way to consistently investigate seasonal environmental effects on pavement behavior (i.e., present deflection response) or performance (i.e., distress, increase in deflection over time, etc.) because the measurements are taken within a few days out of each year.

In the latter portion of LTPP the pavement monitoring program was extended to include seasonal testing of FWD deflection, accompanied by installation of instrumentation capable of monitoring short-term temperature and moisture fluctuations as well as longer term effects due to temperature and moisture regimes (e.g., frost heave). Instrumentation capable of measuring these conditions was installed at a number of selected GPS and SPS sites.

Present Status

Pilot Studies

During the SHRP-LTPP instrumentation program two pilot studies were undertaken to explore installation techniques, costs, and effectiveness of currently available sensors for measurement of temperature and moisture. One of the pilot installations was located in New York State (**5.59**); the other was located in Idaho (**5.60**).

Pavement Type

The Syracuse, New York, site is a flexible pavement section with a thick 9½ in. (23.5 cm) HMAC layer on a thick 22 in. (56 cm) granular base resting on a clayey silt with gravel subgrade. The Idaho site is a rigid pavement section with a 9¼ in. (23.5 cm) to 9½ in. (24 cm) thick PCC layer over a 5 in. (12.7 cm) thick crushed gravel base and a 4 in. (10.2 cm) to

5 in. (12.7 cm) poorly graded gravel and sand subbase, resting on a silt to silty sand subgrade.

Measurement Equipment

The equipment installed at the sites included instrumentation to measure temperature, moisture, frost depth, and depth to water table.

Temperature Measurements

Two types of sensors, thermocouples and thermistors, were used to measure temperature. The sensors were arranged in strings and installed in such a way that temperatures could be measured at different depths beneath the pavement surface. The temperature measurements with depth were expected to define the location of the freezing front; however, it was found at the New York site that a resistivity probe could provide a more definitive location for this phenomenon.

Moisture Measurements

The moisture measurement instrumentation included time-domain reflectometry (TDR) sensors and a frequency-domain moisture monitor (Troxler Sentry 200). The TDR equipment is normally used to locate breaks in buried cable; the frequency-domain equipment is generally used for agriculture purposes.

Frost Measurements

The instrumentation for measuring frost penetration included a Cold Region Research and Engineering Laboratory (CRREL) resistance probe and a resistivity probe. The CRREL measurement method consists of measuring the contact resistance between adjacent probes under an alternating current. The resistivity probe technique used standard geophysical equipment to measure both current and voltage.

Water Table Depth

A piezometer was used to measure the depth to the water table at the Idaho site. A water level observation well consisting of a perforated plastic pipe surrounded by sand and extended to ground level by a solid plastic pipe was used at the New York site.

Temporary Benchmark

Because the sites were located in regions where frost penetrates into the roadbed, the detection of frost heave, volume expansion of wet materials, and growth of ice lenses was paramount. A temporary benchmark was established at each site to provide the capability for monitoring frost heave and volume expansion. The benchmark at the New York site consisted of a 15 ft. (4.6 m) rod anchored at the bottom by a "Borros Point." A similar installation was used at the Idaho site.

Installation

Installation procedures and recommendations were developed for the two sites by SHRP loan staff, the instrumentation engineer, and the appropriate regional personnel. The experience gained by the two pilot studies should be helpful in future instrumentation activities.

References

5.1 Strategic Highway Research Program. "Distress Identification Manual for the PASCO Films (PASCO-DIM)." Washington, D.C., March 1990.

5.2 Gibson, S. "PASCO Film Acceptance Review" (TRDF Technical Memorandum AU-148). Texas Research and Development Foundation, Austin, Texas, July 13, 1990.

5.3 Gibson, S. "Recommended Certification Criteria for PASCO FMA Interpretation Technician" (TRDF Technical Memorandum AU-149). Texas Research and Development Foundation, Austin, Texas, July 13, 1990.

5.4 Roper, H. "PASCO Distress Interpretation Procedure" (TRDF Technical Memorandum AU-154). Texas Research and Development Foundation, Austin, Texas, August 13, 1990.

5.5 Gibson, S., H. Roper, and W. O. Hadley. "Pilot Study for PASCO Distress Interpretation" (TRDF Technical Memorandum AU-164). Texas Research and Development Foundation, Austin, Texas, September 10, 1990.

5.6 Richter, C., Personal correspondence to Shahed Rowshan concerning IMS Level 1 QA/QC checks for distress (PADIAS). Strategic Highway Research Program, Washington, D.C., June 16, 1992.

5.7 Benson, K., et al. *Distress Identification Manual for the Long-Term Pavement Performance (LTPP) Studies* (Report No. SHRP-P-338). National Research Council, Strategic Highway Research Program, Washington, D.C., 1990.

5.8 Benson, K. "Recommended Quality Control of the Manual Distress Survey Data" (TRDF Technical Memorandum AU-158). Texas Research and Development Foundation, Austin, Texas, August 15, 1990.

5.9 Benson, K. "Recommended Certification Procedures for the Manual Distress Survey" (TRDF Technical Memorandum AU-156). Texas Research and Development Foundation, Austin, Texas, August 23, 1990.

5.10 Strategic Highway Research Program. "SHRP-LTPP Manual for FWD Testing and Operational Field Guide. Version 1.0" (Operational Guide No. SHRP-LTPP-OG-002). Washington, D.C., January 1989.

5.11 P-001 Technical Advisory Staff. "Data Readability and Completeness" in *FWDSCAN (Version 1.20) Program Background and User's Guide*, August 1989.

5.12 P-001b Technical Advisory Staff. "Analysis of Section Homogeneity, Nonrepresentative Test Pit and Section Data, and Structural Capacity" in *FWDCHECK Version 2.00, Volume II User's Guide*, January 1991.

5.13 Strategic Highway Research Program. "Layer Moduli Backcalculation Procedures—Rules and Guidelines." Washington, D.C., January 1992.

5.14 Hadley, W. O. "Quality Assurance Checks on FWD Data" (TRDF Technical Memorandum AU-207). Texas Research and Development Foundation, Austin, Texas, May 18, 1992.

5.15 *The AASHO Road Test, Report 5, Pavement Research.* Highway Research Board Special Report 61E. National Academy of Sciences, National Research Council Publication No. 954. Washington, D.C., 1962.

5.16 Roper, H. "Plan for Evaluation and Acceptance of K.J. Law Profilometer" (TRDF Technical Memorandum AU-53). Texas Research and Development Foundation, Austin, Texas, February 28, 1989.

5.17 Roper, H. "Personnel/Operator Requirements for SHRP K.J. Law Profilometers" (TRDF Technical Memorandum AU-54). Texas Research and Development Foundation, Austin, Texas, February 28, 1989.

5.18 Roper, H. "Statistical Analyses of IRI from SHRP Profilometers" (TRDF Technical Memorandum AU-66). Texas Research and Development Foundation, Austin, Texas, July 13, 1989.

5.19 Roper, H. "Preliminary Profilometer Data Analysis" (TRDF Technical Memorandum AU-67). Texas Research and Development Foundation, Austin, Texas, May 31, 1989.

5.20 Roper, H. "FHWA Profilometer Data Analysis" (TRDF Technical Memorandum AU-77). Texas Research and Development Foundation, Austin, Texas, October 29, 1989.

5.21 High, R. "Experimental Plan for the Comparisons of SHRP Profilometers" (TRDF Technical Memorandum AU-100). Texas Research and Development Foundation, Austin, Texas, January 26, 1990.

5.22 Roper, H. "Profilometer Test Plan" (TRDF Technical Memorandum AU-101). Texas Research and Development Foundation, Austin, Texas, January 29, 1990.

5.23 Turay, S. "Ann Arbor Comparative Testing Results" Pavement Management Systems (PMS) Ltd. Memorandum, August 28, 1992.

5.24 Roper, H. "Profile Data Collection Quality Control and Quality Assurance" (TRDF Technical Memorandum AU-82). Texas Research and Development Foundation, Austin, Texas, September 29, 1989.

5.25 Roper, H. "Profile Field QC Procedures" (TRDF Technical Memorandum AU-83). Texas Research and Development Foundation, Austin, Texas, October 6, 1989.

5.26 Roper, H. "Profile QC Procedures for Data Collection Assurance" (TRDF Technical Memorandum AU-85). Texas Research and Development Foundation, Austin, Texas, October 7, 1989.

5.27 Roper, H. "Guidelines of Profile Data Processing" (TRDF Technical Memorandum AU-98). Texas Research and Development Foundation, Austin, Texas, December 31, 1989.

5.28 Roper, H. "Profile Quality Assurance Software" (TRDF Technical Memorandum AU-138). Texas Research and Development Foundation, Austin, Texas, June 15, 1990.

5.29 Roper, H. "Initial Evaluation of the Pre-Processor for Profile Data Processing" (TRDF Technical Memorandum AU-156). Texas Research and Development Foundation, Austin, Texas, August 14, 1990.

5.30 Hadley, W. O. "Initial Statistical Analysis of the February 1990 SHRP Profilometer Workshop Results" (TRDF Technical Memorandum AU-131). Texas Research and Development Foundation, Austin, Texas, May 4, 1990.

5.31 Hadley, W. O. "Status and Plan of Action for Task 2.2.01, Comparative Testing" (TRDF Technical Memorandum AU-140). Texas Research and Development Foundation, Austin, Texas, June 19, 1990.

5.32 Hadley, W. O. and H. Roper. "Comparative Testing of SHRP Profilometers" *(Transportation Research Record 1311)*. Washington, D.C. 1991.

5.33 Roper, H. "Recommendations on the Specifications for the Purchase of Dipstick" (TRDF Technical Memorandum AU-76). Texas Research and Development Foundation, Austin, Texas, October 29, 1989.

5.34 Roper, H. "Dipstick Data Handling Plan" (TRDF Technical Memorandum AU-153). Texas Research and Development Foundation, Austin, Texas, August 13, 1990.

5.35 Roper, H. "SHRP-LTPP Dipstick Acceptance Testing" (TRDF Technical Memorandum AU-92). Texas Research and Development Foundation, Austin, Texas, November 22, 1989.

5.36 Roper, H. "SHRP-LTPP Dipstick Acceptance Testing for Southern Region" (TRDF Technical Memorandum AU-142). Texas Research and Development Foundation, Austin, Texas, June 22, 1990.

5.37 High, R. "Dipstick Data Analysis" (TRDF Technical Memorandum AU-94). Texas Research and Development Foundation, Austin, Texas, December 1, 1989.

5.38 *Strategic Highway Research Program Research Plans, Final Report.* Transportation Research Board, Washington, D.C. May 1986.

5.39 Hallenbeck, M. and K. Gupta. "The SHRP Traffic Data Requirements." Washington State Transportation Center (TRAC), Seattle, Washington, August 1991.

5.40 Strategic Highway Research Program. "Framework for Traffic Data Collection at GPS Test Locations." Washington, D.C., January 1989.

5.41 "SHRP Traffic Data Collection and Analysis Expert Task Group meeting notebook." Compiled by Texas Research and Development Foundation, Austin, Texas, May 1992.

5.42 German, J. L. "SHRP-LTPP Guidelines for Traffic Data Collection Plans." Strategic Texas Research and Development Foundation, Austin, Texas, October 1991.

5.43 Hallenbeck, M. "SHRP-LTPP Traffic Database Design." Strategic Highway Research Program, Washington, D.C., August 1990.

5.44 *Traffic Monitoring Guide.* US Department of Transportation, Federal Highway Administration. Washington, D.C. June 1985.

5.45 Hallenbeck, M. "Procedures for Manipulating SHRP-LTPP Traffic Data." Washington State Transportation Center (TRAC), Seattle, Washington, August 1990.

5.46 German, J. L. "SHRP-LTPP International Traffic Data Collection Handbook." Texas Research and Development Foundation, Austin, Texas, September 1991.

5.47 Strategic Highway Research Program. "Skid Data Collection for SHRP Test Sections" (TRDF Reference Number MG0014). Washington, D.C., May 5, 1989.

5.48 Strategic Highway Research Program. "SHRP Guidelines for Maintenance of General Pavement Studies (GPS) Test Sections" (Operational Memorandum SHRP-LTPP-OM-001). Washington, D.C., July 1988.

5.49 Elkins, G. E. "Policy for Pavement Maintenance on GPS Sections" (TRDF Technical Memorandum T-001). Texas Research and Development Foundation, Austin, Texas, May 26, 1988.

5.50 Strategic Highway Research Program. "Data Collection Guide for Long-Term Pavement Performance Studies," Chapter 6: "Maintenance Data Collection" (Operational Guide SHRP-LTPP-OG-001). Washington, D.C., January, 1990.

5.51 Strategic Highway Research Program. "SPS Data Collection Guidelines for Experiment SPS-1, Study of Structural Factors for Flexible Pavements" (Operational Memorandum No. SHRP-LTPP-OM-026). Washington, D.C., December 1991.

5.52 Strategic Highway Research Program. "SPS Data Collection Guidelines for Experiment SPS-2, Strategic Study of Structural Factors for Rigid Pavements" (Operational Memorandum No. SHRP-LTPP-OM-028). Washington, D.C., February 1992.

5.53 Strategic Highway Research Program. "SPS Data Collection Guidelines for Experiment SPS-5, Rehabilitation of Hot Mix Asphalt Concrete Pavements" (Operational Memorandum No. SHRP-LTPP-OM-015). Washington, D.C., October 1990.

5.54 Strategic Highway Research Program. "SPS Data Collection Guidelines for Experiment SPS-6, Rehabilitation of Jointed Portland Cement Concrete Pavements" (Operational Memorandum No. SHRP-LTPP-OM-023). Washington, D.C., May 1991.

5.55 Strategic Highway Research Program. "Data Collection Guide for Long-Term Pavement Performance Studies," Chapter 2: "Inventory Data Collection for LTPP." (Operational Guide No. SHRP-LTPP-OG-001). Washington, D.C., January 1990.

5.56 Strategic Highway Research Program. "Data Collection Guide for Long-Term Pavement Performance Studies," Chapter 7: "Rehabilitation Data Collection." (Operational Guide No. SHRP-LTPP-OG-001). Washington, D.C., January 1990.

5.57 *America's Highways: Accelerating the Search for Innovation* (Special Report 202, Strategic Transportation Research Study: Highways). Transportation Research Board, Washington, D.C. 1984.

5.58 High, R. "Data Analysis Plan for LTPP Studies" (TRDF Technical Memorandum AU-36). Texas Research and Development Foundation, Austin, Texas, March 29, 1989.

5.59 Pavement Management Systems (PMS) Ltd. "Seasonal Testing Instrumentation Pilot" (GPS 361011; IH481.5.B). E. Syracuse, New York, October 1991.

5.60 Nichols Consulting Engineers. "Seasonal Instrumentation Pilot Study" (Instrumentation Installation, Section 163023IN - Idaho). Reno, Nevada. June 1992.

Section 6
Information Management System (IMS)

Background

A major impediment to past pavement research efforts was the availability and accessibility of comprehensive, diverse, yet consistent traffic materials, structural, and climatic data for different pavement types. There is no doubt that datasets containing variable and inconsistent data make it extremely risky to develop inferential conclusions. Because of historical problems with data comprehensiveness, quality, and consistency, it is of strategic importance to develop a national database that can overcome these flaws and allow researchers to pursue studies of long-term pavement performance with confidence.

The principal goal of the Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) program was to design an approach for the collection of information and development of analysis procedures capable of providing short-, intermediate- and long-term findings for improving overall pavement performance. As a consequence, a major activity of SHRP-LTPP was the establishment of a National Pavement Performance Database (NPPDB) to support the goals, objectives, and needs of LTPP.

LTPP Information Management Systems

From the outset, one of the basic objectives of SHRP was the establishment of the NPPDB to store all the data being collected and generated through LTPP (6.1). The following types of data are collected in LTPP and stored in the NPPDB:

- Inventory (as built)
- Materials Characterization
- Longitudinal Profile
- Deflection
- Transverse (Cross) Profile
- Distress
- Friction
- Maintenance
- Rehabilitation
- Climate
- Traffic

An Information Management System (IMS) consisting of four regional systems and a central system was developed in SHRP-LTPP to service the NPPDB. The National Information Management System (NIMS) is the central system (**6.2**). The NIMS comprises the hardware and software systems that were assembled to house the NPPDB. This system is administered by and resides at the Transportation Research Board (TRB). The four regional systems are designated Regional Information Management Systems (RIMS). LTPP data were generally received, checked, and entered at the RIMS by the Regional Coordination Office Contractor (RCOC) personnel under the direction of a SHRP Regional Engineer. Periodic uploads were made from the RIMS to the NIMS.

A critical function of the IMS is the verification and validation of the accuracy and correctness of the data received and stored in the NPPDB. The NPPDB data must pass several IMS-based quality assurance (QA) checks before being released to the public from NIMS. These checks verify the presence, reasonableness, and validity of the data. The procedures for data checks and data uploads to the NIMS are critical elements in the SHRP-LTPP IMS.

SHRP-LTPP Regions

Regional offices were established to coordinate SHRP-LTPP–related activities across the United States and Canada. Each region includes several states and/or provinces, with test sections located throughout the boundaries. These offices operate as regional data collection and validation centers for pavement test section data.

The four SHRP regions were selected primarily on the basis of climatic considerations (**6.2**). The region boundaries were adjusted to correspond to state boundaries as illustrated in Figure 6.1 (**6.3**). The North Atlantic region corresponds roughly to the wet-freeze American Association of State Highway and Transportation Officials (AASHTO) classification, while the Southern region is primarily a wet-nonfreeze zone. The North Central region is predominantly wet-freeze, while the Western region contains both dry-freeze and dry-nonfreeze.

Note that the climatic zone designations do not necessarily represent the environmental conditions at a specific location within that region. For example, a wet-nonfreeze region (e.g., West Coast states) could in fact contain wet-freeze areas at higher elevations.

RIMS functions involve primarily data collection, data validation, and data entry. Regional staff members maintain a working relationship with all the data providers and have the technical expertise to judge data quality; hence their participation is essential to the success of the IMS.

Inventory, maintenance, rehabilitation, and traffic data are collected at the state level and forwarded to the appropriate regional center. The regional centers are responsible for the collection of test and monitoring data on the pavement sections. All data collected are entered in the RIMS through a menu-driven system or are loaded by programs that read the data from machine-readable media. Quality checks are incorporated into all update programs,

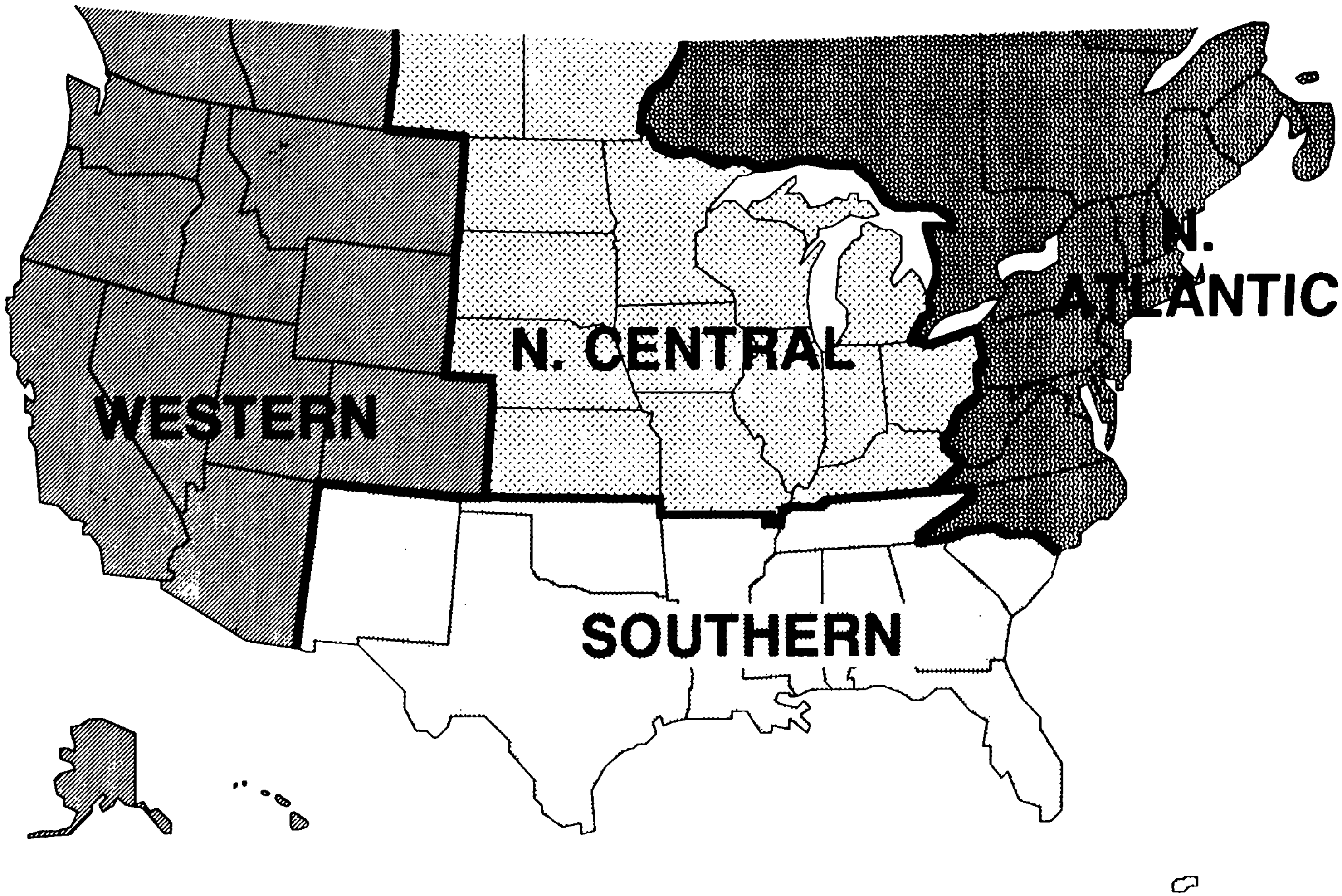


Figure 6.1 SHRP-LTPP Regional Boundaries

and reports are designed to provide additional checks. Pavement data are transferred to the NIMS after validation at the regional level.

Information Sources

Several information sources describe in detail the data housed within the LTPP database and how it was collected for the NPPDB. The SHRP-LTPP "Data Collection Guide" (DCG) (**6.4**) is the main source of data collection instructions and data sheets for the LTPP program. Detailed data collection guides have been developed for the materials characterization and sampling program and for most of the activities defined within the pavement monitoring program (**6.4**).

An IMS schema report describes the data structure as it is implemented in the Oracle Relational Database Management Systems and illustrates the data tables (logical groups of data) and the fields (or data elements) contained within those tables. The schema also identifies the key (index) fields and the data types associated with each field.

The IMS data dictionary report provides a more thorough description of each of the fields (or data elements) and various items of interest about each of the fields.

The IMS schema and data dictionary reports are updated as the IMS develops and evolves, and they are provided on disk to researchers requesting SHRP data. The current versions of the reports are normally included in the latest version of the *Database Structure Reference Manual* (**6.5**) of the LTPP IMS Manuals.

Data Collection Guide

The primary purpose of the DCG is to provide a uniform basis for data collection during long-term monitoring of the performance of LTPP test sections. Data items considered to be of high priority for achieving the goals of LTPP are identified, but data items that are desirable for inclusion in the NPPDB for other purposes are also included. The DCG is able to incorporate modifications and additions that will become necessary as technical advances are made and other research needs become better defined. To ensure that critical data will be available for the future development of pavement performance models, particular emphasis is placed on collection of data items considered essential to long-term pavement performance.

The DCG was initially developed for use with General Pavement Studies (GPS) sections, but many of the DCG sheets are also used with Specific Pavement Studies (SPS) sections. Additional data sheets and tables have been designed and used to record data collected from the SPS sections.

Schema Report

The schema report defines the various tables (categories of data) and fields (individual pieces of data) housed within NPPDB and identifies how they are stored in the database. In addition, the schema identifies the fields in the database that belong together as a record, the records that reside in a certain table, and the tables that constitute a specific data module.

Each of the data modules (inventory, traffic, distress, etc.) consists of numerous tables encompassing one or more data sheets. These tables represent a collection of information about a specific item (the location of all LTPP pavement sections by state, elevation, coordinates, etc.). Each table is a collection of records that contain data about a specific pavement section. Each record consists of individual fields that represent the smallest category of information in the database.

Excerpts from the inventory (INV) data module of the IMS schema are presented in Figure 6.2. Specifically, the INV_AGE and INV_GENERAL tables are included in the figure. One of the records in the Inventory Module is the type of pavement surface (i.e., PAVEMENT_TYPE) existing when a specific pavement section (SHRP_ID and STATE_CODE) was accepted in the LTPP program. This field and many other closely related fields (LANE_WIDTH, SUB_DRAINAGE_TYPE, etc.) that further describe the pavement section are combined to form the IMS INV_GENERAL table. The inventory data are related to one of the seven modules constituting the LTPP IMS database.

Key Fields

Key fields identify a unique set of fields (dataset) that form a record within a table. Similar to indices for arrays, the key fields define how the data will be stored or retrieved. The two principal key fields within the IMS are SHRP_ID and STATE_CODE, which are the two unique fields that identify a specific pavement section. Storage for all data for a particular section is related to these two fields. The key fields are identified in the schema by left-justified names composed of all capital letters. For example, the key fields for IMS table INV_AGE (Figure 6.2) are SHRP_ID, STATE_CODE, CONSTRUCTION_NO, and CONSTRUCTION_DATE; the key fields for table INV_GENERAL are SHRP_ID, STATE_CODE, and CONSTRUCTION_NO.

Other Fields

The other fields (i.e., besides the key fields) are used to identify the individual pieces of data in records and are identified by capitalized name combinations indented one column space to the right. For example, the other fields in IMS table INV_AGE (Figure 6.2) that are related to the project identified by the key fields are TRAFFIC_OPEN_DATE, CONSTRUCTION_COST, YEAR_WIDENED, ORIGINAL_NO_LANES, FINAL_NO_LANE, LANE_ADDED_NO, and RECORD_STATUS.

INV_AGE Age of pavement data (Data Sheet: Inventory 4).

	SHRP_ID	NUMBER(4.0)
Key Fields	STATE_CODE	NUMBER(2,0)
	CONSTRUCTION_NO	NUMBER(2,0)
	CONSTRUCTION_DATE	DATE(7)
	TRAFFIC_OPEN_DATE	DATE(7)
	CONSTRUCTION_COST	NUMBER(5,0)
Other Fields	YEAR_WIDENED	NUMBER(2,0)
	ORIGINAL_NO_LANES	NUMBER(1,0)
	FINAL_NO_LANES	NUMBER(1,0)
	LANE_ADDED_NO	NUMBER(1,0)
	RECORD_STATUS	CHAR(1)

INV_GENERAL Geometric, drainage, and other general information requiring the construction number. (Data Sheets: Inventory 1, 2, 3).

	SHRP_ID	NUMBER(4,0)
Key Fields	STATE_CODE	NUMBER(2,0)
	CONSTRUCTION_NO	NUMBER(2,0)
	NO_OF_LANES	NUMBER(1,0)
	PAVEMENT_TYPE	NUMBER(2,0)
	PAVEMENT_TYPE_OTHER	CHAR(40)
	LANE_WIDTH	NUMBER(3,1
	LANE_NO	NUMBER(1,0)
Other Fields	SUB_DRAINAGE_LOCATION	NUMBER(1,0)
	SUB_DRAINAGE_TYPE	NUMBER(1,0)
	SUB_DRAINAGE_TYPE_OTHER	CHAR(40)
	LONG_DRAIN_DIAMETER	NUMBER(2,1)
	LATERALS_SPACING	NUMBER(3,0)
	DEPTH_TO_RIGID	NUMBER(3,1)
	RECORD_STATUS	CHAR(1)

Figure 6.2. Schema Reports for Two Tables Developed from Inventory Data

These fields can be composed of several types or forms, such as NUMBER, CHAR(acter), or DATE. The assignment of numerical fields (or NUMBER) must be made with a knowledge of the expected ranges of values, based on engineering knowledge and judgments. The assignment of a numeric value, including the total number of digits and decimal digits, implies an absolute range that will be stored in the IMS database. For example, NUMBER(5,2) implies a maximum of five total digits with two of the digits located to the right of the decimal (e.g., 123.45). The maximum value that could be stored in this field is 999.99 and the minimum value would be -99.99 (the minus sign counts as a digit). Therefore, NUMBER(5,2) sets an absolute value range for numeric fields. CHAR(10) type fields are alphanumeric fields that may contain any valid alphanumeric character up to the number specified in the parentheses—10 in this example.

Data Dictionary Report

The data dictionary is a supplemental report that provides the IMS user with descriptions of the various fields or data elements in each table. The Data Dictionary entry identifies the origin of the data (data sheet and item, etc.) and presents a brief description of the field (data type), data ranges, and associated information. An excerpt of the Data Dictionary for portions of the (SKID) data module is presented in Figure 6.3.

The rules associated with the IMS data dictionary determine the amount and type of data that can be input in each field. For example, the data dictionary defines the length of a field, the type of data to be entered (numeric, alphabetic, date, etc.), and the acceptable ranges for the data (e.g., a positive number from 1 to 100). For example, in Figure 6.3 SKID_SURFACE is identified as a number (1.0) data type or integer (i.e., length of 1 with no decimal). The surface type can then be either AC (1), Concrete (2), Surface Treatment (3), or Other (4).

Range checks are conducted to ensure that the numeric field values fall within defined limits. Some ranges are absolute and define the maximum (and/or minimum) values possible for that data element. For example, in a sieve analysis the value must be less than or equal to 100% passing a sieve (i.e., maximum limit of 100) and greater than or equal to 0% passing a sieve (i.e., minimum limit of 0). In this case the absolute range would be 0 to 100. Other range checks represent comparisons of numeric data with normally expected limits of the data element (e.g., a SKID_NO_BEGIN or SKID_NO_END is expected to be between 30 and 70 for treaded tires).

When data are entered in a field, the computer QA program checks the data in the field against the format specified for that field in the data dictionary. If the data fall outside the normal expected range but within the absolute limits, the computer displays warning messages but allows data entry to continue. In this situation the data can be double-checked for accuracy. If the data fall outside absolute limits, an error message is displayed, the value will not be allowed as input, and data entry correction is required before moving from the particular field.

SKID_NO_BEGIN IMS Table: MON_SKID

The skid number (friction number) between the vehicle wheel tire and the pavement at the beginning of the section (between station 0-2).

Data Type:	NUMBER(2,0)		
Units:	Percent	Validation:	
QA Minimum:	X	QA Range:	30 - 70
Source:	MONITORING SKID SHEET 1.	Item number:	3

SKID_NO_END IMS Table: MON_SKID

The skid number (friction number) between the vehicle wheel tire and the pavement at the end of the section (between station 3-5).

Data Type:	NUMBER(2,0)		
Units:	Percent	Validation:	
QA Minimum:	X	QA Range:	30 - 70
Source:	MONITORING SKID SHEET 1.	Item number:	4

SKID_SPEED IMS Table: MON_SKID

The speed at which the vehicle was traveling when the skid numbers were obtained.

Data Type:	NUMBER(2,0)		
Units:	MPH	Validation:	
QA Minimum:	X	QA Range:	35 - 45
Source:	MONITORING SKID SHEET 1	Item number:	5

SKID_SURFACE IMS Table: MON_SKID

Code for the general type of pavement surface.

Data Type:	NUMBER(1,0)		
Units:		Validation:	AC (1), Concrete (2), Surface Treatment (3), Other (4)
QA Minimum:		QA Range:	
Source:	MONITORING SKID SHEET 1	Item Number:	11

Figure 6.3. Data Dictionary Excerpt for Friction (SKID)

Certain fields (particularly the primary key fields) are mandatory and cannot be successfully completed until an acceptable entry has been entered in that field. Because some records depend on information residing in basic parent records, data for parent records must be entered before data can be entered in dependent records, or an error message will occur.

Data Types, Elements, and Sources

The NPPDB (or NIMS) is the central repository for all LTPP data. The NPPDB consists of data uploaded from the four regional centers along with data entered directly at the national center. All requests for LTPP information or data files from the user community are processed at the NPPDB (or NIMS). The data processed directly at the NIMS include the environmental data and all administrative data (e.g., information for new pavement sections, experiment assignments, and code tables). Each region is responsible for the data on the SHRP pavement sections located within its assigned states; therefore, there is no data collection overlap between states. Table 6.1 presents an IMS data processing summary.

The process of transferring data from the RIMS to the NIMS is termed a NIMS upload, and the collection of programs that control the process is called NIMS upload software. Administrative data are periodically sent to the RIMS. All new procedures, modifications to the IMS structure, and code changes are also initiated at the NIMS. This process of transferring data from the NIMS to the RIMS is termed a NIMS download. The procedures for the transfer of information are described in the SHRP *Programmer's Reference Manual* (6.6) and in the LTPP NIMS and RIMS *User Manuals* (6.7, 6.8).

IMS QA Process

The QA concept of data checks is presented graphically in Figure 6.4. The data checks involve (1) internal QA checks by state highway agencies (SHAs) of historical data, (2) QA checks by SHRP contractors of specific data such as environmental and distress data, (3) regional QA checks of all data by RCOCs, and (4) sophisticated and comprehensive QA checks of all data within the NPPDB. The final checks result in the eventual release of data at the section (Level 1) or experiment (Level 2) levels. This QA process is necessary to assure the researchers that the data can be trusted and that their findings and recommendations are based on quality data.

Specifically, the components of the IMS QA plan are performed in the following sequence:

1. Data collection procedures are documented and executed for each module in the IMS to ensure that historical and monitored data are collected in similar format, types, conditions, etc. Internal QA checks are instituted to check for obvious mistakes, data anomalies, etc.

Table 6.1. IMS Data Processing Summary (6.4)

Data Type	Collection Frequency	Source
Inventory	Once	SHA
Maintenance	Per activity	SHA
Monitoring		
Falling Weight Deflectometer	Varies (1)	FWD
Distress	Every 1 to 2 years	PASCO/Manual
Transverse Profile	Every 1 to 2 years	PASCO/Dipstick
Profile	Annual	Profilometer/ Dipstick
Skid	Every 2 years	SHA
Rehabilitation	Per activity	SHA
Materials Testing	Once	SHRP Testing Lab
Traffic	Varies (2)	National Traffic Database (NTDB)
Climate	Update every 2 years	National Climatic Database (3) (NCDB)

(1) 12–14 times per year in alternate years for seasonal monitoring; once every 5 years for other sites.
(2) Continuous weigh-in-motion (WIM) or continuous automated vehicle classification plus seasonal WIM.
(3) Data obtained from National Climatic Data Center (NCDC).

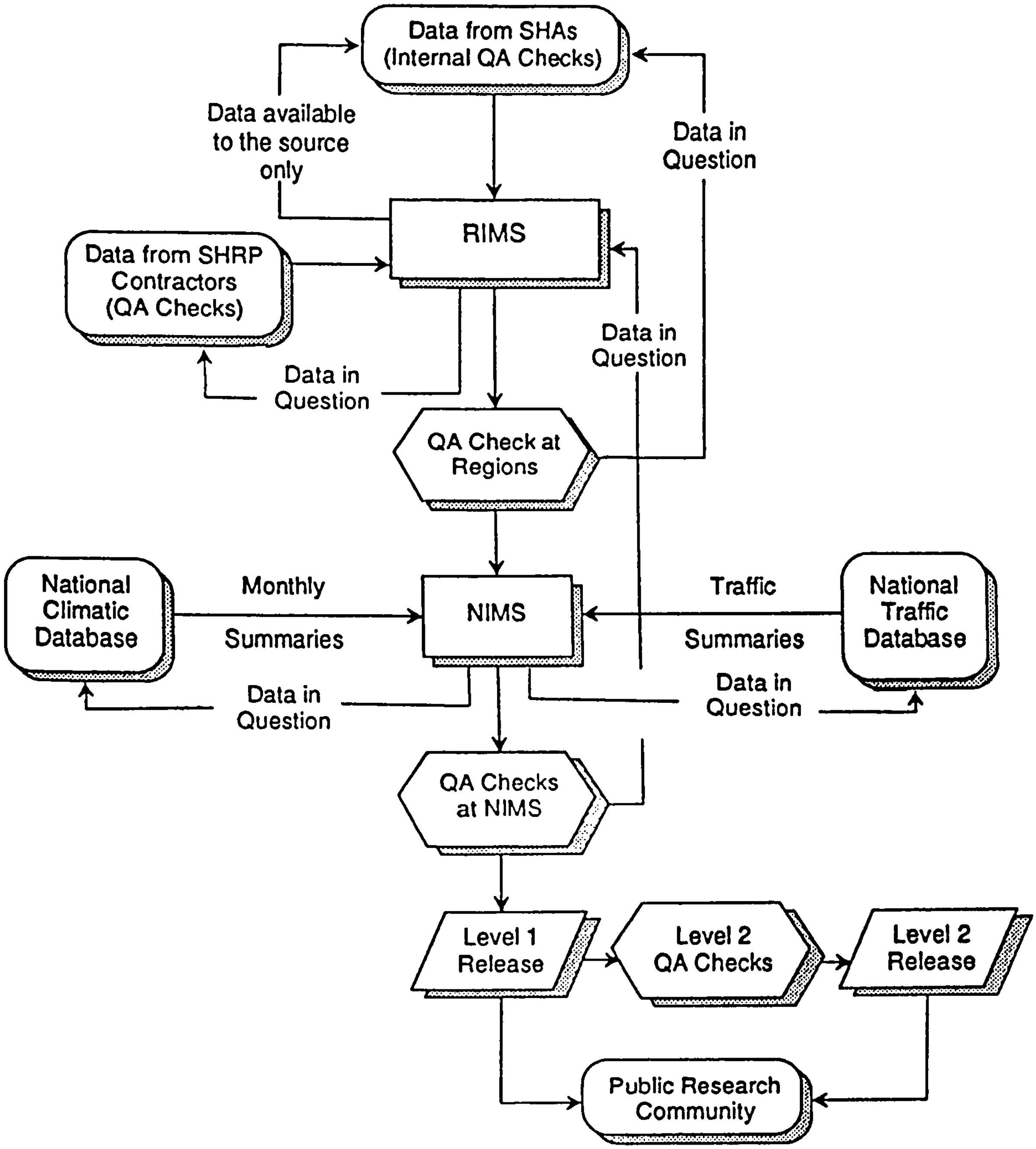


Figure 6.4. Data Flow in the LTPP IMS

2. Regional review of all input at RIMS is undertaken to identify obvious data collection and data entry errors.

3. Internal checks are executed at the NIMS to identify data entry problems and errors.

4. The formal IMS QA software programs are executed at the NIMS. This component involves nine categories of QA checks defined within two release levels.

The formalized computer-based QA checks involve data entry checks at the RIMS and NIMS, five QA checks at the NIMS on a section-by-section basis, and four QA checks at the NIMS on an experiment-by-experiment basis.

RIMS/NIMS Data Entry Check

Data entry checks programmed in the RIMS/NIMS include mandatory, logic, range, and data verification checks (**6.9**). The mandatory checks involve checks for non-null entries in all key fields and other designated fields. The RIMS will require entry in these positions or will invoke an audible warning and message that data are required in the field.

Logic checks are also included to ensure data compatibility across tables. An example of a logic check is checking that the minimum data value is less than or equal to the mean, which is less than or equal to the maximum for a given parameter.

Range checks are enforced to ensure that numeric field values fall within defined limits. Absolute limits (i.e., theoretically possible range limits) and warning or expected limits (i.e., practical range limits) are used.

Verification checks are instituted systemwide in the NIMS to verify that the SHRP-LTPP sections have been authorized for LTPP and are included within the EXPERIMENT_SECTION table before any data from that section can be entered in the IMS.

Level 1: Section Release

The first release level is a section-by-section release process involving five individual QA checks defined as A through E checks (**6.3, 6.10**). The Level 1 release QA checks are presented in Figure 6.5 and involve the following activities:

Check	Description
A	Random checks to ensure correct RIMS-NIMS upload exchange
B	Data dependency checks to ensure that basic, essential section information is recorded in NIMS (location, elevation, etc.)
C	Minimum data search for critical elements (e.g., friction data should include skid number)

D Expanded range checks to identify data elements that fall outside an expected range

E Intramodular checks to verify the consistency of data within data modules

These Level 1 data checks are structured to ensure data quality in a particular SHRP section, but do not address QA requirements between sections, states, and regions. These more sophisticated checks are required at the next release level.

The five checks (A—E) in the Level 1 release category (**6.9**) are hierarchical in concept and must be conducted in succession as indicated in Figures 6.5 and 6.6. In this concept, the data dependency checks (i.e., B check) will not be processed until the RIMS-NIMS data check transfer (i.e., A check) has been successfully completed. Similarly, the E—level checks (intramodular) are not initiated until the range checks (D check) have been successfully completed. After the E check has been conducted and the data in the particular IMS table passes the check, that IMS table can be released for public use.

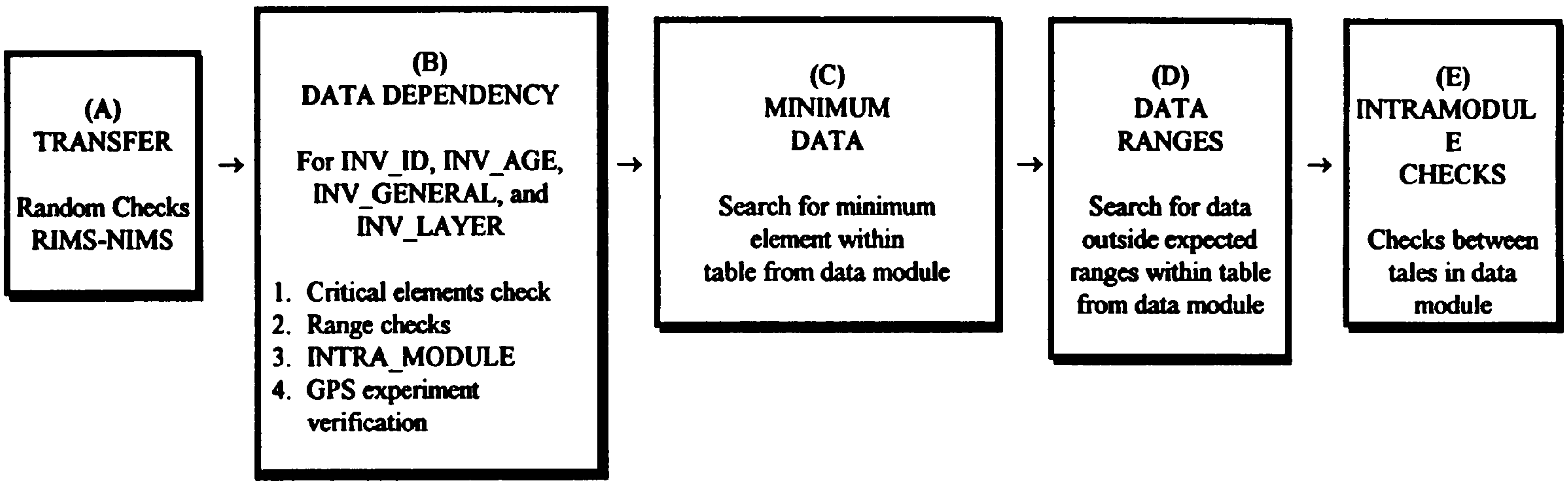
It should be noted that the QA checks are conducted on the individual tables within IMS and not on the SHRP sections as a whole. For that reason, the Level 1 release could allow some data to be released for a section (e.g., friction results) while other section data that fail to meet the checks (e.g., climate) would not achieve the release status.

Once records have passed through sublevel E, the data are available for a section release (**6.10**). These data are accompanied by an appropriate disclaimer from SHRP:

SHRP-LTPP Section Release Disclaimer

The SHRP-LTPP data are available for release at two levels. The first level of data release (Level 1) involves section-by-section data availability searches of the IMS, and includes a minimal number of pre-release data checks on the individual SHRP test sections. The second level of release data checks on the data availability searches of the IMS on an experiment-by-experiment basis, and requires the completion of a designated number of global data checks before approval for release.

The SHRP-LTPP information and data from a Level 1 release represent a release on a section-by-section basis. At this time there are insufficient data available in the IMS to support a Level 2 release. Because of this situation, it is recommended that the data and information only be used for evaluation and analysis at an individual section level. If a report, paper, or technical document is generated using results from this release, then a statement must be included indicating that the SHRP-LTPP information and data were obtained from a SHRP-LTPP Level 1 release and the date the data were obtained.



Except INV_D, INV_AGE, INV_GENERAL, and INV_LAYER tales in inventory module

Figure 6.5. IMS Level 1 (Section) Release Quality Check

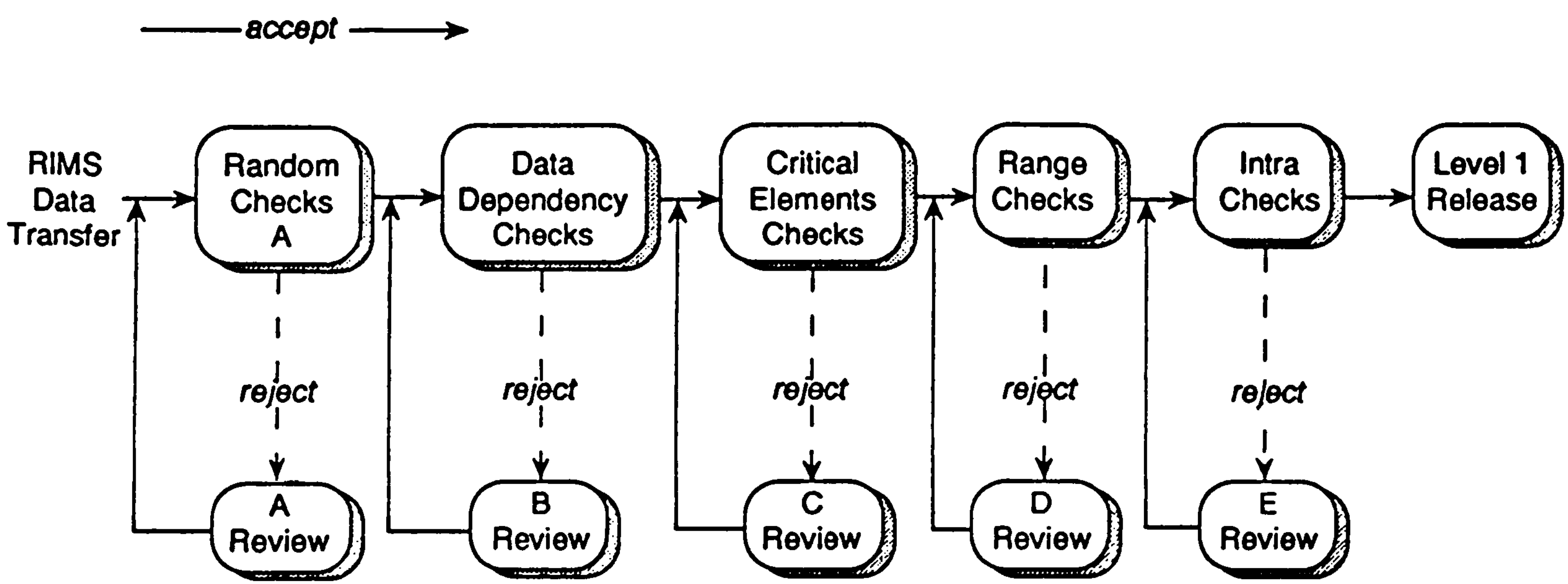


Figure 6.6. Data Level Advancements with Quality Control Checks

During SHRP-LTPP, the Level 1 checks were defined and installed within the NIMS. Four Level 1 data releases have been completed using the checks. In the process the checks have been reviewed, expanded, and revised as necessary.

Level 2: Experiment Release

A Level 2 IMS release is classified as an experiment release and includes QA checks across data modules (**6.11**), confirmation of GPS experiment and cell assignments (**6.12**), and statistical checks on the data and IMS tables (**6.13**) within each designated GPS experiment. The successful completion of these checks means that the LTPP data would be available for a general experiment-by-experiment evaluation and analysis. The IMS Level 2 release QA checks involve the following activities:

Check	Description
F	Intermodular cross-checks applied to verify existence and consistency of data for related categories
G	Experiment and cell assignment checks based on collected data
H	Various checks involving frequency distributions and bimodal and variance checks
I	Statistical checks for outliers, missing data, and completeness of experiment

Figure 6.7 presents an example of the type of intermodular cross-checks (QA Check F) included in the QA program. For assessing falling weight deflectometer (FWD) deflection data at SHRP sites, it would be essential to have information on environment (temperature), materials (layer thicknesses and resilient modulus estimates), and depth to rigid layer. Similarly, an analysis of AASHTO performance such as the Present Serviceability Index (PSI) would require information on roughness (profile), cracking and patching (distress), rutting, and surface material types. This check is in fact conducted for a specific SHRP-LTPP section but is representative of the checks that are performed across data modules.

This check must be completed before the initiation of the experiment and cell assignment checks (or G check).

The experiment and cell verification (G check) is essential for establishing the completeness of each GPS experiment matrix. As illustrated in Figure 6.8, the process is conducted for each SHRP section and involves

- Confirmation of the GPS experiment assignment
- Confirmation of the cell assignment within the GPS experiment matrix
- Assessment of experiment completeness

In essence, this IMS QA check is used to ensure appropriate GPS experiment assignment and to confirm that the distribution of LTPP sections within the experiment matrix is good enough to ensure unbiased data. This check must be successfully completed before checks H and I commence.

INTERMODULAR CROSS CHECKS
Behavior Considerations

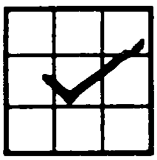
Nondestructive testing: FWD	–	**Load deflection**
Environment	–	**Mean monthly temperature**
Materials	–	**Layer thickness**
Materials	–	**Depth to rigid layer**
Materials	–	**Mr values**

INTERMODULAR CROSS CHECKS
Performance Considerations

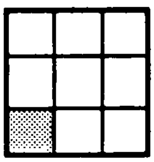
Profile	–	**International Roughness Index (IRI)**
Distress	–	**Cracking & patching**
Rutting	–	**Rut depth**
Materials/Inventory	–	**Surface type**

Figure 6.7. IMS Level 2: F Checks

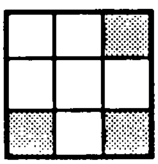
EXPERIMENT / CELL VERIFICATION



GPS Experiment Confirmation



Experiment Cell Confirmation



Completeness of Experiment

GPS Experiment Definition

GPS-1	Asphalt Concrete (AC) on Granular Base
GPS-2	AC on Bound Base
GPS-3	Jointed Plain Concrete Pavement
GPS-4	Jointed Reinforced Concrete Pavement
GPS-5	Continuously Reinforced Concrete Pavement
GPS-6A	Existing AC Overlay of AC Pavement
GPS-6B	Planned AC Overlay of AC Pavement
GPS-7A	Existing AC Overlay of Portland Cement Concrete (PCC) Pavement
GPS-7B	Planned AC Overlay of PCC Pavement
GPS-8	Unbound PCC Overlay of PCC Pavement

Figure 6.8. IMS Level 2: G Check

The variation in data across and within regions for each experiment will be analyzed as part of the H check to assess nonuniformity in variance distributions and to check for unusual occurrences or biases that may affect future analyses. Examples of this type of QA check are presented in Figure 6.9.

The final check before an IMS Level 2 release is illustrated in Figure 6.10 and involves statistical checks of each GPS experiment to identify missing and aberrant data and to confirm outliers. The process includes initial variance analyses at both regional and national levels and preliminary regression analyses to investigate important factors and variability materials and construction.

Once the data and IMS tables have passed through Checks A–I, the data are available for an experimental analysis release (**6.3, 6.9**). These data are accompanied by the following disclaimer from SHRP:

SHRP-LTPP Experiment Analysis Release Disclaimer

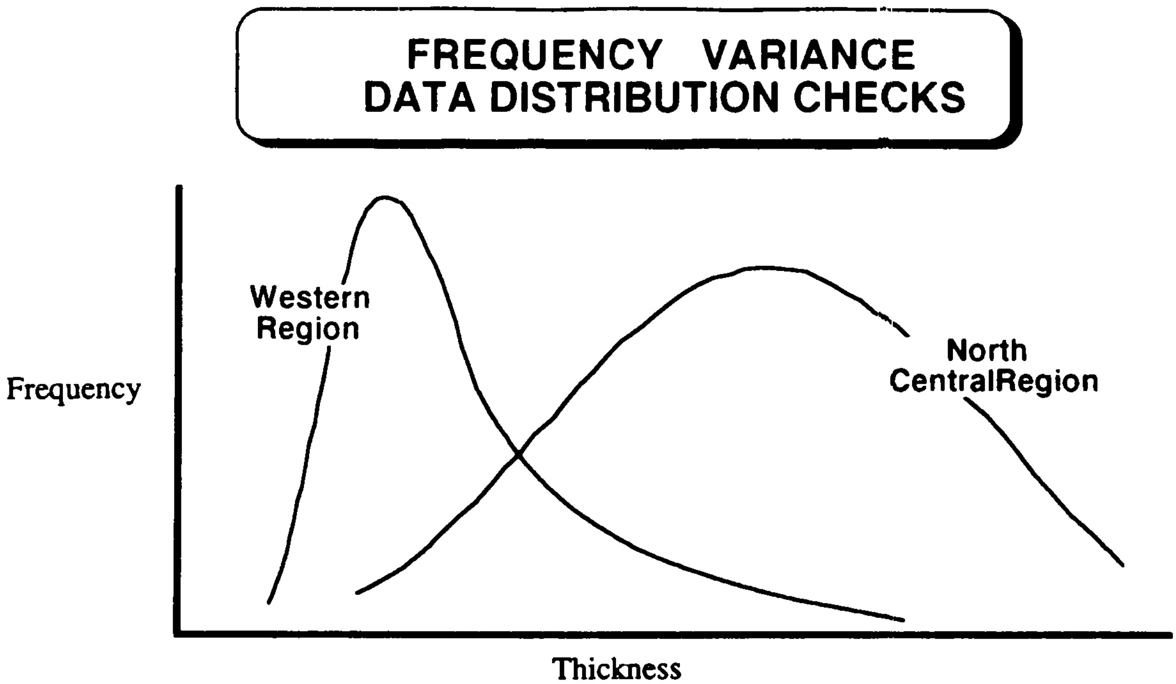
The SHRP-LTPP data are available for release at two levels. The first level of data release (Level 1) involves section-by- section data availability searches of the IMS, and includes a minimal number of pre-release data checks on the individual SHRP test section. The second level of release (Level 2) involves data availability searches of the IMS on an experiment-by-experiment basis, and requires the completion of a designated number of global data checks before approval for release.

The SHRP LTPP information and data from a Level 2 release represent a release on an experiment-by-experiment basis. Unless specifically notified otherwise, there should be no limitation on evaluation or analysis of the released data. If a report, paper, or technical document is generated using the results from this release, then a statement must be included indicating that the SHRP-LTPP information and data were obtained from a SHRP-LTPP Level 2 release and the date the data were obtained.

Data Availability

Data are generally made available to the public from the NIMS after appropriate QA checks have been concluded. To obtain LTPP data from the NIMS, requests must be made to the TRB IMS Administrator using a completed LTPP IMS data request form. All data requests are processed at TRB by the IMS Administrator.

In return, TRB will provide the requester with a package including the data on the requested media, a diskette containing significant portions of the *Database Structure Reference Manual* (**6.5**), and a notice describing major changes to the database in the previous 6 months. The package will include a detailed LTPP schema and the LTPP data dictionary. The schema identifies the fields in each IMS table along with the columns where these data are available in flat ASCII files. The LTPP data dictionary includes a description of each field including



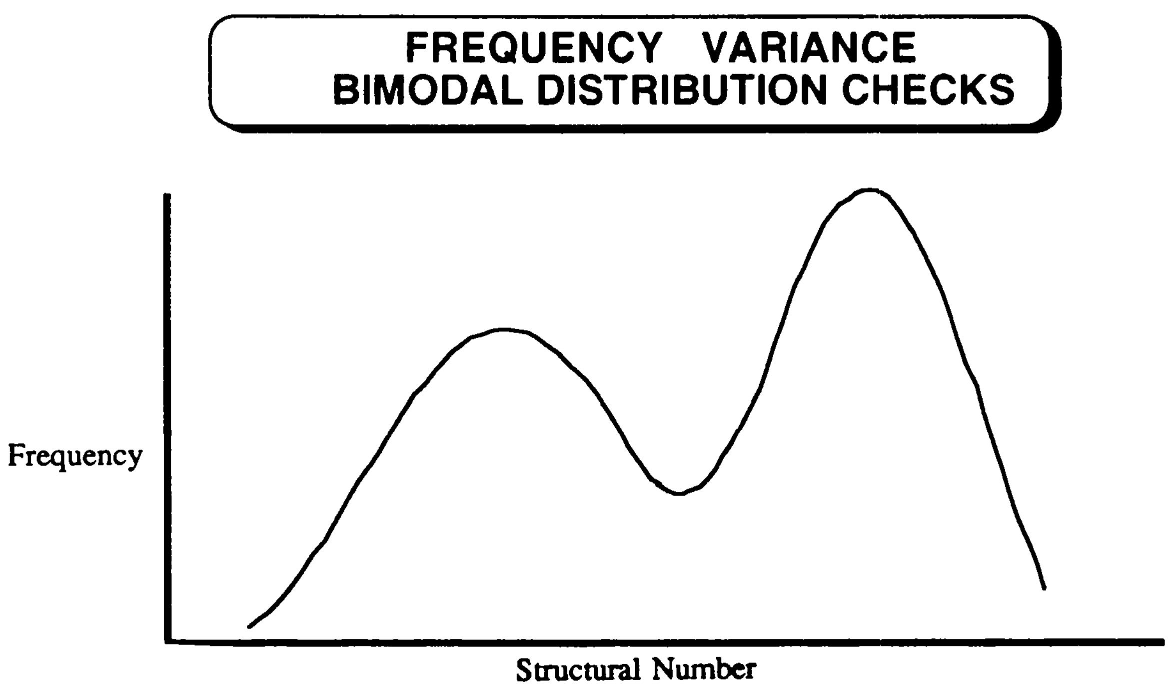


Figure 6.9. IMS Level 2 - H Check

STATISTICAL CHECKS / ANALYSES

Data Investigation

- Missing data
- Aberrant data

Initial Variance Analyses

- Regional
- National

Regression Analyses (Prelim)

- Important Factors
- Materials/construction variability

Figure 6.10. IMS Level 2: I Check

the size, units, and expected ranges, and it identifies the names of the table where these fields can be found.

Specific Data

Requests can be submitted for individual sections, states, regions, or experiment types. To specify data for a specific SHRP test section, however, the researcher must supply the SHRP section number. States can be specified by entering the standard two-character abbreviation or the full state name.

Status of IMS Releases

During SHRP-LTPP, four public data releases were conducted, all at Level 1 involving only GPS data. The releases were completed at 6-month intervals because of the large volume of data inserted in the RIMS during this start-up period. This can be seen in the amount of data that was released each time as shown in Table 6.2. The table names (e.g., INV_ID) were selected to represent the status of the tables' associated data modules.

The first data release (January 1991) was the initial trial of both the data release procedures and the QA checking software. As expected, this initial release produced many anomalies involving missing inventory data. This information would never be available because it was never collected originally or had been lost or destroyed over the years since the GPS section in question had been built. Accordingly, a COMMENTS table (**6.14**) was added to the IMS structure so that the regions could document the missing data and allow the data to pass through the QA process without being permanently held at that level (and never being released). The initial release included 226 releasable sections (see INV_ID), and the only other module to successfully pass through Level 1 was Friction (skid). The first release of distress data (MON_DIS and MON_DIS_PADIAS) occurred during the fourth release.

MON_RUT_MASTER is the table that contains the Cross-Profile data. REF_LAYER represents the Materials and Testing Data Module, which includes records for each pavement layer. MON_DEFL_MASTER represents the FWD data, MNT_HISTORY represents the Maintenance data, RHB_IMP represents Rehabilitation data, and MON_PROFILE_MASTER represents the Profilometer data.

IMS Products

The products generated during development of the IMS include the NIMS and RIMS databases, the supplemental databases, and the QA methodology. All these items represent significant improvements in the entry, acceptance, and processing of pavement performance data. These products should facilitate future pavement performance research and evaluation.

Table 6.2. Examples of Level 1 Releases

Table	Release Dates			
	Jan. 91	July 91	Jan 92	July 92
INV_ID	226	561	660	668
MON_SKID	95	416	560	720
MON_RUT_MASTER	-	2	355	896
REF_LAYER	-	118	296	456
MON_DEFL_MASTER	-	497	515	6
MNT_HIST	-	-	9	25
RHB_IMP	-	-	1	2
MON_PROFILE_MASTER	-	-	2860	4288
COMMENTS	-	913	2386	2800
TRF_BASIC_INFO (Historical Traffic Only)	-	-	2386	121
MON_DIS (Manual)	-	-	-	398
MON_DIS_PADIAS	-	-	-	457

References

6.1 *Strategic Highway Research Program Research Plans, Final Report*. Transportation Research Board, National Research Council, Washington, D.C., May 1986.

6.2 *Long-Term Pavement Performance Information Management System Operations and Quality Assurance Manual*. Strategic Highway Research Program, National Research Council, Washington, D.C., April 1990.

6.3 *Long-Term Pavement Performance Information Management System Researchers Guide*. Strategic Highway Research Program, National Research Council, Washington, D.C., July 1991.

6.4 "Data Collection Guide for Long-Term Pavement Performance Studies" (Operation Guide SHRP-LTPP-OG-001). Strategic Highway Research Program, National Research Council, Washington, D.C., January 1990.

6.5 "Database Structure Reference Manual." Long-Term Pavement Performance Information Management System. Strategic Highway Research Program, National Research Council, Washington, D.C., January 1990.

6.6 "Programmer's Reference Manual." Long-Term Pavement Performance Information Management System. Strategic Highway Research Program, National Research Council, Washington, D.C., July 1989.

6.7 "NIMS Users Manual." Long-Term Pavement Performance Information Management System. Strategic Highway Research Program, National Research Council, Washington, D.C., March 1990.

6.8 "RIMS Users Manual." Long-Term Pavement Performance Information Management System. Strategic Highway Research Program, National Research Council, Washington, D.C., January 1990.

6.9 *LTPP IMS Data Quality Assurance Checks* (Draft). Long-Term Pavement Performance Information Management System. Strategic Highway Research Program, National Research Council, Washington, D.C., May 1992.

6.10 Hadley, W. O., C. Copeland, R. High, and H. Roper, "LTPP Data Availability Policy Recommendations." (IMS Message No. TRDF-40, Revised). Texas Research and Development Foundation, Austin, Texas, October 25, 1990.

6.11 Hadley, W. O. "IMS Level 2: F Checks—Intermodal" (IMS Message No. TRDF-134). Texas Research and Development Foundation, Austin, Texas, September 29, 1992.

6.12 Hadley, W. O. "IMS Level 2: G Checks—Experiment and Cell Verification" (IMS Message No. TRDF-88). Texas Research and Development Foundation, Austin, Texas, September 23, 1991.

6.13 High, R. and W. O. Hadley. "IMS Level 2: Statistical Quality Control and Assurance Procedures" (IMS Message No. TRDF-134a). Texas Research and Development Foundation, Austin, Texas, September 11, 1992.

6.14 Copeland, C. "Comments Table Review and Usage Recommendations for SHRP-LTPP Regions." (IMS Message No. TRDF-56). Texas Research and Development Foundation, Austin, Texas, May 3, 1991.

Section 7
Data Analysis Studies

Introduction

The principal objective of the Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) program was the development of a comprehensive database for pavement performance data covering a wide range of conditions and service life factors (7.1). The database was structured to address pavement management and engineering design issues including

- Pavement rehabilitation design and construction procedures
- Effects of pavement maintenance
- Cost of deferred maintenance
- Climatic and environmental effects
- Long-term load effects
- Validity of the American Association of State Highway and Transportation Officials (AASHTO) Road Test load equivalency factors (LEFs)
- Relative effects and interactions of load, environmental conditions, and materials properties
- Effects of subgrade material
- Load carrying capacity beyond pavement design life
- Effects of alternative drainage designs (7.1)

The extent and scope of information contained within the LTPP Information Management System (IMS) also provides the resources not only to evaluate or revise existing design equations but to develop new ones.

A more specific research plan was developed for the LTPP program with the stated goal "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" (7.2). In this effort six specific objectives were established:

1. To evaluate existing design methods

2. To develop improved design methods and strategies for pavement rehabilitation

3. To develop improved design equations for new and reconstructed pavements

4. To determine the effects of load, environment, materials properties, variability, construction quality, and maintenance levels on pavement distress and performance

5. To determine the effects of specific design features on pavement performance

6. To establish a national long-term pavement performance database to support SHRP objectives and future needs

During SHRP-LTPP a series of data analysis studies were undertaken to "exercise" the National Pavement Performance Database (NPPDB), to define availability, and to undertake the initial studies and evaluations using SHRP-LTPP data. The data analysis studies were generally targeted toward the goals and objectives of SHRP-LTPP.

The principal SHRP technical assistance contract involved data analysis related to construction variability (Objective 4), SHRP LEF approach (Objective 5), and pavement rutting (Objective 4).

The principal SHRP data analysis contract involved data analysis activities related to evaluation of existing design methods (Objective 1), improved design equations (Objective 3), effects of load and environment on pavement distress and performance (Objective 4), and effects of specific design features on pavement performance (Objective 5). The second SHRP data analysis contract represented an initial effort to evaluate the AASHTO equations using mechanistic-empirical analysis techniques. A separate SHRP contract was undertaken to assess the effectiveness of six pavement maintenance treatments, in response to Objective 2.

Several non-SHRP contracts are also pursuing LTPP goals. The Canadian (CSHRP) SHRP—LTPP program is exploring high-risk research aimed at developing procedures to determine the cost-effectiveness of rehabilitation alternatives. The University of Birmingham (U.K.) is pursuing two contracts related to a proposed approach for SHRP database analysis; these approaches involve measurements of pavement life cycle cost sensitivity to traffic, materials, and maintenance and rehabilitation processes, as well as development of network-level pavement performance models.

Data Analysis: General Pavement Studies (GPS) Materials and Construction Variability

One of the objectives of SHRP-LTPP was to investigate the effects of materials properties, materials variability, and construction quality on pavement performance (**7.2**). The goal was to find a way to incorporate these variables into specific predictive equations for rigid and flexible pavement performance parameters. The basic analytical approach was outlined in a previous document (**7.3**). A detailed presentation of this study is included in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**).

Approach

The construction variability factors were classified as Distress and Performance Variables, Primary Structural Factors, Materials Properties, and Nonstructural Variables (Figure 7.1). Consequently, the conceptual distress prediction model is composed of a nonstructural variables component (traffic, environment, age, etc.), a structural and materials factor means component, and a third component involving structural and materials factor variances (Figure 7.2).

The actual analytical approach used in this investigation consisted of a linear regression analysis relating the logarithm (log) of a pavement performance or distress variable to the logs of the nonstructural variables, logs of mean structural and materials factors, logs of variances of structural and materials factors, and their cross-products (Figure 7.3). The factors composing the regression equations can then be used to identify the factors and/or variances that significantly affect the specific pavement performance or distress variable.

Construction Variability in Rigid Pavements

The construction variability factors included in the rigid pavement investigation are identified below. The specific site information and data for the LTPP sections investigated in the rigid pavement construction variability study are presented in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**).

Rigid Pavement Construction Variability Factors

Distress and Performance Variables (*D*)
International Roughness Index (IRI)
AASHO PSI-Loss

Primary Structural Variables (*S*)
Portland Cement Concrete (PCC) Layer Thickness
PCC Layer Modulus
PCC Layer Poisson's Ratio
Modulus of Subgrade Reaction (*K*)

Nonstructural Variables (*E*)
Age (years)
Traffic (KESALs)
Temperature (freeze vs. nonfreeze)
Moisture (wet vs. dry)

Regression analyses were completed for the performance variables of roughness (IRI) and AASHO Serviceability Loss. The serviceability loss quantities were estimated from the relationship PSI = 7.06 - 1.79 log(IRI), which was developed in the report *PSI Estimates from*

Distress and Performance Variables (D)

- Rutting
- Roughness
- Present Serviceability Index (PSI)
- Cracking

Primary Structural Factors (S)

- Layer Thicknesses
- Layer Moduli
- Subgrade Moduli

Materials Properties (M)

- Mix Design Variables
- Layer Properties

Nonstructural Variables (E)

- Traffic (KESALs)
- Environment
- Moisture

Figure 7.1. Construction Variability Factors

D, distress function, is a function of

f (ESALs; Environment)

$*$

g (Structural Factor Means S_1, S_2, etc.;

Materials Factor Means M_1, M_2, etc.)

$*$

h (Structural Factor Variances S_1^2, S_2^2, etc.;

Materials Factor Variances M_1^2, M_2^2, etc.)

Figure 7.2 Distress Prediction Model

- Linear Regression Using logarithms:

$\log D$

$\log \text{KESALs}$

$\log S_1$

•

•

$\log M_1$

•

•

$\log (S_1^2)$

•

•

$\log (M_1^2)$

- Significant Effects

Figure 7.3 Actual Analytical Approach

SHRP Profilometer Roughness (7.5). The equations resulting from this investigation are presented in the *SHRP-LTPP Data Analysis: Five-Year Report* (7.4).

Longitudinal Roughness in Rigid Pavements, log(IRI)

The predictive equation for log(IRI) included main effects of

log(KESALs)
log(Mod)
log(*K*),
log(MOIST)
log(KESALs) * log(K-Var)
log(AGE) * log(Mod-Var)
log(SUBG) * log(Ts-Var)

where

IRI	=	pavement roughness as measured in IRI values from SHRP profilometer data
KESALs	=	cumulative traffic in thousands of equivalent single axle loads (KESALs) based on historical traffic data
MOD	=	surface (PCC layer) modulus
K	=	modulus of subgrade reaction (pci)
MOIST	=	moisture conditions: dry +1, wet +2
AGE	=	age of section (yrs)
Ts	=	thickness of surface PCC layer (in.)
K-Var, Mod-Var, Ts-Var	=	variances of K, Mod, and Ts, respectively.
SUBG	=	subgrade type: fine-grained +1, coarse-grained +2

These results indicated that pavement roughness generally increased with lower modulus of subgrade reaction (*K*), wetter environments, higher surface modulus, greater pavement age, and greater variation in surface modulus (Mod). It should be noted that the variabilities in *K*, Mod, and surface thickness (Ts) apparently contributed to pavement roughness.

AASHO Serviceability Loss

The predictive equation for log(AASHO Serviceability Loss) contains no main effects but is composed of eight interaction or cross-product terms. Four of the interactions involve mean values of the factors, and four involve variances of the factors. The equation includes

log(KESALs) * log(TEMP)
log(*K*) * log(Ts)
log(TEMP) * log(SUBG)
log(SUBG) * log(PR)
log(KESALs) * log(PR-Var)
log(AGE) * log(K-Var)
log(SUBG) * log(Ts-Var)
log(Ts) * log(Ts-Var)

where

AASHO PSI Loss	=	4.5 - *p* where *p* is present serviceability
KESALs	=	cumulative traffic (KESALs) based on historical traffic data
TEMP	=	temperature zone: nonfreeze +1, freeze +2
K	=	modulus of subgrade reaction, (pci)
Ts	=	thickness of surface PCC layer (in.)
SUBG	=	subgrade type: fine-grained +1, coarse-grained +2
PR	=	Poisson's ratio of surface PCC layer
AGE	=	age of section (yrs)
PR-Var, K-Var, Ts-Var	=	variances of PR, *K*, and Ts, respectively

The significant consideration in this relationship was the large number of variance terms. This investigation indicated that the variation in surface layer thickness (Ts), surface layer Poisson ratio (PR), and modulus of subgrade reaction (*K*) apparently had a significant influence on AASHTO Serviceability Loss. These variances translate into primary structural influences (i.e., Ts, *K*) and materials influences (i.e., PR). In addition, the serviceability loss was affected by various combinations of traffic (KESALs), environment (TEMP), and primary structural factors (i.e., *K*, Ts, SUBG, and PR).

Construction Variability in Flexible Pavements

The construction variability factors included in the flexible pavement investigation are identified below. The specific site information and data for the LTPP sections investigated in the flexible pavement construction variability study are presented in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**).

Flexible Pavement Construction Variability Factors

<u>Distress and Performance Variables *(D)*</u>
Rutting (Layer)
Rutting (Deep-Seated)
IRI
AASHO PSI-Loss

<u>Primary Structural Variables *(S)*</u>
Surface Layer Thickness (Ts)
Base Layer Thickness (Tb)
Structural Number (SN)
Surface Layer Modulus (Es)
Base Layer Modulus (Eb)
Subgrade Modulus (Esg)
Subgrade Type (SUBG)

<u>Materials Properties *(M)*</u>
Asphalt Content (AC)

<u>Nonstructural Variables *(E)*</u>
Age (Yrs)
Traffic (KESALs)
Temperature (freeze vs. nonfreeze)
Moisture (wet vs. dry)

Regression analyses were completed for the distress and performance variables of rutting (within upper pavement layers), deep-seated rutting (including the subgrade), and AASHO Serviceability Loss. The equations developed in this investigation are presented in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**). It should be noted that the rut type classification method developed in the Rut Initiation Studies (**7.6**) was used here to categorize rutting as either "layer" or "deep-seated." The AASHTO Serviceability Loss variable was estimated for the various SHRP-LTPP sections through a relationship developed as a part of this study (**7.6**).

log(Layer Rutting)

The predictive equation for log(Layer Rutting) included a main traffic (or log KESALs) effect and four interaction factors (or cross-products) involving traffic and subgrade modulus (log KESALs * log Esg), asphalt content and structural number (log AC * log SN), asphalt content and surface layer thickness (log AC * log Ts), and subgrade modulus and surface layer thickness (log Esg * log Ts). The predictive equation is presented in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**).

The interaction terms included in the predictive equation involved primarily mean value effects, with only a single variance term for surface thickness present. This investigation indicated that increased layer rutting corresponds to

- Increased traffic
- Lower subgrade modulus at any traffic rate and minimum surface thickness
- Higher asphalt contents and higher pavement structural numbers
- Thinner surface layers
- Higher surface thickness variation with any subgrade modulus

One of the important results in this investigation is the influence of surface thickness variation on layer rutting. Closer control of surface thickness in the construction process could help prevent rutting.

It is interesting to note that the combination of the interaction terms involving asphalt content (AC) could shed light on the compromises that are possible between structural number (SN) and surface layer thickness (Ts). The combined terms from the layer rutting predictive equation are

$$\log(AC)*[0.754 * \log(SN) - 1.127 * \log(Ts)]$$

For a given AC value, an increase in SN (i.e., generally a thicker section) apparently results in the potential for greater rutting because of the positive coefficient (+0.754) associated with log(SN). This effect can be offset, however, by an appropriate selection of Ts because log(Ts) has a negative coefficient (-1.127). Hence an appropriate selection of SN and Ts values could be beneficial in minimizing layer rutting.

log(Deep-Seated Rutting)

The predictive equation for log(Deep-Seated Rutting) developed in this analysis includes no main effects but is composed of four interaction or cross-product terms. Three of these cross-product terms involve variances of subgrade modulus, surface layer thickness, and surface layer modulus. Structural number, temperature zone, subgrade classification, and KESALs are also included in the interaction terms.

This investigation indicated that deep-seated rutting corresponds to

- Colder locations with coarse-grained soils
- Lower structural numbers
- Greater age and higher variation in surface layer thickness
- Lower variation in surface layer modulus at any traffic rate

The phenomenological difference between layer rutting and deep-seated rutting can be observed in the impact of the structural number factor. Layer rutting is more likely in pavements with higher structural numbers, while deep-seated rutting is less likely in similar pavements with high structural numbers.

AASHO Serviceability Loss

The predictive equation for log(AASHO Serviceability Loss - 4.2 present serviceability, *p*) contains no main effects but does include eight interaction terms. Four of these cross-product terms include variance terms for subgrade modulus, surface layer thickness, and surface modulus. Temperature zone, age, subgrade classification, moisture conditions, structural number, KESALs, and subgrade modulus were included in the equation.

This investigation indicated that greater serviceability loss corresponds to

- Older pavements
- Higher structural numbers
- Higher traffic rates and higher variance in surface modulus
- Thinner surface layers
- Lower subgrade modulus with associated subgrade modulus variance
- Greater variance in surface layer thickness in the wetter zones

It is important to note that mean structural number and surface layer thickness were influential and apparently affect the amount of serviceability loss. The variances of surface layer modulus and surface layer thickness likewise can influence serviceability. Because all these items are related to the structural/materials design process, it appears possible to identify specification controls, construction methods, and other measures that could be used to "harness" these factors and reduce pavement serviceability loss.

Conclusions

This investigation of materials and construction variability within rigid and flexible SHRP-LTPP pavement sections successfully identified significant effects, interactions, and variances of effects that can influence pavement distress and performance.

The results represent an initial effort in defining construction variability and should be expanded to include more LTPP sections, as well as other distress and performance variables as they become available in the LTPP database.

The analytical approach used in this study (7.3) appears to produce valid results and should be considered for use in future analytical efforts to define construction variability.

Improvement of Load Equivalency Factors (LEFs) From SHRP-LTPP Data

How to improve LEFs was one of the questions posed in *America's Highways: Accelerating the Search for Innovation* (**7.1**). It was proposed that the effects of varying pavement strengths (or structural support), pavement structures, types of materials, and environments on the AASHO Road Test LEFs could be investigated in a comprehensive database such as SHRP-LTPP. This study was undertaken to define an approach (or approaches) that could be used to investigate LEFs from the SHRP-LTPP database.

There is no doubt that improved LEFS—which are specific to a particular distress and applicable to wider ranges of pavement structure and environmental conditions---would provide a basis for justifying decisions on cost allocation, pavement management, and maintenance and rehabilitation strategies. One consideration relative to LEFs is whether the SHRP-LTPP database contains sufficient data to investigate distress-specific LEFs. An approach must be defined that uses the LTPP database in an assessment of improvements of LEFs from SHRP-LTPP data.

In the course of the SHRP-LTPP LEF study (**7.7**), it was recognized that present serviceability estimates (**7.8**), serviceability loss (**7.9**), and traffic estimates (**7.10**) would be needed to accomplish the proposed evaluation. The results of these previous work efforts have been combined herein to complete an evaluation of the LEF approach (**7.7**) proposed for this study (**7.11**). The evaluation included both rigid and flexible pavement sections (see Table 7.1). A detailed presentation of this study is included in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**).

LEF Evaluation Approach

For this exploratory study, a family of LEFs and resultant cumulative equivalent single axle load (ESAL) estimates were generated. The elements included not only the AASHO LEFs but also ranges on either side of the AASHTO values. LEF values were developed for a variety of B_1 and B_2 exponent values using the basic AASHO Road Test LEF equation:

$$\text{LEF(XL)} = (L_1/18)^{B_1}/(L_2)^{B_2}$$

where

LEF(XL)	=	load equivalency factors for axle load XL
L_1	=	axle group weight
L_2	=	number of axles in the axle group
B_1, B_2	=	exponents

Conventional multiple regression analysis techniques were used to generate individual distress prediction equations for roughness, rutting, and serviceability loss in the case of flexible pavements, and for roughness and serviceability loss in the case of rigid pavements. It was originally proposed that the evaluation include cracking in both the flexible and rigid

Table 7.1. Flexible and Rigid Pavement Sections Included in the LEF Study

Section	State	Pavement Type
062051	California	Flexible
062647	California	Flexible
068201	California	Flexible
182008	Indiana	Flexible
382001	North Dakota	Flexible
512004	Virginia	Flexible
063042	California	Rigid
124000	Florida	Rigid
183031	Indiana	Rigid
385002	North Dakota	Rigid
485336	Texas	Rigid
537409	Washington	Rigid

pavements; however, the paucity of distress data in the SHRP-LTPP database eliminated this option.

For a given LTPP section a series of regression equations for the various combinations of B_1 and B_2 exponents were developed that relate pavement performance (e.g., rutting, roughness, PSI loss) to cumulative ESALs, annual ESALs, and pavement structural and site environmental conditions. The ESAL estimates for this analysis were obtained through the transformation of traffic load information by LEFs appropriate to the combinations of axle loads and axle configurations. The LEF values were developed for various combinations of exponents B_1 and B_2 using the basic AASHO equation described above.

Each regression analysis produced a coefficient of determination (R^2), a standard error of estimate (RMSE), and a coefficient of variation (CV). These statistics quantify the goodness of fit of the particular predictive equation. It was expected that comparisons of these statistics, along with consideration of the regression coefficients and their standard errors, would indicate which combinations of B_1 and B_2 values lead to "best" fits.

Interaction effects (represented by cross-product terms of ESALs, pavement structure, and environment) are expected to be important indicators of the extent to which ESAL effects vary with structural and environmental factors.

Rigid Pavement LEF Evaluation

The pavement performance indicators evaluated in this study included roughness and PSI loss. The roughness indicator is the International Roughness Index (IRI) generated by the SHRP Law profilometers. PSI-Loss was defined as the difference between an assumed initial PSI value of about 4.5 (similar to AASHO Road Test Analysis (**7.12**) and the present serviceability value. The present serviceability value was developed from the following equation using the profilometer-generated IRI value:

$$\text{PSI} = 7.06 - 1.79 \log(\text{IRI}) \quad \textbf{(7.8)}$$

Evaluation of log(IRI)

The equation for roughness, measured as IRI, for the rigid pavement sections is a logarithmic form including cross-products of log(Annual ESALs) and log of moisture and temperature. The form is as follows:

$$\log(\text{IRI}) = K_1 + K_2 * [\log(\text{ESALs}) * \log(\text{MOIST})] + K_3 * [\log(\text{ESALs}) * \log(\text{TEMP})]$$

where

MOIST	=	moisture conditions: dry +1, wet +2
TEMP	=	temperature zone: nonfreeze +1, freeze +2
K_1, K_2, K_3	=	regression coefficients

The combination of $B_1 = 4.0$ and $B_2 = 3.0$ represents the normal AASHO-type LEF coefficients. In this analysis, however, the combination of $B_1 = 3.0$ and $B_2 = 3.5$ produced the highest R^2 value, the lowest RMSE, and the lowest CV for the previous equation. This combination apparently fulfills the best fit criteria and can be considered in possible development of new LEFs.

Evaluation of log(PSI-Loss)

The equation for AASHO PSI-Loss (4.2 - present serviceability, p) for rigid pavement sections is a logarithmic form including cross-products of log(Cumulative ESALs) and log of moisture and log of temperature. The form of the equation is

$$\log(\text{PSI-Loss}) = K_1 + K_2 \text{ Log(Cumulative ESALs)} * \log(\text{MOIST}) + K_3 \log(\text{Cumulative ESALs}) * \log(\text{TEMP})$$

where

MOIST	=	moisture conditions: dry +1, wet +2
TEMP	=	temperature zone: nonfreeze +1, freeze +2
K_1, K_2, K_3	=	regression coefficients

In this instance the combination of $B_1 = 3.0$ and $B_2 = 3.5$ again produced the best fit (the highest R^2 and the lowest RMSE and CV), although all other combinations yielded similar characteristics. It should be noted that the CV for the equation is high, at about 34%.

Possible Effect on LEF Values for Rigid Pavements

A comparison of the LEF values of the best fit combination (3.0, 3.5) with the AASHO combination (4.0, 3.0) leads to the conclusion that the acceptance of the use of the combination of $B_1 = 3.0$ and $B_2 = 3.5$ could result in the following changes in AASHO-type (IRI) and log(PSI-Loss):

<u>Increase in LEFs</u>
Single Axles below 18 kips
Tandem Axles below 12 kips

<u>Decrease in LEFs</u>
Single Axles above 18 kips
Tandem Axles above 12 kips
Tridem Axles (all loads)
Quadrem Axles (all loads)

Flexible Pavement LEF Evaluation

The pavement performance indicators evaluated in this study included rutting, roughness, and PSI-Loss. The rutting indicator is defined with a classical AASHTO definition in units of millimeters, while the roughness is characterized by the IRI values generated by the SHRP-LTPP Law profilometer. PSI-Loss is defined in two ways. The first involves a value defined as the difference between an initial estimate of 4.2 (similar to that assumed in the AASHO Road Test equation) and the present serviceability level. It should be noted that this approach negates the influence of variation in initial serviceability estimates, since a fixed value of 4.2 is defined for all sections. The second method involves the use of the PSI-Loss estimates obtained from the following equations that were developed as a part of this study:

$$\text{SHRP PSI Loss} = K/(1-K) * (p_n - 2.0) \quad (7.9)$$

where

p_n = present serviceability at time n, and
K is defined by the following equations:

$$K = 0.6718 + 0.156 * (\text{TEMP}) + 2.605 \times 10^{-6} * (\text{ESALs}) + 0.0625 * (\text{SUBG*MOIST}) - 0.8306 \times 10^{-6} * (\text{ESALs*SN})$$

where

TEMP = temperature zone: nonfreeze -1, freeze +1

ESALs = annual ESALs rate of $\sum_{o}^{n}$ESALs/n years

SUBG = subgrade type: fine-grained +1, coarse-grained +2
MOIST = moisture conditions: dry -1, wet +1
SN = structural number of the pavement section

The present serviceability value was estimated from the following equation using the profilometer-generated IRI value:

$$\text{PSI} = 7.06 - 1.79 \log(\text{IRI}) \quad (7.8)$$

Evaluation of Rutting

The equation for rutting (in millimeters) for the flexible pavement sections was a logarithmic form including a main effect of log(Cumulative ESALs) and a cross-product containing log(Surface Layer Modulus) and log(Cumulative ESALs). The form of the equation is

$$\log(\mathrm{RUT}) = K_1 + K_2 * \mathrm{Log}(\Sigma\mathrm{ESALs}) + K_3 * \log(E_{SURF}) * \log(\Sigma\mathrm{ESALs})$$

where

ΣESALs	=	cumulative ESALs based on B_1 and B_2 values
E_{SURF}	=	surface layer modulus in ksi
K_1, K_2, and K_3	=	regression coefficients

In this instance the combination of $B_1 = 5.0$ and $B_2 = 2.0$ produced the equation with the highest R^2 value, lowest RMSE, and lowest CV. The AASHTO combination of B_1 and B_2 yielded the next best combination of regression equation attributes (i.e., R^2, RMSE, and CV). It should be noted that a B_1 coefficient of 5.0 is relatively high and could indicate the principal influence and magnitude of wheel load on the development of rutting.

Evaluation of Roughness (IRI)

The equation for roughness also exhibited a logarithmic form, including a main effect of log(Cumulative ESALs) and a cross-product of log(Cumulative ESALs) and log(Surface Layer Modulus). The form of the equation is

$$\log(\mathrm{IRI}) = K_1 + K_2 * \log(\Sigma\mathrm{ESALs}) + \mathrm{K}_3 * \log(E_{SURF}) * \log(\Sigma\mathrm{ESALs})$$

where

ΣESALs	=	cumulative ESALs based on B_1 and B_2 values,
E_{SURF}	=	surface layer modulus in ksi
K_1, K_2, K_3	=	regression coefficients

In a review of the regression analysis results, there were four combinations of B_1 and B_2 values that yielded high R^2 values; however, the AASHO combination produced the equation with the highest R^2 (.95), lowest RMSE (.037), and lowest CV (1.89). Therefore, in the case of longitudinal roughness in flexible pavements, the AASHO LEFs apparently produce cumulative ESAL estimates that correspond to the level of roughness developed in the flexible pavement sections included in this study.

Evaluation of AASHO Serviceability Loss

The equation for AASHO serviceability loss is a logarithmic form including

$$\log[1 + (4.2 - p)] = K_1 + K_2 * \log(\Sigma\text{ESALs}) + K_3 [\log(\Sigma\text{ESALs}) * \log(E_{SURF})]$$

where

$4.2 - p$	=	AASHO Serviceability Loss
ΣESALs	=	cumulative ESALs based on B_1 and B_2 values
E_{SURF}	=	surface layer modulus in ksi
K_1, K_2, K_3	=	regression coefficients

From this portion of the study it was found that the best fit equation for log(1 + AASHO Serviceability Loss) corresponds to the B_1 and B_2 combinations identified with the original AASHO LEFs. Although (B_1, B_2) combinations (3.0, 3.0 and 4.0, 3.5) yielded acceptable regression equation attributes, the AASHO-based combination yielded the equation with the highest R^2, lowest RMSE, and lowest CV. Similarly, since serviceability (and serviceability loss) can be estimated from log(IRI), best fit B_1 and B_2 coefficients for log(IRI) and AASHTO coefficients are likewise expected.

Based on these results, the AASHO LEF values will apparently yield cumulative ESAL estimates that correspond well to pavement serviceability trends. This is not unexpected, since the original AASHO road test serviceability concept is based on a serviceability loss factor established for an initial PSI value of 4.2.

Evaluation of SHRP Serviceability Loss [{K/(1 - K)}(p_n - 2.0)]

The SHRP serviceability loss estimate $[\{K/(1 - K)\}(p_n - 2.0)]$ for this investigation was generated from an equation for K [or $(W/p)^\beta$] that was developed from the results of six different road test evaluations, including Loop 4 of the AASHO Road Test (**7.12**).

where

W	=	cumulative 18 KESALs applied at end of time, t
p	=	function of design and load variables denoting the expected number of axle load applications to a terminal serviceability
β	=	a function of design and load variables that influence the shape off serviceability, p, versus cumulative ESALs, W, curve

The equation for K is

$$K = (W/p)^\beta = 0.06718 * 0.1560 * (\text{TEMP}) + 2.605 * 10^{-6} * (\text{ESALs}) \\ + 0.0625 * (\text{SUBG} * \text{MOIST}) - 0.8306 * 10^{-6} * (\text{ESALs} * \text{SN})$$

where

TEMP	=	temperature zone: nonfreeze -1, freeze +1
ESALs	=	annual average ESAL rate $(\sum_{0}^{n}\mathrm{ESALs}/n)$
SUBG	=	subgrade type: fine-grained +1, coarse-grained +2
MOIST	=	moisture conditions: dry -1, wet +1
SN	=	structural number of the pavement section

The equation for the SHRP-estimated serviceability loss for flexible pavement sections is a logarithmic form including cross-products of log(Subgrade Modulus) by log(Cumulative ESALs) and log(Precipitation) by log(Days over 90°F). The form of the equation is as follows:

$$\log(\text{SHRP PSI Loss}) = K_1 + K_2 * [\log(\text{Esg}) * \log(\Sigma\text{ESALs})] + K_3 * [\log(\text{PRECIP}) * \log(\text{DAYS})]$$

where

SHRP PSI Loss	$= [K/(K-1)] * (p_n - 2.0)$
p_n	= Present Serviceability Index (PSI)
Esg	= subgrade modulus in ksi
ΣESALs	= cumulative ESALs for combination of B_1 and B_2 values
PRECIP	= annual precipitation in inches/year
DAYS	= average annual number of days over 90°F
K_1, K_2, K_3	= regression coefficients

Three combinations of B_1 and B_2—(2, 2), (3, 3), (3, 3.5)—produced equations with better attributes than the AASHO combination of B_1 and B_2. Of the four combinations, however, the best fit was obtained for the combination of $B_1 = 3$ and $B_2 = 3.5$. The equation has the highest R^2, the lowest RMSE, and the lowest CV.

In a general assessment of the equation, it can be inferred that serviceability loss is reduced for higher subgrade moduli, higher precipitation rates, and higher number of days exceeding 90°F.

Possible Effect on LEF Values for Flexible Pavements

A comparison of the best fit combinations of B_1 and B_2 for the four performance variables leads to the possibility that the acceptance of best fit values could result in the LEF changes identified in Table 7.2. No changes are expected in AASHTO LEFs for IRI and AASHO PSI-Loss. On the other hand, the AASHO LEFs could be significantly increased for all axle configurations if pavement rutting is predicted. In the case of the SHRP serviceability loss, the LEFs could be increased for loads below 18,000 pounds and decreased for loads exceeding 18,000 pounds.

TABLE 7.2. Possible LEF Changes Identified in This Study

Performance Variable	Load Level (thousands of pounds)	Impact on LEFs by Axle Type: Single	Tandem	Tridem	Quadrem
Rutting					
$B_1 = 5.0$	<18	Smaller	Greater	Greater	Greater
$B_2 = 2.0$	>18	Greater	Greater	Greater	Greater
IRI					
$B_1 = 3.9$	<18	Same	Same	Same	Same
$B_2 = 3.5$	>18	Same	Same	Same	Same
AASHO PSI-Loss					
$B_1 = 3.9$	<18	Same	Same	Same	Same
$B_2 = 3.5$	>18	Same	Same	Same	Same
SHRP PSI-Loss					
$B_1 = 3.0$	<18	Greater	Greater	Greater	Not Available
$B_2 = 3.5$	>18	Smaller	Smaller	Smaller	Smaller

Conclusions and Recommendations

The results of this study indicate that the approach proposed for improving AASHO LEFs using SHRP-LTPP data is viable. In addition, it appears that the data contained in the SHRP-LTPP database are sufficient to conduct a comprehensive study. It is recommended that an expanded analysis be undertaken in the near future when additional performance data are available.

Rutting Initiation Studies

Introduction

The development of rutting in flexible pavements is an expected phenomenon that affects pavement serviceability and influences rehabilitation decisions. The rutting phenomenon is complicated; it can develop within the pavement layers (i.e., layer rutting) because of layer densification or possible material shoving, or it can occur within the total pavement structure including the subgrade soil (i.e., deep-seated rutting). The definition of the source or cause of initiation of rutting within a pavement structure is needed to enhance flexible pavement design and evaluation.

An evaluation of the distortion in a pavement cross-profile can be used to establish pavement rut depth but can also provide insight into the underlying cause or location of initiation of the rutting phenomenon. The availability of PASCO cross-profile data for all SHRP flexible pavement sections offers an excellent opportunity to investigate the rutting phenomenon, particularly since detailed section information on pavement structure, environmental conditions, material values, traffic, and geographic information is available in the NPPDB.

This data analysis effort was undertaken to develop information on factors influencing type of rutting (i.e., layer or deep-seated), source of rut initiation, and distortion of the pavement cross-profile that develops within a pavement structure. The factors to be investigated included prevailing moisture and temperature conditions, subgrade type, traffic, and layer thickness. Regression equations were developed that related the amount of rutting and extent (or type) of rutting to the various factors.

A majority of the raw, transverse profile data for SHRP GPS sections is collected in an automated fashion using the PASCO Data Collection Vehicle (**7.13**). In addition, cross-profile information for some of the GPS sections is generated using the Face DIPstick™.

The PADIAS data generation package developed by PASCO (**7.14**) includes a method for estimating rut depths from cross-profile data. In many instances, however, the PASCO technique does not conform to the classic straightedge measurement method. Because of this situation, a technique was developed (see Figure 7.4) to estimate rut depths by simulating placement of straightedges of variable length on the existing PASCO cross-profile data (**7.15, 7.16**). In addition, a pavement distortion assessment method was developed as an aid in

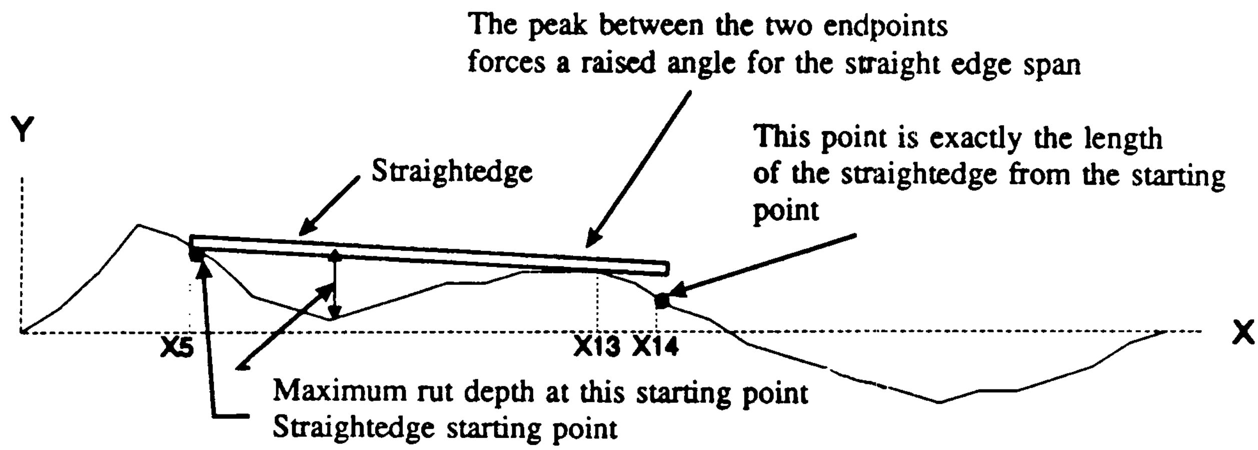


Figure 7.4 Example of Intermediate Point to Higher Elevation Between Starting Point (X5) and Ending Point (X14) of a Straightedge

identifying possible causes and location of rutting (**7.15**). The pavement distortion possibilities are presented in Figure 7.5. A detailed presentation of this study is included in the *SHRP-LTPP Data Analysis: Five-Year Report* (**7.4**).

Analytical Approach

Several parameters were considered and subsequently selected to investigate their influence on initiation and extent of rutting. Distortion in pavements can be caused by consolidation of one or more of the structural layers and/or the subgrade; consequently, rutting can develop in the subgrade, base, or surface layers. This pavement distress can arise from deformation under traffic loading and can be affected by the climatic condition as well as the moisture content of the subgrade. This analysis of rutting will involve a number of factors:

- <u>Structural number (SN).</u> The SN, which is an index number reflecting pavement structural capacity (including influence of material type and thickness of the pavement layers), was generated by a program developed for estimating the results from on-site drilled cores of inventory data.

- <u>Structure (ST).</u> Four types of pavement structure were considered:

  1. Asphalt concrete over granular base (AC/GB)
  2. Asphalt concrete over stabilized base (AC/SB)
  3. Asphalt concrete overlay of asphalt concrete (AC/AC)
  4. Asphalt concrete overlay of portland cement concrete (AC/PCC)

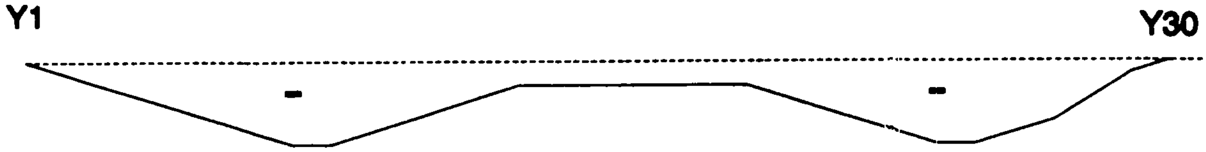
- <u>Surface thickness (T_S).</u> The thickness of the surface layer was defined from drilling and sampling results for the particular SHRP-LTPP section.

- <u>Type of subgrade (SG).</u> The subgrade type was defined as either FINE or COARSE on the basis of inventory data from the GPS studies.

- <u>Modulus (*E*).</u> The modulus was computed for every layer from falling weight deflectometer (FWD) data. The pavement structure was characterized as a three-layer system with the three modulus values Esg, Eb, and Es identifying the modulus of subgrade, base, and surface layers, respectively.

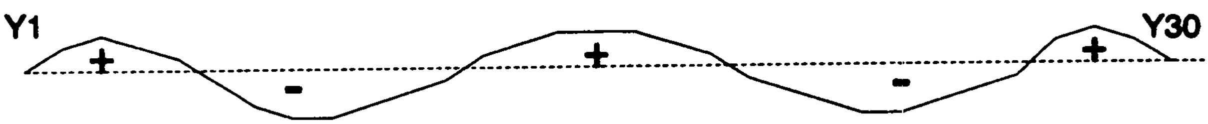
- <u>Moisture condition (*M*).</u> The moisture condition reflects the moisture content expected in the subgrade soil for that LTPP section and was categorized as either WET for high moisture content or DRY for low moisture content. The weather condition classifications are based on SHRP environmental regions (see Figure 7.6).

Net distortion is negative.
(no + values)



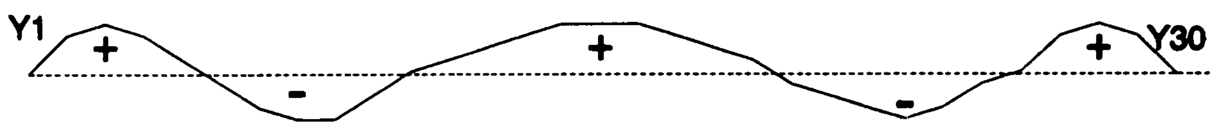
Case 1: Deep Subgrade Rutting

Net Distortion is near zero.



Case 2: Rutting Within Pavement Layer

Net distortion is positive.



Case 3: Shoving Within Upper Layer

Figure 7.5 Pavement Distortion Possibilities

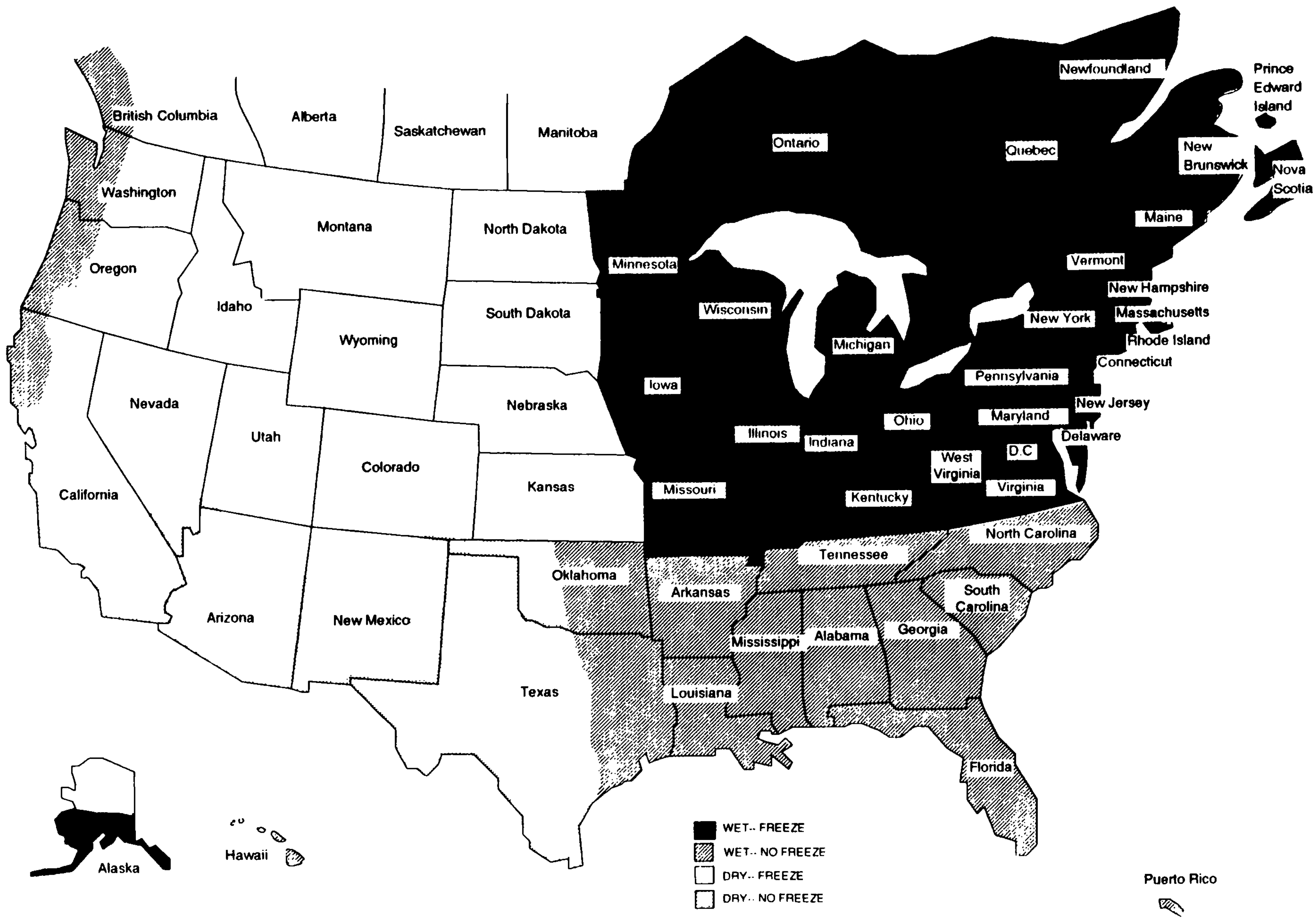


Figure 7.6 Environmental Zones for SHRP-LTPP Experiments

- Environmental Condition (C). The environmental condition characterizes the climatic state at the pavement sections and indicates the influence of weather on the surface distortion caused during rutting. This parameter was classified as either a freeze or nonfreeze situation in accordance with the SHRP-LTPP environmental regions (Figure 7.6).

- Traffic rate (TF). The amount of traffic was defined in KESALs and was obtained from the state highway agency (SHA) historical traffic data.

Definition of Rutting Type

The pavement cross-profiles vary from one section to another, producing different rut depth values as well as varying total distortion for each pavement. The rutting at each section is classified as deep-seated or layer type. This classification is based on the amount of distortion at each pavement, established from the PASCO cross-profile data, and provides an insight into the type of rutting phenomenon. The deep-seated distortion would be indicative of a subgrade breakdown, while the surface distortion type would be related to distress in the surface and other pavement layers. This classification of the distortion was developed for each pavement section and was considered for analysis as a rutting type parameter (R_T).

The deep-seated case was identified as rutting type 1, while the intermediate and the surface cases were classified as type 2. In addition, rut type could be classified as case 3 (i.e., shoving within the upper layer) or case 4 (i.e., heaving).

Sixty sections were investigated, forming a matrix of twelve fields for sixty observations. The sections were selected from the four SHRP regions to provide a uniform distribution of pavement characteristics across the United States. AC/GB, AC/SB, AC/AC, and AC/PCC pavements were designated types 1 through 4, respectively.

Type of Rutting

The type of rutting (i.e., layer or deep-seated) was analyzed by linear regression techniques to identify variables influencing rutting development. The analysis was completed for an HMAC surface layer over a stabilized base, an HMAC surface layer over a granular base, and an HMAC overlay of an original HMAC surface layer. Deep-seated rutting developed in only one of the five sections with an HMAC surface layer over a granular base.

- HMAC on stabilized base. The source of rutting regression equation for HMAC on a stabilized base is presented in Figure 7.7 along with the particulars associated with the equation. The dependent variable is R_T, which approaches a value of -1 for a deep-seated rutting condition and +1 for a layer rutting condition.

$$R_T = 0.5 - 0.36(T_s - 2.73) - 0.42(Es\text{-}750)$$
$$- 0.55(C) + 0.55\,(M * C)$$

where

R_T	=	rut type: layer +1, deep -1
T_s	=	surface thickness (in.)
E_s	=	surface modulus
C	=	temperature zone: freeze +1, nonfreeze -1
M	=	moisture condition: wet +1, dry -1
R^2	=	0.65
RMSE	=	0.64
CV	=	173.9

18 sites

Figure 7.7. Source of Rutting: HMAC on Stabilized Base

The equation incorporates four independent variables including surface thickness T_S, temperature (C) and moisture (M) zones, and surface layer modulus. The signs of the coefficients of these variables provide an indication of the effect of the variables on type of rutting (i.e., layer or deep-seated) expected to develop. The interaction (or cross-product) between the temperature and moisture zones, $M * C$, must be considered.

In general, an increase in surface thickness T_S, or surface modulus, E_S, tends to produce deep-seated rutting when the negative coefficients (-0.36 and -.42) are considered. In addition, sections in the colder ($C = +1$) and drier ($M = -1$) climatic zones would tend to develop deep-seated rutting $(-0.42(1) + 0.55(-1 * +1) = -0.97)$. On the other hand, the sections within the warmer ($C = -1$) and drier ($M = -1$) climatic zones would tend to develop rutting in the layers.

An interesting phenomenon could exist in the colder ($C = +1$) and wetter ($M = +1$) climatic zones because the main effects of temperature (C) could essentially cancel the effect of the interaction between temperature and moisture (i.e., $M \neq C$). In this case the surface layer thickness becomes the apparent dominant effect.

- HMAC on granular base. The source of rutting regression equation is presented in Figure 7.8 for HMAC on a granular base, along with the characteristics associated with the equation. The equation incorporates the two independent main effects of moisture condition (M) and pavement structural number (SN). The value of the moisture coefficient (0.63) indicates that moisture exerts a significant influence on rut type in wet environments, since it results in a R_T value of +1 (layer rutting) for structural numbers of about 4.7. Deep-seated rutting (R_T of -1) could be expected for pavement sections located in dry environments with structural numbers approaching 6.0.

- HMAC overlay of HMAC. The source of rutting regression equation for an overall flexible pavement is presented in Figure 7.9. The equation was developed from the results of ten LTPP sections. The equation incorporates two independent main effects: moisture condition (M) and overlay layer thickness (T_{OL}). The coefficient of 0.63 implies that the moisture condition has a significant direct influence on type of rutting developed; however, the overlay thickness must also be considered to produce a near unit value (positive or negative) for the dependent rut type term.

- Shoving (case 3) distortion. Shoving within the upper layer was observed in four of the twenty-six sections included in the analysis of the flexible pavements with stabilized bases. In these four sections the subgrade soil was classified in inventory data as coarse-grained. It is important to note that none of the flexible pavements with granular bases were found to exhibit a shoving distortion.

$$R_T = 0.47 - 0.68(\mathrm{SN} - 4.72) + 0.63(M)$$

where

R_T	=	rut type: layer +1, deep -1
SN	=	structural number
M	=	moisture condition: wet +1, dry -1
R^2	=	0.97
RMSE	=	0.225

5 sites

Figure 7.8. Source of Rutting - HMAC on Granular Base

$$R_T = 0 + 0.63(M) - 0.25(T_{OL} - 3.87)$$

where

R_T = rut type: layer +1, deep -1

M = moisture condition: wet +1, dry -1]

T_{OL} = overlay thickness (in.)

R^2 = 0.76

RMSE = 0.56

10 sites

Figure 7.9 Source of Rutting - HMAC Overlay of HMAC

- Heaving (case 4) distortion. Heaving was defined for five of the twenty-six sections included in the study of LTPP flexible pavement sections with stabilized bases. In four of the five sections the inventory subgrade classification was designated as a fine-grained soil. Three of the sites were located in the warmer-drier climatic zones, while the other two were located in the cooler-wetter climatic zone. In addition, none of the seven flexible pavement sections with granular bases were found to exhibit pavement heaving.

Rut Prediction Equations

Once the rut type was designated for each SHRP-LTPP section included in this study, equations for predicting the magnitude of each type of rutting (layer or deep-seated) for each pavement type were developed by simple linear regression techniques.

- HMAC on granular base. Equations for estimating rut depth (in millimeters) for layer and deep-seated distortion are presented in Figure 7.10. Both equations have relatively high R^2 values (0.80 for deep-seated and 0.85 for layer) but were developed from a small number of sites (four and three). These equations should therefore be considered preliminary and should eventually be confirmed with additional results.

  The magnitude of rut depth in the deep-seated category is primarily a function of the structural number (SN) or structural capacity of the section. An increase in SN would produce lower rut depths. Therefore the composite effect of the pavement structure influences the magnitude of rutting throughout the total pavement structure (including the subgrade).

  The rut depth that develops in the upper layers of a pavement structure is primarily related to the thickness of the top pavement layer. Greater rut depths are expected for a pavement with a thicker surface layer.

- HMAC on stabilized base. The equations for estimating rut depth (in millimeters) for layer and deep-seated distortion are presented in Figure 7.11. Both equations have reasonable R^2 values (0.83 for deep-seated and 0.62 for layer) and were developed from a total of seventeen sites. These equations should also be considered preliminary and should be confirmed with additional results.

  The magnitude of rut depth in the deep-seated category is a function of the subgrade modulus and thickness of the HMAC surface layer. From the deep-seated rut equation, it can be observed that lower subgrade moduli combined with thicker surface layers contribute to distortion within the overall pavement structure.

  The magnitude of rut depth that could possibly develop in the upper layers of a pavement structure (i.e., layer rutting) is related to the asphalt content, subgrade modulus, and age). From this relationship it can be observed that layer rutting increases with age, lower layer moduli, and lower asphalt contents.

Deep-seated $RD = 6.3 - 2.4(SN - 4.72)$

where

SN	=	structural number
R^2	=	0.80
RMSE	=	1.4
4 sites		

Layer $RD = 7.1 + 0.8\,(T_s - 2.7)$

where

T_s	=	surface thickness
R^2	=	0.85
RMSE	=	1.2
3 sites		

Figure 7.10. Rut Depth Regression Equations - HMAC on Granular Base

Deep $\quad RD = 5.8 - 0.2(E_{SG} - 22.0)$

where

E_{SG} = subgrade modulus (ksi)

T_S = surface thickness (in.)

R^2 = 0.83

RMSE = 1.2

5 sites

Layer $\quad RD = 6.1 - 1.69(AC - 5.16) - 0.05(E_{SG} - 25.5) + 0.302(AGE - 10.9)$

where

AC = asphalt content (%)

E_{SG} = subgrade modulus (ksi)

Age = age of pavement (yrs.)

R^2 = 0.62

RMSE = 1.6

12 sites

Figure 7.11. Rut Depth Regression Equations - HMAC on Stabilized Base

- HMAC overlay of HMAC. The equations for estimating rut depth development in flexible overlay sections are presented in Figure 7.12. Both equations have relatively high R^2 values (0.90 for deep-seated and 0.91 for layer rutting) and were developed from a total of ten SHRP-LTPP sites. These equations should be considered preliminary and should be confirmed in future analyses.

  From Figure 7.12, it can be observed that deep-seated rutting is a function of temperature zone (C), subgrade modulus (E_{SG}), original layer modulus (E_{OL}), and surface layer modulus (E_S). Deep-seated rutting would apparently be greater for dry climates (C = -1), lower subgrade moduli, and higher original and surface layer moduli.

  On the other hand, the magnitude of layer rutting is influenced primarily by the modulus of the original surface layer, with higher moduli values resulting in greater rutting depths.

- HMAC overlay of PCC. The equation for estimating rut depth development in an HMAC overlay layer of a rigid pavement (Figure 7.13) is a function of subgrade type (fine- or coarse-grained), overlay layer thickness, and moisture conditions. The equation has a reasonable R^2 (0.68) and is based on the results from ten SHRP-LTPP sections. Because of the structure, deep-seated rutting would not develop in this type pavement.

  From Figure 7.13, it can be observed that the magnitude of rutting is expected to be greater for coarse subgrades (SG = +1), thicker overlays, and wetter climates (M = +1).

Applications

The equations presented in this document can be used in the initial pavement design selection process to identify pavement structural sections that are prone to develop greater rutting depths and cross-profile distortion.

The R_T equations (Figures 7.7, 7.8, and 7.9) could be used to identify the type of rutting (layer or deep-seated) that could be expected to develop within the proposed design section. Preliminary adjustments in the designs could be made to minimize the potential of development of both layer and deep-seated rutting.

Once the rut type is established for the proposed design section, the appropriate rut depth prediction equation (Figures 7.10, 7.11, 7.12, and 7.13) could be used estimate the expected magnitude of long-term rutting. At this point in the process, the design section specifically could be adjusted (i.e., T_S, AC, E_S, E_{OL}) to minimize the predicted magnitude of rutting.

This proposed process is based on rutting only. The possible development of other types of distress (e.g., fatigue) in the pavement structure should be considered in developing final flexible pavement structural sections.

Deep	RD =	$3.6 - 1.75(C) - 0.06(E_{SG} - 31)$ $- 0.001(E_{OL} - 300)$ $+ 0.005(E_s - 750)$

where

C	= temperature zone: freeze +1, nonfreeze -1
E_{SG}	= subgrade modulus (ksi)
E_{OL}	= original layer modulus (ksi)
E_s	= overlay layer modulus (ksi)
R^2	= 0.90
RMSE	= 0.8
6 sites	

Layer	RD =	$7.4 + 0.005(E_s - 750)$

where

E_s	= overlay layer modulus (ksi)
R^2	= 0.91
RMSE	= 0.4
4 sites	

Figure 7.12. Rut Depth Regression Equations - HMAC Overlay of HMAC

$$RD = 1.0 + 4.1(S_G) + 6.8(T_{OL} - 2.2) + 6.8(M)$$

where

S_G = subgrade: coarse +1, fine -1

T_{OL} = overlay thickness (in.)

M = moisture conditions: wet +1, dry -1

R^2 = 0.68

RMSE = 3.8

10 sites

Figure 7.13. Rut Depth Regression Equations - HMAC Overlay of PCC

SHRP Data Analysis Contract

Introduction

The first analysis of the SHRP-LTPP data has been completed by Brent Rauhut Engineering Inc. (BRE) and ERES Consultants Inc. (ERES). BRE conducted the flexible pavement analyses and ERES the rigid pavement analyses. SHRP's objectives for this research effort were to (1) develop and implement a strategic approach to the analysis of LTPP data to support the overall goals of SHRP and LTPP and (2) to develop data analysis plans to be followed in future analyses with LTPP data. The results of this study are included in five volumes (**7.17, 7.18, 7.19, 7.20, 7.21**).

To accomplish these objectives, the following activities were conducted:

1. Data were received and processed into suitable databases for analysis, and statistical evaluations of the databases were conducted.
2. The LTPP data were used to evaluate the AASHTO design equations, and improved design equations were developed.
3. Sensitivity analyses were conducted to identify independent variables with significant effects on pavement performance and quantify the relative effects of each.
4. The experience gained from these early data analyses was used to recommend future data analysis requirements and approaches.

Several databases were formed, each representing a combination of distress type and pavement type. The statistical evaluations of the separate databases provided characterizations of the data in the databases and identified shortcomings in the data. This information will allow future planning to overcome these shortcomings.

Limitations Resulting from Data Shortcomings

This project involved the analysis of data observed on in-service pavements, and none of the early results should be expected to be of better quality than the database from which they are developed. There are limitations to the studies that are an unavoidable consequence of the timing of the early data analyses. Data was analyzed which had not been exposed to the comprehensive quality assurance, quality control checks at either the regional information management system (RIMS) or the national information management system (NIMS). For instance, excellent traffic data from the monitoring equipment recently installed will be available for future data analysts; however, this early data analysis was based on estimates of past ESALs of very limited accuracy. While years of time-sequence monitoring data will eventually become available, these studies included distress measurements for only one point in time, or at most two. For most distresses, an additional data point could be inferred for conditions immediately after construction (e.g., rutting, cracking, and faulting of joints may generally be taken as zero initially). For most test sections, analyses for roughness increases depended on educated estimates for initial roughness (derived from SHA estimates of initial

PSI). Similarly, the evaluations of the AASHTO design equations depended on the SHA estimates of initial PSI.

Another shortcoming of the databases that influenced the results involved missing items of inventory data, particularly the data from SHA project files concerning the design and construction of the pavements. Some data elements were available for all the test sections, while other data for some test sections were unknown and unavailable. Unfortunately, it will not be possible to obtain much of this missing inventory data, which will be missing for future analyses as well.

Many of the test sections were not yet displaying distresses, and those with distresses would generally exhibit only one or two types. The only type of distress that was generally available for all test sections was roughness in the SHRP-LTPP time frame, and it was therefore necessary to estimate the initial roughness to study increases in roughness. For flexible pavements, rutting information was also available for nearly all test sections. It was not possible to study alligator cracking in flexible pavements because only 18 test sections were reported to have any alligator cracking. Similarly, raveling and weathering could not be studied because only three test sections had experienced this distress. The only three distress types for flexible pavements for which sufficient data were available to support the studies were rutting, change in roughness (measured as IRI), and transverse (or thermal) cracking.

Predictive models for PCC pavements could be developed for ten combinations of pavement type and distress type. The models included joint faulting for doweled and non-doweled joints, transverse cracking for jointed plain concrete pavement (JPCP), transverse crack deterioration for jointed reinforced concrete pavement (JRCP), joint spalling for JPCP and JRCP, and IRI for doweled JPCP, non-doweled JPCP, JRCP, and continuously reinforced concrete pavement (CRCP). Insufficient data were available to develop regional predictive models.

The study of overlaid pavements was to have been of high priority. Pavement condition before overlay was considered a critically important variable; however, this information was not available for pavements that were overlaid before to entering GPS. It was decided early in the implementation of the LTPP studies that pavement test sections would be sought for which overlays were imminent, so that the condition before overlay would be available. Several test sections have been implemented, but none are old enough to have appreciable distress. The total numbers of overlaid pavements were limited, and few had sufficient information for successful analyses. Consequently, analyses for the overlaid pavements were limited to an evaluation the 1993 AASHTO Overlay Design Equations. More overlaid test sections exhibiting more distress would benefit future studies.

Sensitivity Analyses and Results

"Sensitivity analysis" is not a term commonly used by either research engineers or statisticians, but it has come to have a specific meaning to some from both disciplines. In this research effort, sensitivity analyses are defined as statistical studies to determine the sensitivity of a dependent variable to variations in independent variables (sometimes called explanatory variables) over reasonable ranges.

There is no single method of conducting sensitivity analyses; however, all approaches require development of an adequate equation (or model) as a beginning. The procedures used for these studies involved setting all explanatory or independent variables in a predictive equation at their means and then varying them one at a time from one standard deviation above to one standard deviation below the mean. The relative sensitivity of the distress prediction for a particular variable is the change in the predicted distress across the range of two standard deviations. These changes in predicted stresses are compared with distress changes when the other explanatory variables are varied in the same manner.

It became apparent early in the analysis that satisfactory predictive flexible pavement (HMAC) models could not be developed from all the data in the NPPDB because of the size of the inference space, which included all of the United States and parts of Canada. Consequently, where sufficient test sections displaying the distress of interest were available, regional databases were formed for each of the four environmental regions and separate predictive HMAC models were developed. This regionalization was not possible for the PCC pavements because the resulting regional databases would include too few data.

An example of a sensitivity analysis is presented in Table 7.3 for the predictive equation for rutting in a wet-freeze environmental zone. The form of the equation is presented at the top of the table, and the explanatory variables or interactions are included in the table, along with the coefficients that provide the details of the equation. The exponents B and C are calculated by multiplying the explanatory variables or interactions in the left column by the regression coefficients b_i and c_i and adding the results. For example, the constant b_1 for this model is 0.183 and is equal to B because all the other b_i's are 0. To calculate C, the constant term is 0.0289, the log of air voids in HMAC is multiplied by -0.189, and so forth.

The results of the sensitivity analyses conducted with this predictive equation appear as Figure 7.14. From Figure 7.14, it can be seen that the greatest effect on the occurrence of rutting in the wet-freeze environment may be expected to be the number of KESALs. The dashed lines to the left indicate that reductions in KESALs decrease rutting; however, it should be recognized in this case that the standard deviation for KESALs is greater than the mean, and negative KESALs are not possible. Freeze index is the next most important, followed by percent of the HMAC aggregate passing a #4 sieve, air voids, and so forth. It can also be seen from the directions of the arrows that increasing KESALs and freeze index may be expected to increase rut depths, while increasing amounts of aggregate passing the #4 sieve, air voids, and asphalt thickness may be expected to decrease rutting.

To illustrate how the sensitivities may differ from one environmental region to another, the sensitivity analysis results for the dry-nonfreeze environmental zone are included as Figure 7.15. In comparing the results of the two datasets, it can be seen that the majority of the variables are the same but that there are some differences and that the relative levels of sensitivities vary between environmental zones.

Table 7.3. Coefficients for Regression Equations Developed to Predict Rutting in HMAC on Granular Base for the Wet-Freeze Dataset

$$\text{Rut Depth} = N^{B}\, 10^{C}$$

where

N = number of cumulative KESALs (In.)
B = $b_1 + b_2\, x_1 + b_3\, x_2 + \ldots + b_n\, x_{n-1}$
C = $c_1 + c_2\, x_1 + c_3\, x_2 + \ldots + c_n\, x_{n-1}$

Explanatory Variable or Interaction Freeze Index (x_i)	Units	Coefficients for Terms In	
		b_i	c_i
Constant Term	--	0.183	0.0289
log(Air Voids in HMAC)	% by volume	0	-0.189
log(HMAC Thickness)	In.	0	-0.181
log(HMAC Aggregate < #4 Sieve)	% by weight	0	-0.592
Asphalt Viscosity at 140°F	Poise	0	1.80×10^{-5}
log(Base Thickness)	In.	0	-0.0436
Annual Precipitation	In.	0	
	Degree-days	0	3.23×10^{-6}

n = 41
R^2 = 0.73
Adjusted R^2 = 0.68
RMSE in $\log_{10}$(Rut Depth) = 0.19

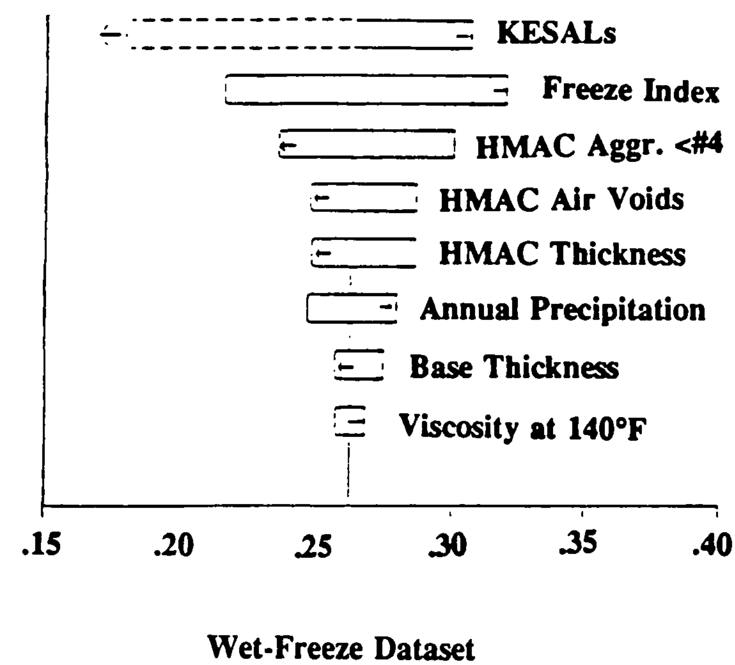


Figure 7.14. Results from Sensitivity Analysis for Rutting in HMAC Granular Base

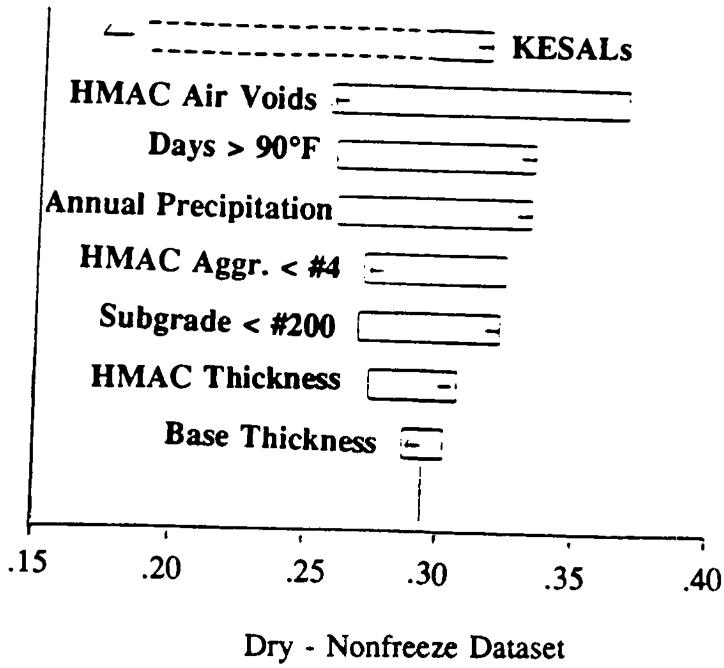


Figure 7.15. Results from Sensitivity Analysis for Rutting in HMAC on Granular Base

Similar studies were conducted for rutting in other environmental regions, as well as for increases in roughness and transverse crack spacing in all four environmental regions. For PCC pavements, equations to predict the occurrence of distresses were developed using the entire databases, and sensitivity analyses were carried out in the same manner.

While the sensitivity analyses offer useful insight, it must be remembered that most of these pavements are in very good shape, so some important interactive effects---such as water seeping through cracks and expediting deterioration in lower layers---are not necessarily represented in these results.

Summary of Sensitivity Analysis Results for HMAC Pavements

The twelve significant variables from the sensitivity analyses for HMAC pavements are listed in Table 7.4 by distress type, by relative ranking, with the most significant variable at the top and the least significant at the bottom.

Nine variables were significant in all three distress types. The exceptions are listed below:

- Air-void level in HMAC was not significant for transverse cracking
- Percentage of HMAC aggregate passing a #4 sieve was not significant for change in roughness
- Annual number of freeze-thaw cycles was not significant for rutting
- Average annual minimum temperature and daily temperature range were significant only for rutting and change in roughness, respectively

In addition, four environmental variables were found to be significant for rutting, five for change in roughness, and four for transverse cracking.

Some recommendations and comments associated with the sensitivity analyses follow:

1. Most of the rutting for these pavements apparently occurred soon after they were opened to traffic. These pavements do not necessarily represent the case of advanced deterioration.

2. It is important to achieve sufficient compaction so that the early compaction under traffic is not excessive.

3. The amount of HMAC aggregate passing the #4 sieve was selected to represent the effects of gradation. Within the inference spaces of the separate datasets, increasing amounts of aggregate passing the #4 sieve appeared to reduce rutting.

Table 7.4. Sensitivity Analysis Results: HMAC

Rutting	Change in Roughness	Transverse Cracking
KESALs	KESALs	Age
Air Voids in HMAC	Asphalt Viscosity	Annual Precip.
HMAC Thickness	Days with Temp. > 90°F	HMAC Thickness
Base Thickness	HMAC Thickness	Base Thickness
Subgrade < #200 Sieve	Base Thickness	Asphalt Viscosity
Days with Temp. > 90°F	Freeze Index	Base Compaction
HMAC Aggregate < #4 Sieve	Subgrade < #200 Sieve	Freeze Index
Asphalt Viscosity	Air Voids in HMAC	Days with Temp. >90°F
Annual Precipitation	Base Compaction	Subgrade < #200 Sieve
Freeze Index	Annual Precipitation	KESALs
Base Compaction	Daily Temp. Range	Annual Freeze-Thaw Cycles
Average Annual Min. Temp.	Annual Freeze-Thaw	HMAC Agg. < #4 Sieve Cycles

4. As expected, traffic loading is the strongest contributor to rutting and roughness, while pavement age had the strongest effect on transverse cracking.

5. Thicker HMAC surfaces and granular base layers may be expected to generally decrease all three types of distress.

Some of these results are difficult to explain. For example, the studies indicate that increases in base compaction, annual precipitation, asphalt viscosity, or annual freeze-thaw cycles (or freeze index) tend to increase transverse crack spacing (reduce cracking). These results are difficult to understand and cannot be explained entirely in terms of reliabilities of the equations, since the regional equations had fairly good statistics.

In summary, most of the results from the sensitivity analyses for HMAC pavements appear to be reasonable; however, other results appear as surprises that may (1) result from the specific characteristics of the datasets on which they are based, (2) represent mechanisms not yet understood, (3) result from interactions not explained by the equation forms, or (4) result from other unknown causes.

Summary of Sensitivity Analysis Results for PCC Pavements

The results of the sensitivity analyses on PCC pavements are presented in Table 7.5. The independent variables are listed below in order of "combined rankings," one based on average rankings and one based on number of models in which the variable was included (in case of a tie, the other ranking basis was used to order the two).

The rankings are almost identical for the two methods. However, the results in Table 7.5 do not tell the whole story, since the rankings depend on type of pavement and type of distress. Conclusions concerning the three PCC pavement types (JPCP, JRCP, and CRCP) have been developed from the results of the sensitivity analysis and past experience. The conclusions are presented in the following sections.

Design Recommendations for JPCP

1. Use of dowels of sufficient size for the traffic loadings (the larger the dowel diameter, the less faulting) will ensure that faulting will not become significant and cause severe roughness. Use of dowels is particularly important for heavy traffic in cold and wet climates. Thicker slabs by themselves do not reduce faulting significantly. Longitudinal subdrainage will help reduce faulting of non-doweled joints. Use of a tied concrete shoulder will reduce doweled joint faulting.

2. Increased slab thickness has a very strong effect on reducing transverse slab cracking and providing a smoother JPCP (lower IRI) over time.

Table 7.5. Sensitivity Analysis Results: PCC

Ranking by Average	Ranking by Number of Models Found Significant
Age	Age
Cumulative ESALs	Cumulative ESALs
Slab Thickness	Slab Thickness
Static *k* Value	Static *k* Value
Precipitation	Precipitation
Joint Spacing	Edge Support (Tied Shoulders)
Percent Steel	Joint Spacing
Edge Support (Tied Shoulders)	Percent Steel
Annual Freeze-Thaw Cycles	Annual Freeze-Thaw Cycles
Type of Subgrade	Type of Subgrade
PCC Flexural Strength	PCC Flexural Strength
Monthly Temperature Range	Monthly Temperature Range
Widened Traffic Lane	Widened Traffic Lane
Freeze Index	Freeze Index
Dowel Diameter	Dowel Diameter
Subdrainage	Subdrainage
Type of Base	Type of Base

3. Provision of increased subgrade support, as indicated by the back-calculated *k* value, results in lower IRI and a smoother pavement. Increased support over an existing soft subgrade would likely require either treatment of the soil or a thick granular layer over the subgrade.

4. Use of shorter slabs for JPCP will reduce the amount of joint faulting and transverse cracking and will result in a smoother pavement (lower IRI) over time.

5. Specification of durable concrete in freeze climates is desirable, so that freeze and thaw cycles and other climatic factors do not result in significant joint spalling.

Design Recommendations for Jointed Reinforced Concrete Pavement (JRCP)

1. Use of dowels of sufficient size for the traffic loadings (the larger the dowel diameter, the less faulting) will ensure that faulting will not become significant and cause severe roughness. Use of dowels is particularly important for heavy traffic in cold and wet climates. Thicker slabs by themselves do not reduce faulting significantly. Longitudinal subdrainage will help reduce faulting of non-doweled joints. Use of a tied concrete shoulder will reduce doweled joint faulting.

2. Increased slab thickness has a very strong effect on reducing transverse slab cracking and providing a smoother JPCP (lower IRI) over time.

3. Provision of increased subgrade support, as indicated by the back-calculated *k* value, results in lower IRI and a smoother pavement. Increased support over an existing soft subgrade would likely require either treatment of the soil or a thick granular layer over the subgrade.

4. Use of shorter JRCP slabs will reduce the amount of joint faulting.

Design Recommendations for CRCP

1. Increased percentage of longitudinal reinforcement provides a smoother CRCP (lower IRI) over time. The increased percentage of steel reduces the number of punchouts and the deterioration of transverse cracks.

2. Increased subgrade support results in fewer deteriorated transverse cracks and a lower IRI (smoother pavement). Increased support over an existing soft subgrade would likely require either treatment of the soil or placement of a thick granular layer over the subgrade.

3. Widened traffic lanes will provide a smoother CRCP (lower IRI) over time.

4. Increased slab thickness results in somewhat smoother CRCP (lower IRI) over time, probably because there are fewer punchouts as a result of the thicker slab.

Evaluation of the AASHTO Flexible Pavement Design Equation

The equation to be evaluated is the one included in the 1986 *AASHTO Guide for Design of Pavements*:

$$\log W = Z_R * S_o + (G_t / \beta) + 2.32 \log M_r - 8.07$$

where

G_t	=	$\beta (\log W - \log \rho) = \log (\Delta PSI/2.7)$
W	=	number of 18-kip ESALs
ρ	=	$0.64 (SN + 1)^{9.36}$
β	=	$0.4 + 1094/(SN + 1)^{5.19}$
SN	=	$a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 + ... + a_n D_n m_n$
D_i	=	thickness of Layer i (in.)
a_i	=	structural coefficient for the material in Layer *i*
m_i	=	drainage coefficient for the material in Layer *i*
Z_R	=	standard normal deviate
S_o	=	overall standard deviation
M_r	=	resilient modulus (psi)

Because this equation was used for research instead of design, a 50% reliability was assumed, which resulted in $Z_R = 0$.

The original equation for calculating current PSI was reported in the *AASHO Road Test Report 5* as follows:

$$PSI = 5.03 - 1.91 \log(1 + sv) - 1.38 rd^2 - 0.01\, c + p$$

where

sv	=	average slope variance as collected using the CHLOE profilograph
rd	=	average rut depth based on a 4-ft straightedge
c	=	Class 2 and Class 3 cracking (ft^2 per 1000 ft^2)
p	=	bituminous patching (ft^2 per 1000 ft^2)

This equation, commonly used in the past for estimating PSI, was used to determine current PSI values for the SHRP-LTPP sections from values of slope variance derived from surface profiles measured with a Law profilometer and rut depths measured by PASCO's RoadRecon unit. The cracking and patching terms were not included in the calculation of the current PSI, since significant cracking and patching (C&P) were noted for only a few test sections. In addition, the effect of the C&P term was not considered significant because its coefficient was only 0.01. The mean value of current PSI for the SHRP-LTPP sections included in this analysis was 3.53, with a standard deviation of 0.49.

Observed PSI loss was defined as the difference between the initial PSI and the calculated current PSI value. The mean value for observed PSI loss was 0.70 and the standard deviation was 0.51. Initial values of PSI were estimated by the SHAs, resulting in a mean value of 4.25 and a standard deviation of 0.23.

The basic AASHTO equation was used to predict the total KESALs required to cause the observed losses in PSI. Rearranging the equation slightly results in

$$\Delta PSI = 2.7\ (W/pS_m)^{\beta}$$

where

$$S_m = (M_r)^{2.32} * 10^{-8.07}$$

The predicted PSI losses caused by the traffic estimated by the SHAs were calculated with this equation.

Resilient moduli estimates for the subgrade (M_r) were obtained from the back-calculation procedures recommended in the 1986 *Guide*, using the deflections measured by an outer sensor of an FWD. Historical traffic data provided by the SHAs were used for the traffic data (W) in these calculations. The cumulative KESALs for each section were divided by the number of years since the test section was opened to traffic to obtain average values per year. This allowed extrapolation to an extra year or two beyond 1989 to obtain traffic level estimates associated with the dates of monitoring activities. Most of the monitoring data used were obtained in 1990 or 1991.

During the investigation it was found that the KESALs were consistently much higher than those estimated by the SHAs. Only 9 of the 244 predictions were lower than the SHA estimates, while the predictions were more than 100 times the SHA estimates for 112 test sections. As the predictions from the design equation appeared to be very poor for in-service pavements, the thrust of the research turned toward identifying its problems and developing more reliable equations.

As partial explanation, it was noted that 74% of the in-service test sections in this study had experienced a loss in PSI of 1.0 or less, while those in the road test experienced losses of 2 to 3. Further, the average absolute deviation of observed PSI from the computed curves at the AASHTO Road Test was 0.46, so some 39% of the in-service test sections in this study had experienced losses of PSI within the "noise" at the road test.

Linear regressions conducted on the database resulted in an equation with an R^2 of 0.09, indicating that the equation form simply did not represent in-service pavement performance. Additional factorial studies indicated that the equation appears to falter for structural numbers less than 3, cumulative traffic greater than 5 million ESALs, or subgrade moduli greater than

10,000 psi (a value of 3000 psi was assumed for the road test data)—that is, for conditions outside the inference space of the AASHO Road Test.

Linear regression analyses were also conducted to model the ratio of predicted to observed traffic. These analyses resulted in a model with R^2 of 0.77, which included structural number, subgrade modulus, and PSI loss but also average annual rainfall and average number of days below freezing. Attempts have been made through the years to extrapolate the equation outside its inference space, but these have apparently been unsuccessful.

The back-calculated subgrade moduli appeared to be quite high, but laboratory testing for resilient moduli was just getting started when these analyses were being conducted. Subsequent comparisons of 106 test sections for which laboratory results became available indicated that the mean ratio of back-calculated to laboratory-derived moduli was 4.48, with a standard deviation of 2.47. These 106 laboratory moduli were substituted for the back-calculated moduli, and the ratios of predicted to observed ESALs were considerably decreased. The number of "reasonable predictions" (with ratios of 2 or less) changed from 13 with the back-calculated subgrade moduli to 60 with the laboratory moduli. While the predictions improved greatly, the ratios for 46 predictions still ranged from 2 to more than 100, corroborating the weaknesses in the equation noted throughout the studies. It appears certain that future design equations must take into account differences between back-calculated and laboratory-derived resilient moduli.

Other limitations of the flexible pavement design equation were noted:

1. The accelerated trafficking to "failure" at the road test was not representative of in-service pavements. Pavement engineers typically intercede with overlays or other rehabilitation long before serviceability loss approaches the level considered as failure at the road test.

2. The subgrade elastic moduli were assumed to be 3000 psi for the development of equations at the road test, whereas much higher moduli result from back-calculation or current laboratory protocols.

Evaluation of the AASHTO Rigid Pavement Design Equation

The analyses were carried out using the original AASHO design equation and the 1986 extension of the original design equation, which was unchanged in the 1993 guide. The analysis using the AASHO original equation was undertaken to determine whether the improvements to the prediction model were beneficial.

The AASHO design equations were evaluated by comparing the predicted 18-kip (80-kN) ESALs for each test section determined from the design equation to the "observed" ESALs (estimated from traffic data) carried by the section. The predicted ESALs are calculated with the concrete pavement equations from the original Road Test and the latest extended form in the 1986 *AASHTO Design Guide for Pavement Structures*.

The original 1960 AASHO design equation is a relationship between serviceability loss, axle loads and types, and slab thickness:

$$G_t = \beta(\log W_t - \log p) = \log([4.5 - p_t] / [4.5 - 1.5])$$

where

G_t	=	logarithm of the ratio of loss in serviceability at time t to the potential loss taken to a point at which serviceability equals 1.5
β	=	a function of design and load variables that influence the shape of the p-versus-W serviceability curve
W_t	=	cumulative 18-kip ESALs applied at end of time t
p	=	a function of design and load variables that denotes the expected number of axle load applications to a terminal serviceability index
$\log p$	=	$7.35 \log(D + 1) - 0.06$
D	=	slab thickness (in.)
4.5	=	mean initial serviceability value of all sections
p_t	=	terminal serviceability

In the 1986 and 1993 *AASHTO Design Guides*, the PCC pavement design model is given as:

$$\log W_{18} = Z_R S_o + 7.35 \log(D + 1) - 0.06 + \frac{\log\left(\frac{\Delta PSI}{4.5 - 1.5}\right)}{1 + \frac{1.624 * 10^7}{(D + 1)^{8.46}}}$$

$$+ (4.22 - 0.32 p_t) \log\left(\frac{S_c' C_d (D^{0.75} - 1.132)}{215.63\ J \left[D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}\right]}\right)$$

where

ΔPSI	=	loss of serviceability ($p_i - p_t$)
D	=	thickness of PCC pavement (in.)
S_c'	=	modulus of rupture of concrete (psi)
C_d	=	drainage coefficient
E_c	=	elastic modulus of concrete (psi)
k	=	modulus of subgrade reaction (psi/in.)
J	=	joint load transfer coefficient
W_{18}	=	cumulative 18 kip ESALs at end of time t
p_i	=	initial serviceability
p_t	=	terminal serviceability

Z_R = standard normal deviate
S_o = overall standard deviation

Five sets of analyses were performed individually for GPS experiments 3 (JPCP), 4 (JRCP), and 5 (CRCP) to examine the ability of the equations to predict the amount of traffic actually sustained by each test section. Initially, analyses were conducted on all data available for each experiment. Then the datasets for each pavement type (JPCP, JRCP, and CRCP) were further separated by environmental regions. Analyses were then performed for each of the four environmental regions for each of the pavement types.

The predicted KESALs were plotted against the estimated KESALs on scattergrams to visually examine the scatter of the data. The results were also presented in bar graphs showing the ratio of predicted to actual KESALs.

As an example, the plot of predicted versus actual KESALs using the original AASHO model appears in Figure 7.16 for JPCP and JRCP. If the predictions were unbiased for all regions, half the points would fall on each side of the line of equality.

It can be seen that the original AASHO model overpredicts KESALs for a majority of test sections (78% of JPCP and 82% of JRCP). Similar scatterplots were developed for separate environmental regions.

The plots of predicted versus actual KESALs for JPCP, using the 1986 or 1993 AASHTO model, are shown in Figure 7.17. It can be seen that the 1993 model predicted much better than the original AASHO model for these analysis datasets, suggesting that the addition of several design factors considerably improved the performance prediction of the model. However, there is much scatter about the lines of equality, even on these log-log plots. This scatter may be due to several causes, including inadequacies in the model, errors in the inputs, and random performance variations (or pure error). Similar plots were prepared and evaluated for JPCP and CRCP.

To analytically determine the ability of the AASHTO concrete pavement design model to predict the actual KESALs observed for the pavement sections, a statistical procedure was followed that determined whether two sample datasets (actual and predicted) are from the same population. The paired-difference method, using the Student *t* distribution, was used to determine whether the KESALs as predicted by the AASHTO equation statistically belong to the same population as the actual measured KESALs.

Appropriate statistical analysis tools were used to compare the observed KESALs with those predicted by the AASHTO equations. The calculated *t* statistic (*t*-calc) was compared with a tabulated *t* statistic (*t* table) for a specific confidence level. If *t* calc is greater than *t* table, the null hypothesis (that they are from the same population) is rejected with a 5% chance of error, since the confidence level selected for this analysis is 95%.

It was observed that *t* calc is greater than *t* table for half the datasets when the original AASHTO model was used, which indicates that the original AASHTO model is not a reliable predictor of the ESALs actually sustained by the pavement sections. However, for the 1993

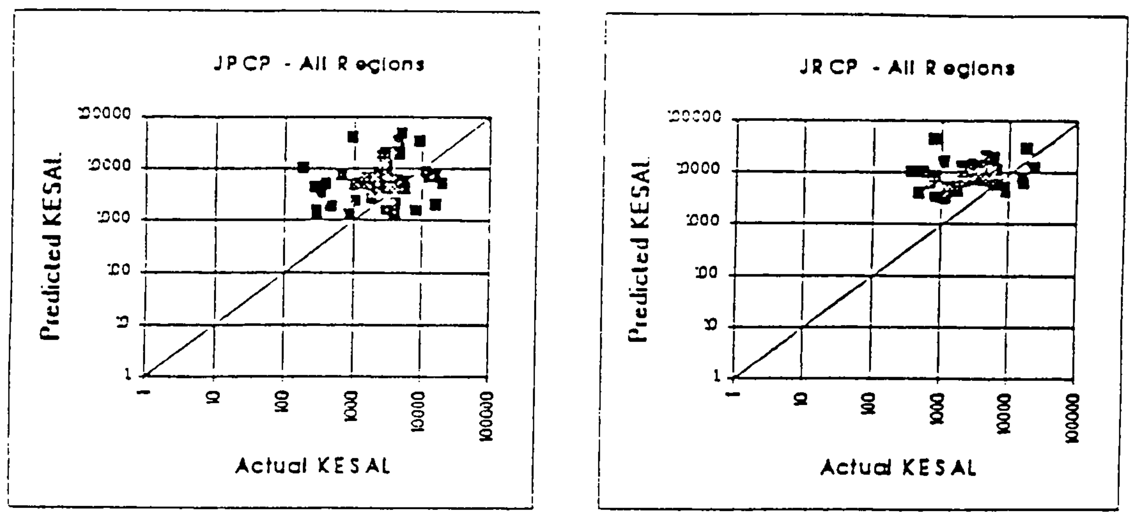


Figure 7.16 Predicted KESALs versus Actual KESALs for JPCP and PRCP Using Original AASHTO Prediction Models

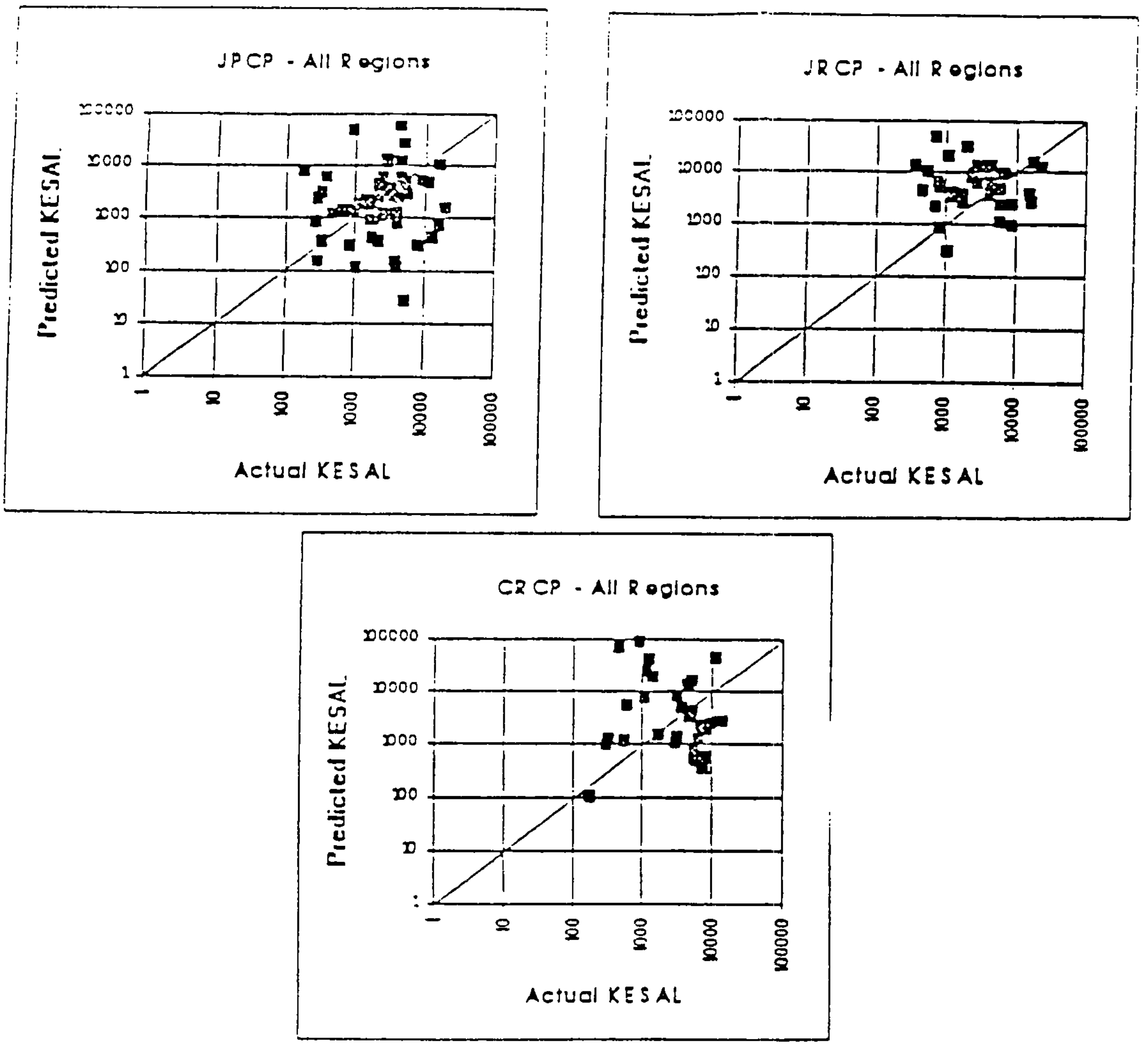


Figure 7.17 Predicted KESALs versus Actual KESALs for JPCP, JRCP, and CRCP Using 1993 AASHTO Prediction Models

AASHTO model, the results show that the null hypothesis is not rejected. This holds true for all climatic regions. These results show that the improvements to the original AASHO model increased the accuracy of the design equation.

Another comparison was made between the actual KESALs and predicted KESALs at a particular level of design reliability. Thus, the mean log $W_{50\%}$ prediction is reduced by $Z_R S_o$ (where Z_R = 1.64 for 95% reliability and S_o = 0.35). The predicted (at 95% reliability) versus actual KESALs were plotted. Most of the points were below the line of equality, indicating that the consideration of design reliability definitely results in a large proportion of sections (77%) with a conservative design, a desirable result. A statistical test was also conducted as before.

The results of these studies were then summarized. The 1986 (or 1993) model appears to provide more or less unbiased predictions in that the plots of predicted versus actual KESALs tend to center on the lines of equality. Although the scatter is not very apparent on the log-log plots, which are used to include all the data points, the actual scatter is obvious when reviewed arithmetically. Thus, even though collectively the adjustments to the 1993 model seem to have improved prediction capabilities in comparison with the original AASHTO model, the evaluation points to the need for further improvements to increase the accuracy of the predictions.

Improved Design Equations: Applications and Limitations

It became apparent early in the research that most of the highway community was not totally interested in continuing use of the PSI for design. The preference was for separate design equations for the several significant distress types, so that the equations could be used both for pavement management and for balanced designs to minimize the distresses individually. This was the approach followed in this research.

For any proposed pavement structure, the key distress and roughness indicators are predicted using the best available LTPP models over the design traffic and life. The adequacy of the design is judged by the predicted performance in terms of individual distresses, including roughness. Design modifications can be made if any aspect of performance is found to be deficient. This sequence can then be repeated until an acceptable design is obtained. An example of this approach is provided below.

HMAC Pavements

The distress types considered to be significant were alligator cracking, rutting, transverse (or thermal) cracking, increases in roughness, and loss of surface friction. However, alligator cracking could not be studied at this early stage, since only 18 pavements displayed that distress and the data collected were inadequate for modeling loss of surface friction.

The original intent was to rearrange the models developed for the sensitivity analyses as design equations, but separate consideration of HMAC and unbound base thicknesses was problematic because the separate effects for some distress types and environmental zones were not additive. That is, increasing thickness of either did not necessarily result in a decreased required thickness for the other. Consequently, it was decided to use structural number, in lieu of the HMAC and unbound base thicknesses separately, to develop models that were more reasonable.

The models were redeveloped on the basis of structural number, but the results discussed above are still reflected in the design models. These models for separate environmental zones had values of adjusted R^2 that varied from 0.69 to 0.88 and are similar in format to the example in Table 7.3.

The researchers were unable to satisfactorily explain this surprising result, but they do know from the sensitivity analyses that increasing base thickness for the dry-freeze dataset strongly indicates increasing roughness. Assuming that the base compaction provided for these pavements was not sufficient or later deteriorated because of environmental or other effects, it can be seen that increasing depths of base could result in more differential rutting and thus roughness. Future studies should be conducted to gain understanding of unexpected results, as in this example.

While these models may prove over time to be reasonable, they are based in this early analysis on very limited time sequence data (generally an initial point and another in 1990 or 1991 for the distresses) and should be used with care and only as design checks in concert with other design procedures. While a good distribution of pavement ages undoubtedly helped in explaining "curvature" in the relationship that could well be enhanced by future time sequence data, these models are not recommended for general use at this time.

PCC Pavements

The same approach described above for HMAC pavements was used for the PCC pavements, and the same limitations on quality of models apply. The distress models described previously for the PCC sensitivity analyses are available for use in design checks.

The following presentation illustrates the potential use of distress models for evaluation or development of pavement designs. Future versions of these models should be greatly improved and should be adequate for use in design. A JRCP pavement design has been proposed, based on an SHA standard design procedures and design standards. The values selected for the required design inputs for the LTPP models are summarized below:

Design life:	30 years		
Traffic:	30 million ESALs in design lane		
Climate:	PRECIPitation	=	30 in. (762 mm)
	TemperatureRANGE	=	60°F (33.3°C)
Subgrade:	STATIC subgrade reaction	=	300 psi/in. 82.7 Pa/mm)
Base:	Treated granular material		
Slab:	THICKness	=	9 in. (229 mm)
	%STEEL	=	0.12% area
Joints:	Jspacing	=	40 ft. (12 m)
	dowel diameter	=	1.25 in. (32 mm)
Shoulders:	Asphalt concrete, edge support	=	0

These pavement design inputs and characteristics were used with all the predictive models for JRCP to estimate performance over the 30-year design life and beyond (note that prediction beyond about 20 years exceeds the inference space for the current LTPP models). Joint faulting, joint spalling, transverse crack deterioration, and IRI were predicted. Since some readers may not be familiar with the values of the IRI, the corresponding PSI has been estimated with a recently developed model from user panel data. The results are shown in Table 7.6. Some interesting results are summarized as follows:

- Faulting of only 0.10 in. (2.5 mm) was predicted at 30 years. A level of approximately 0.25 in. (6.4 mm) is critical from a roughness standpoint for a JRCP with long joint spacing. Thus, joint load transfer is adequate over the 30-year period.

- Joint spalling (converted from percent joints deteriorated to number of joints per mile) is predicted to increase rapidly after 15 years until at 30 years about 106 joints per mile (67 joints/km) have deteriorated. Joint repair will be required after about 15 to 20 years to keep the pavement in service unless some improvement in joint design is obtained.

- Transverse crack deterioration is relatively low over most of the 30-year design period. However, crack deterioration increases greatly at about 30 years, requiring considerable repair. Increased reinforcement would reduce the amount of crack deterioration as subsequently shown.

- The IRI remains within an acceptable range over the 30-year design period as indicated by the PSR values.

Evaluation of the 1993 AASHTO Overlay Design Equations

The 1993 revisions to the AASHTO overlay design procedure were intended to provide overlay thicknesses that address a pavement with a structural deficiency. A structural deficiency arises from any conditions that impair the load-carrying capability of the pavement

Table 7.6. Use of LTPP Predictive Models for Evaluating a JRCP Design Example

Age	Cum. CESAL	JT Space	K Static	Edge SPRT	Dowel DIA	% Steel	Temp Range	Precip	Thick	Fault	Spall	Crack	IRI	PSI
Yrs	10^6	ft	psi/ in.	*	in.	%	°F	in.	in.	in.	joints /mi.	crack /mi.	in. /mi.	**
5	5	40.0	300	0	1.25	0.12	60	30	9	0.01	0***	0***	69	3.8
6	6	40.0	300	0	1.25	0.12	60	30	9	0.01	0	0	70	3.8
7	7	40.0	300	0	1.25	0.12	60	30	9	0.01	0	0	71	3.7
8	8	40.0	300	0	1.25	0.12	60	30	9	0.02	0	0	72	3.7
9	9	40.0	300	0	1.25	0.12	60	30	9	0.02	0	0	72	3.7
10	10	40.0	300	0	1.25	0.12	60	30	9	0.02	0	0	73	3.7
15	15	40.0	300	0	1.25	0.12	60	30	9	0.03	21	0	78	3.6
20	20	40.0	300	0	1.25	0.12	60	30	9	0.05	46	7	82	3.6
25	25	40.0	300	0	1.25	0.12	60	30	9	0.07	74	17	86	3.5
30	30	40.0	300	0	1.25	0.12	60	30	9	0.10	106	26	90	3.5
40	40	40.0	300	0	1.25	0.12	60	30	9	0.17	176	45	99	3.3
50	50	40.0	300	0	1.25	0.12	60	30	9	0.28	256	64	107	3.2

* EDGESUP = 1 for tied PCC shoulder, = 0 for any other shoulder type.
** PSI = $5 * e^{(-0.0041*IRI)}$
*** Values that were negative were set at zero.

1 in. = 25.4 mm; 1 ft. = 0.3 m; 1 psi/in. = 275.6 Pa/mm

structure. These conditions include inadequate thickness as well as cracking, distortion, and disintegration.

The AASHTO pavement overlay design procedures are based on the concept that time and traffic loading reduce a pavement's ability to carry loads. An overlay is designed to increase the pavement's ability to carry loads over a future design period. The structural capacity required for a PCC or HMAC pavement to carry future traffic is calculated with the appropriate AASHTO 1993 pavement design equation. The effective structural capacity of the existing pavement is evaluated using procedures for overlay design presented in the *Guide*. These procedures can be based on visual survey and materials testing results, on the remaining life of the pavement in terms of the traffic that can be carried, or on nondestructive testing (NDT) of the existing pavement. An overlay is then designed on the basis of the structural deficiency represented by the difference between the structural capacity required for future traffic and the effective structural capacity of the existing pavement.

LTPP data from GPS-6A, GPS-6B, GPS-7A, GPS-7B, and GPS-9 were used to evaluate the 1993 version of the AASHTO overlay design equations. While data on design life and levels of reliability sought were not available, a limited set of test sections was identified that had sufficient data for limited evaluations. The set included nine sections with HMAC overlays of HMAC, five with HMAC overlays of PCC, and six with unbonded PCC overlays of PCC. Even for these test sections, it was necessary to use existing data to estimate values for some of the inputs to the design equations.

The design equations were then used to predict overlay thicknesses required, and these thicknesses were compared with the thicknesses of the overlays actually constructed. The results from recent profile measurements and distress surveys were also used to evaluate the adequacy of the AASHTO design equation for establishing an appropriate design overlay thickness. Table 7.7 is a summary of the results from these comparative evaluations.

Although these evaluations were seriously constrained by data limitations, for this small dataset of five test sections the equation appears to work quite well for AC overlays of PCC. The evaluations were generally inconclusive for AC overlays of AC and unbonded PCC overlays of PCC.

It is hoped that in the future, data will be available with sufficient design periods and levels of reliability appropriate to design of overlays that can be used for comparative evaluations. Conclusive evaluations are probably not possible until this information becomes available so that the comparisons can be made on the same design basis.

Recommendations for Future Analyses

One of the primary objectives of this research was to provide recommendations for future analyses when more time series data will be available. Some of the many products achieved were:

Table 7.7. Results from Comparative Evaluation of 1993 AASHO Overlay Equations

Test Section Number	Type of Pavement	Results From Comparisons			
		Conservative	Adequate	Inadequate	Inconclusive
016012	AC/AC		X		
016109	"				X
351002	"				X
356033	"				X
356401	"		X		
486079	"		@95%		
486086	"		Reliability		X
486160	"	X			
486179	"				X
Subtotals for AC/AC:		1	3	0	5
087035	AC/PCC		X		
175453	"		X		
283097	"		X		
287012	"		X		
467049	"			X	
Subtotals for AC/PCC:		0	4	1	0
69049	PCC/PCC			X	
89019	"				X
89020	"				X
269029	"				X
269030	"				X
489167	"				X
Subtotals for PCC/PCC:		0	0	1	5
Overall subtotals:		1	7	2	10

1. Usable databases for combinations of pavement and distress types
2. Statistical characterizations of the data
3. Identification of biases in the data
4. Distress models
5. Valuable insight into the need for regional models
6. Procedures for developing models from LTPP data
7. Identification of variables with significant effects on specific distresses
8. Procedures for conducting sensitivity analyses on LTPP data
9. Identification of procedures that don't work
10. Identification of mechanistic variables and "clusters" for future modeling
11. Identification of the shortcomings of the AASHTO design equations
12. Identification of potential improvements to the AASHTO design equations
13. Recommendations to follow in future analyses

Some additional studies that were not included in the contract but that the research staff hoped to achieve were (1) development of mechanistic-empirical models, using mechanistic responses (stresses and strains) as independent variables in nonlinear regression models; and (2) development of load equivalence factors separately for specific distresses modeled. These studies can be undertaken later as more time sequence data become available.

Future analytical objectives should include (1) development of distress models for use in design procedures, pavement management, and sensitivity analyses; (2) calibration of existing mechanistic-empirical models using LTPP data; (3) combining knowledge from SHRP studies of asphalt, concrete, and long-term performance to improve performance models and gain additional insight into effects of independent variables on performance; (4) development of models for layer stiffnesses in terms of component characteristics; (5) follow-up on unexpected phenomena resulting from analyses; and (6) evaluation of seasonal changes in layer stiffnesses and surface profiles.

Several modeling techniques were suggested by various experts for future analyses, each with its own set of strengths and weaknesses. Techniques that should be considered during future analyses should include (1) those developed for these early analyses, (2) discriminate analysis, (3) techniques using "censored data" (World Bank procedures used in the Brazil Study and others), (4) survival analysis, (5) neural network approaches (relatively new applications to engineering systems), and (6) other nonlinear models.

As a final comment on future analyses of LTPP data, the processing of data into databases and the analyses for a spectrum of combinations of pavement type and distress type and analytical objectives are both time consuming and expensive. Future analyses should be sufficiently funded to fully harvest the results from the $100 million—plus effort undertaken by SHRP, FHWA, and the SHAs.

SHRP Data Analysis Contract: Michigan State University

This study is based on mechanistic evaluations of the AASHTO design procedures using the data from the SHRP database relative to the asphalt-surfaced GPS sections. The results of the mechanistic analysis were originally to be used to accomplish the following objectives:

1. Calibrate the AASHTO design equations.
2. Verify and calibrate the concept of the AASHTO drainage coefficient.
3. Revise the AASHTO LEFs.
4. Develop mechanistic-empirical models.

Because of the gaps in the database and missing data elements (e.g., layer moduli or layer coefficients) that are required for the mechanistic analysis, the research plan was modified as follows:

1. Establish a full-factorial experiment design matrix that consists of 243 artificial flexible pavement sections. For each section, assign material properties and traffic volumes (in terms of 18-kip ESAL) within the typical ranges used by various SHAs. Design each pavement section (determine the required layer thicknesses) by the AASHTO design procedure. Use the layer thicknesses and the materials properties to calculate the mechanistic responses (stresses, strains, and deflections) of each pavement section.

2. Analyze the sensitivity of the mechanistic responses to the layer thicknesses determined by the AASHTO procedure. Evaluate and revise as possible the AASHTO design equation and the concept of drainage coefficients.

Based on the results of this study, several observations and conclusions were made and are summarized below.

Premises of the AASHTO Design Procedure for Flexible Pavements

The findings of the sensitivity analyses of the layer thicknesses of the 243 pavement sections and of the AASHTO flexible pavement design equations have confirmed the present knowledge regarding the AASHTO design procedure. These findings are enumerated below:

1. The dependent variable of the AASHTO flexible pavement design equation is the structural number (SN) of the pavement. The SN is a function of the traffic volume (in terms of 18-kip ESAL), design reliability, overall standard deviation, total loss of serviceability during the performance period, and resilient modulus of the roadbed soil. The structural number is computed so that the pavement will have the structural capacity required to carry the anticipated traffic load and volume and will experience the specified loss of serviceability during the performance period. Hence, for any pavement structure, the AASHTO required structural number is independent of the quality and properties of the asphalt, base, and subbase layers. The properties (e.g.,

layer coefficients) of these layers play a major role in determining the thickness of each layer but not the overall pavement structural capacity in terms of the SN.

2. After determining the required SN of a pavement section, the layer thicknesses are computed by the AASHTO recommended layer analysis method. In this regard, the AASHTO method assumes that the structural capacity of the pavement is the sum of the structural capacity of each of its layers. Further, the SN of any pavement layer is the product of its layer and drainage coefficients and its thickness. That is, the structural capacity of a relatively weak pavement layer can be enhanced by increasing its thickness.

3. Although the AASHTO design guide advocates the use of good-quality materials with reasonable costs, the AASHTO procedure assumes that the effects of drainage on pavement performance can be eliminated by adjusting the thickness (by using a drainage coefficient) of the affected layer. That is, a base layer with an excellent drainage quality would perform exactly the same as one with poor drainage quality if the thickness of the layer is increased by the ratio of the values of their drainage coefficients.

4. The effects of serviceability loss due to environmental conditions (freeze-thaw and swelling soils) can be eliminated by increasing the structural capacity (SN) of the pavement. Higher environmental loss of serviceability requires higher structural capacity.

Mechanistic Evaluation/Calibration of the AASHTO Design Procedure

After the 243 pavement sections were designed and the thicknesses of the various pavement layers were determined by the AASHTO design procedure, the mechanistic responses (stresses, strains, and deflections) of each pavement section were computed by using the linear option of the MICHPAVE computer program (a linear/nonlinear finite element program). The findings of the sensitivity analyses of the mechanistic outputs and results of comparison with the present knowledge of the AASHTO design procedure (previous section) are presented below:

1. For pavement sections with various layer properties that have been designed by the AASHTO procedure to be supported on the same roadbed soil, to carry the same traffic volume, and to have the same serviceability loss during an equal performance period, the mechanistic analyses indicate that:

    a) The peak pavement surface deflection (a mechanistic response) is almost the same for all sections. Hence the amount of the overall damage due to compression delivered to the various pavement sections (or the overall protection level) is constant and independent of the layer properties. This finding implies that the AASHTO design procedure produces a balanced design relative to the global damage delivered to the pavements. Stated differently, the results of the mechanistic analyses tend to support the structure and validity of the SN concept of the main AASHTO design equation.

b) The induced stresses and strains experienced by any one layer vary from one pavement section to another. Hence, the amount of damage delivered to any one pavement layer is a function of the material properties of that layer. This implies that while the AASHTO design procedure ensures that the global damage of the pavement sections remains constant (item 1), the relative damage delivered to each layer is not. Thus, the results of the mechanistic analyses do not support the AASHTO layer coefficient or the AASHTO concept that the SN of the pavement is the sum of the SNs of its layers.

c) The tensile stress and the ratio of the tensile stress to the asphalt layer modulus induced at the bottom of the AC layer depend on the properties and thicknesses of all pavement layers. This implies that the AASHTO design procedure does not produce pavement sections with equal fatigue life. However, the global damage due to compression in the pavement sections remains the same. Once again, the results of the mechanistic analyses do not support the AASHTO layer coefficient or the AASHTO concept that the SN of the pavement is the sum of the SNs of its layers.

2. For those pavement sections with the same layer properties that have been designed by the AASHTO procedure to be supported on various roadbed soils, to carry the same traffic volume, and to have the same serviceability loss during an equal performance period, the mechanistic analyses indicate that the stresses, strains, and deflections induced in the pavements are not the same. This implies that the role of the resilient modulus of the roadbed soil in the AASHTO main design equation needs to be calibrated.

3. For those pavement sections with the same layer properties but different drainage coefficients that have been designed by the AASHTO procedure to be supported on the same roadbed soils, to carry the same traffic volume, and to have the same serviceability loss during an equal performance period, the results of the mechanistic evaluations indicate the following:

a) The magnitude of deflections (amount of compression) experienced by the various pavement sections under a 9000-lb load varies from one pavement section to another. That is, the amount of damage delivered to each section is not the same, and so the loss of serviceability is not equal.

b) The magnitudes of the stresses and strains induced in the pavement sections and in each layer vary from one pavement section to another. Stated differently, the amount of damage experienced by pavement layer varies with the structure, and this variability causes different losses of serviceability.

These two findings indicate that the role of the drainage coefficient (in adjusting the layer thicknesses) in the AASHTO design procedure is not accurate. Mechanistic calibration of the role of the drainage coefficient was undertaken. After several trials, the following mechanistic modifications in the role of the AASHTO drainage coefficients are recommended:

$$a_{ci} = (a_i)(m_i)^{0.5}$$

$$MR_{RBd} = (MR_{EFF})(m_3)^{0.5}$$

where

a_{ci}	=	effective layer coefficient of layer i
a_i	=	layer coefficient of layer i
m_i	=	drainage coefficient of layer i
MR_{RBd}	=	design value of the resilient modulus of the roadbed soil
MR_{EFF}	=	effective resilient modulus of the roadbed soil
m_3	=	drainage coefficient of the subbase material or the layer immediately above the roadbed soil

The mechanistic modification of the effects of the AASHTO drainage coefficients on the pavement design produces layer thicknesses such that the amount of damage delivered to the pavement sections in terms of stresses, strains, and deflections is almost the same.

4. The effect of the drainage coefficient on pavement performance was also analyzed from a different perspective. Rather than using the drainage coefficient to decrease or increase the layer thicknesses, the effect of the quality of drainage on the service life of the pavement was assessed and presented in an easy-to-read nomograph. The method allows the pavement design engineer to analyze the cost and benefit of improving the drainage quality. This makes the effect of drainage quality on the pavement performance comparable with that for loss of serviceability due to environmental factors.

5. Results of the mechanistic evaluation of the AASHTO concept of loss of serviceability due to environmental factors indicate the following:

    a) The AASHTO loss of serviceability concept is linear (the total loss of pavement serviceability is the sum of the loss of serviceability due to traffic and the losses due to swelling and frost heave potentials). The concept does not account for the interaction between the various serviceability losses. However, from the mechanistic viewpoint, the AASHTO concept seems to be reasonable.

    b) The loss of serviceability due to environmental conditions can also be expressed in terms of the effective roadbed resilient modulus.

Pavement Maintenance Cost-Effectiveness

This 5-year study began in October 1987 and assesses the effectiveness of six pavement maintenance treatments. The study is being conducted under the direction of SHRP's Highway Operations Program and is included here for completeness and to heighten awareness of this important pavement performance study. Preventive maintenance treatments for flexible pavements to be studied include chip seals, thin overlays, slurry seals, and crack sealings (SPS-3). Preventive maintenance treatments for rigid pavements include joint sealing, crack sealing, and undersealing (SPS-4). The test sites for SPS-3 were constructed during the summer and fall of 1990 and are adjacent to GPS sites to make use of traffic monitoring and to expedite data collection. Each site also has a control section without any maintenance treatment. Construction of SPS-4 test sections began in the late fall of 1990 and will extend through the summer of 1991.

Analysis of this pavement performance data will quantify the ability of different maintenance treatments to extend service life or reduce distress rates. This information will be of great value to efforts to develop pavement life-cycle cost models.

Canadian SHRP (CSHRP)—LTPP Technical Analysis Project

The Canadian Strategic Highway Research Program Long-Term Pavement Performance (CSHRP—LTPP) program is exploring high-risk research aimed at developing procedures to determine the cost-effectiveness of rehabilitation alternatives. Clayton, Sparks, and Associates Ltd. (CSA) and Decision Focus Inc. (DFI) have prepared two draft reports, *A Review of the Technical Analysis for the C-LTPP Project* and *Design of a Long-Term Pavement Monitoring System for the Canadian SHRP*. This work focuses primarily on asphalt concrete overlay studies (7.23).

In the first report, the data being assembled in the CSHRP-LTPP and SHRP-LTPP programs will be reviewed to determine whether they support statistical analysis. The data to be reviewed include the 53 C-LTPP sections, the 11 Canadian sections committed to GPS-6 (asphalt concrete overlays of asphalt concrete), the 95 U.S. sections committed to GPS-6, and the 128 overlaid asphalt concrete pavement sections at 16 sites planned for the SPS-5 experiment. For the 53 C-LTPP and the 128 SPS-5 pavement sections, the performance observations will start at the time of construction. Of the 16 SPS-5 sites desired, 6 have been constructed, 6 are being designed, and 2 have been nominated. Thus, it may be several years before significant results are provided. On the other hand, there is currently only one GPS-6 data observation for each pavement section at various times throughout the life of the project. In short, after a review of data types, quality, and quantity, CSA and DFI concluded that augmenting the C-LTPP database with SHRP data would fail to provide a large enough sample for regression analysis. Thus, they have proposed to apply a Bayesian statistical approach to address the problem of small sample size. They also advise that it is necessary to integrate costs into the analysis to meet the C-LTPP objectives.

In the second report, CSA and DFI describe an incremental and systematic multiphase program to develop pavement management systems from LTPP monitoring information. The contractors consider it essential to develop an understanding of the effects of monitoring data on pavement management decisions.

The first phase will use Bayesian statistical methods to assemble and process C-LTPP information. The first task in this phase will outline a design for the overall Bayesian statistical method to be used. A detailed description of the expected data will be prepared. A commercial statistical data management package will be selected to accept and store the raw input data. Plans will be developed for a customized software system to implement the Bayesian statistical approach to retrieve the data and calculate results. The way critical pavement deterioration information inferred from the monitoring data will be presented will also be developed. Guidelines for coordinating existing information with these new C-LTPP results will be developed to support decision making by pavement managers. Finally, the design flexibility to accommodate future changes will be developed.

In the second task, commercial statistical packages will be reviewed to identify the one most suitable for the C-LTPP Bayesian statistical program. The third task will be to prepare a comprehensive and detailed paper design of the Bayesian statistical module. The design will begin with the development of the prior probability distribution, the likelihood function, and the posterior probability distribution based on a linear model. The simple model will first be extended to the multivariate case with linear pavement deterioration functions. Consideration will be given to several key issues: autocorrelation in the data when error terms are strongly correlated with error terms in one or more prior years, missing variable bias, heteroscedasticity (differences of the variances in the error terms), and nonlinear pavement deterioration models. A detailed technical report will be produced outlining the Bayesian statistical equations to be programmed, the flowchart logic, the required inputs, and the model outputs.

The fourth task is to implement testing of the Bayesian statistical module. A programming language will be selected that is compatible with the statistical package and meets the speed and other requirements; the most likely choices are FORTRAN, PASCAL, and C. To test the module, C-LTPP will provide three realistic and difficult databases: one with a small sample size, a systematically autocorrelated database, and a very large database. The deliverable for this task will be the basic multivariate Bayesian statistical module operating without autocorrelation or heteroscedasticity.

The fifth task will interface the Bayesian statistical module with the selected commercial statistical data management package. Following this implementation, the capabilities will be incorporated to deal with the three most troublesome complexities in the database: autocorrelation, multicollinearity, and heteroscedasticity. The basic Bayesian module will be extended to accept more complex dynamic pavement deterioration functional forms and error terms to increase the predictive power of the data. Standard classical regression analysis approaches to deal with multicollinearity will be extended to accommodate the Bayesian approach. Additionally, the Bayesian module will be extended to deal with heteroscedasticity errors in data.

Final tasks of this phase will be to prepare a hypothetical database to test the statistical package with the Bayesian statistical module, as well as a user manual and a training program. This phase, which will produce a mathematical means to integrate new information obtained from the monitoring programs with current knowledge, began in January 1991 and is expected to last about 16 months.

Later phases proposed by CSA and DFI consist of implementation activities that may be funded by CSHRP at a later date.

United Kingdom, Science and Engineering Research Council Research Grant: Information Management System for Predicting Long-Term Pavement Performance

The University of Birmingham has conducted two contracts related to its proposed approach for SHRP database analysis. In the first, *Pavement Design Sensitivity to Errors in Data,* the sensitivity of pavement total life-cycle costs was related to traffic loads, material parameters, and maintenance and rehabilitation practices. In the second, *Development of a Road Network Model Based on Indicators of Pavement Condition,* network-level pavement performance models have been developed.

In addition, the University of Birmingham was awarded the present contract to conduct similar work by the U.K. Government Science and Engineering Research Council. This 3-year study that began in April 1990. The research is in two concurrent parts. The first is in collaboration with the LTPP study and will derive relationships to predict pavement performance. The second part is to extend this work to include data from maintenance management systems. It is proposed to screen maintenance management systems databases to collect pavement condition data for all combinations of traffic loads, pavement type, and maintenance history. The analysis method will adopt a statistical approach; rather than simply taking the average change in condition from year to year, the distribution of the magnitudes of the changes will be collected.

The specific work plan is to record the annual change in defect severity levels in the form of statistical distributions. These will show the variability in pavement deterioration within each matrix cell. This data will be analyzed further to yield information on the performance of the network in the form of statistical distributions. From these, the average defect severity levels, together with the standard deviations, can be calculated. These procedures will be implemented to run on a microcomputer.

References

7.1 *America's Highways: Accelerating the Search for Innovation* (Special Report 202, Strategic Transportation Research Study: Highways, pp. 93—94). Transportation Research Board, National Research Council, Washington, D.C., 1984.

7.2 *Strategic Highway Research Program Research Plans, Final Report* (pp. TRA2—6). Transportation Research Board, National Research Council, Washington, D.C., May 1986.

7.3 Irick, P., and W. O. Hadley, "Pilot Study of the Effects of Materials and Construction Variabilities on Pavement Distress and Performance" (TRDF Technical Memorandum AU-203). Texas Research and Development Foundation, Austin, Texas, April 6, 1992.

7.4 Hadley, W. O. *SHRP-LTPP Data Analysis: Five-Year Report* (Report No. SHRP-P-688). Strategic Highway Research Program, National Research Council, Washington, D.C., Forthcoming.

7.5 Hadley, W. O. "PSI Estimates from SHRP Profilometer Roughness" (TRDF Technical Memorandum AU-219). Texas Research and Development Foundation, Austin, Texas, October 16, 1992.

7.6 Hadley, W. O. "Rutting Initiation Studies" (TRDF Technical Memorandum AU-214). Texas Research and Development Foundation, Austin, Texas, September 31, 1992.

7.7 Hadley, W. O. "Approach for Improving AASHTO Load Equivalence Factors Using SHRP-LTPP Data" (TRDF Technical Memorandum AU-218). Texas Research and Development Foundation, Austin, Texas, October 13, 1992.

7.8 Hadley, W. O. "PSI Estimates from SHRP Profilometer Roughness" (TRDF Technical Memorandum AU-215). Texas Research and Development Foundation, Austin, Texas, October 12, 1992.

7.9 Hadley, W. O. "A Method of Estimating Serviceability Loss for Existing SHRP-LTPP Flexible Pavement Sections" (TRDF Technical Memorandum AU-216). Texas Research and Development Foundation, Austin, Texas, October 12, 1992.

7.10 Hadley, W. O. "Traffic Data Assessment for the SHRP-LTPP Load Equivalence Factor Improvement Study" (TRDF Technical Memorandum AU-217). Texas Research and Development Foundation, Austin, Texas, October 12, 1992.

7.11 Irick, P. and W. O. Hadley. "An Approach to Improvements of Load Equivalence Factors from SHRP-LTPP Data" (TRDF Technical Memorandum AU-204). Texas Research and Development Foundation, Austin, Texas, May 3, 1992.

7.12 *AASHO Road Test, Report 5, Pavement Research* (Highway Research Board Special Report 61E. National Academy of Sciences, National Research Council Publication Number 954). Washington, D.C., 1962.

7.13 Kohn, S. D. *Manual for Profile Measurements: Operational Field Guidelines* (Report No. SHRP-P-378). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.14 "PASCO Film Interpretation Manual (PASCO-FMA)" (Operational Guide No. SHRP-LTPP-OG-0024). Strategic Highway Research Program, National Research Council, Washington, D.C., May 1990.

7.15 Hadley, W. O., and M. G. Myers. "Rut Depth Estimates Developed from Cross Profile Data" (TRDF Technical Memorandum AU-179). Texas Research and Development Foundation, Austin, Texas, April 1, 1991.

7.16 Hadley, W. O. "Rut Depth Estimates from PASCO Cross-Profile" (TRDF Technical Memorandum AU-185). Texas Research and Development Foundation, Austin, Texas, June 28, 1991.

7.17 Rauhut, J. B., and M. I. Darter. *Early Analyses of LTPP General Pavement Studies Data. Executive Summary* (Report No. SHRP-P-392). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.18 Killingsworth et al. *Early Analyses of LTPP General Pavement Studies Data: Data Processing and Evaluation* (Report No. SHRP-P-684). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.19 Simpson, A. L., J. B. Rauhut, P. R. Jordahl, et al. *Sensitivity Analyses for Selected Pavement Distresses* (Report No. SHRP-P-393). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.20 Daleiden, J. S., J. B. Rauhut, B. Killingsworth, et al. *Evaluation of the AASHTO Design Equations and Recommended Improvements* (Report No. SHRP-P-394). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.21 Daleiden, J. S., J. B. Rauhut, B. Killingsworth, et al. *Early Analyses of Long-Term Pavement Performance General Studies Data: Lessons Learned and Recommendations* (Report No. SHRP-P-680). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.22 Baladi, G. and F. X. McKelvey. *Mechanistic Evaluation and Calibration of the AASHTO Design Equations and Mechanistic Analysis of the SHRP Asphalt Surface Pavement Sections* (Report No. SHRP-P-678). Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

7.23 "A Review of the Technical Analysis for the Canadian Long-Term Pavement Performance (C-LTPP) Project." Clayton, Sparks & Associates Ltd. and Decision Focus Inc., Draft, August 1990.

Section 8
Traffic Data Collection and Analysis

Background

The planners of the Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) project (**8.1**) identified the need to retrieve historical traffic volume and axle-load data for each General Pavement Studies (GPS) test location before beginning the data monitoring phase, as well as the need to collect traffic and axle-load data at each GPS test location during the data monitoring phase of LTPP. Because the American Association of State Highway and Transportation Officials (AASHTO) designs are based on the number of 18,000-lb. equivalent single axle loads (ESALs) projected over a pavement life, it was considered important in SHRP-LTPP to evaluate pavement performance according to the actual number of ESALs accumulated by a test section since it was opened to traffic in its present configuration.

The options for obtaining the cumulative annual axle-load data (ESALs) included (1) direct traffic measurements by permanently installed weigh-in-motion (WIM) equipment located and operating continuously at the test location and (2) estimates based on a combination of traffic volume, vehicle classification data, and portable WIM measurements. The original SHRP plan for traffic data collection at GPS test locations was based on the first option and involved "low-cost" WIM devices operating continuously at each site (**8.1**).

Subsequently it was determined that, although the use of piezoelectric cable-based low-cost WIM devices was not a viable option for truck weight studies, the devices could reliably be used for vehicle classification studies (**8.2**). Many state highway agencies (SHAs) insisted that bending plates and load cells must be used in conjunction with WIM equipment to obtain valid weight data. The high cost of the higher quality WIM systems required a change in the original plan for SHRP.

Traffic Expert Task Group (ETG) Activities

One of the unique features of the traffic program was the role of the Traffic ETG in recommending and defining actions taken by SHRP in traffic data collection and analysis. This role evolved because the need for traffic loading data for GPS was not sufficiently defined before SHRP-LTPP began. This became evident early in SHRP-LTPP, and the Traffic ETG was established to address traffic loading data issues.

To enhance the traffic experience of SHRP-LTPP, the LTPP Program Manager allowed the Traffic ETG to become more directly involved in the traffic data collection program, to provide direction to the SHRP staff, and to provide general guidance for the activities of the consultants and Regional Traffic Representatives.

The ETG was instrumental in several decisions that concerned

- SHRP traffic requirements
- Traffic data collection requirements
- Site-specific data collection
- Traffic database needs
- "Truth in data" and data availability concepts
- Need for guidelines in traffic variability and precision
- Adoption of Federal Highway Administration (FHWA) vehicle classification system
- WIM requirements
- ESAL calculations

The contributions of the ETG were instrumental in and essential to the development of the present SHRP-LTPP traffic program.

Traffic Data Collection Program

A modified traffic data collection program was subsequently developed that recognized that it would not be possible to install a WIM device at each site, nor would it be possible to operate WIM equipment continuously at each site (8.2). In this modified plan (8.3) three levels of traffic data collection were established: (1) a preferred approach that relied on continuously operated WIM equipment, (2) a desirable level that substituted automated vehicle classifiers (AVCs) for WIM and added portable WIM measurements for a week each quarter of the year, and (3) a minimum response that was similar to the desirable level but reduced the length of time for the portable WIM counts.

The modified plan continues to be the basis for traffic data collection by the SHA for the GPS experiments. The SHAs were more responsive to the desirable option that allowed for the installation of AVCs at GPS test sites coupled with portable WIM measurements on a quarterly basis. At the end of SHRP-LTPP, more than 60% of the GPS sites will have included the AVC option only, while more than 270 installations will have included permanent WIM equipment. This total represents a marked increase over the number of such installations in place across the United States and Canada before SHRP (8.4).

The application of WIM technology by SHRP-LTPP spurred increased attention to traffic data collection by SHAs. The capability to collect continuous data on traffic volumes, vehicle classes, and individual truck weights with one device was a major breakthrough. Although WIM technology had been available since the early 1970s, its use had been minimal. The newly expanded use of WIM equipment required major changes in the data collection, processing, and summarization procedures used by SHAs. SHRP-LTPP led the way in implementing these changes and devising new procedures for their use.

The SHRP-LTPP data collection methodology involves a flexible framework designed to provide the best possible traffic data within the limitations of each SHA. The SHRP traffic data collection plan requires minimum standards for traffic data collection at each LTPP site, but encourages SHAs to provide more extensive and better quality data collection when fiscal and physical limitations could be overcome (8.3). The plan identified three alternatives for traffic data collection and allowed each SHA the option of selecting any one of the three. Since the selection could be made independently for each LTPP site, this approach allowed the SHA the option of defining differing levels of traffic data collection at the various LTPP sites located within a state or province.

The three alternatives for monitoring traffic data are defined as follows:

- Preferred traffic data collection—permanent, year-round WIM equipment installed at each site and operated continuously

- Desirable traffic data collection—a permanent, year-round site-specific AVC, supplemented by 1 week of WIM measurements for each season of the year at each study site

- Minimum traffic data collection—a year-round vehicle classifier, counting at least 1 full year during each 5-year period, supplemented by one 48-hour weekend and one 48-hour weekday WIM session during each season of the year

The SHRP-LTPP plan, therefore, gave SHAs the flexibility in traffic data collection that would permit optimal use of their scarce resources. At the same time, the traffic data collection requirements could provide sufficient information to SHRP researchers for development of reasonable estimates of traffic loading at each LTPP test section.

Site-Specific versus Site-Related Data Collection

The SHRP-LTPP plan recommended that all traffic data collection take place immediately upstream or downstream of the LTPP test sections (8.5). Traffic loading estimates for a particular section were to be based on traffic data collected at that test location, since traffic loading characteristics can vary considerably between sites.

The necessity for site-specific traffic measurements was substantiated early in SHRP-LTPP, when the Minnesota Highway Department and the North Central regional office of SHRP joined to conduct an analysis of truck volume and weight data that had been collected at four permanent WIM sites in Minnesota over the previous 4 years (8.6). In comparing the variation of truck volumes with truck weight and ESAL calculations, several conclusions were reached:

- The patterns for loading (ESALs) varied greatly from volumes for the "eighteen-wheeler" class of trucks (3S2).
- Variation between the loading patterns at each of the four sites was significant.
- Low truck volumes on weekends actually resulted in higher equivalent loadings because unusually heavy vehicles ran on weekends.
- Location, direction, time of day, and classification of the highway also significantly affect the number of trucks, weight of the trucks, and resulting ESALs.

The Minnesota results demonstrated the need for site-specific traffic and weight data collection equipment. After a series of traffic data collection workshops conducted in all FHWA regions and in Canada, the site-specific approach was accepted and plans to infer or estimate data at a given site from statewide data were eventually abandoned.

The location of the traffic data collection equipment was selected to ensure that no interruption or interference in the traffic stream or flow could develop between the LTPP test section and the traffic data collection site. If the traffic counting and weighing station was separated from the LTPP test location and the truck traffic was expected to vary between the two locations, additional traffic data were collected at each site to document the difference in traffic loading between the two sites.

While SHRP-LTPP's traffic data collection requirements provided more realistic traffic data collection options for the SHAs, they increased the difficulties that future LTPP researchers will face when they analyze the traffic data because the amount and types of available traffic data will vary from one LTPP site to another. As a result, analysts will need a method for handling the differences in the available traffic data. As an aid to future analysts, the traffic data are assigned both a quantitative measure of variability and reliability and a qualitative description of the traffic data residing in the database.

Traffic Data Collection Plans

Because of the variety of options available to the SHAs in installing traffic data collection equipment and measuring traffic and axle-load data, each SHA was requested to prepare a Traffic Data Collection Plan based on a set of guidelines issued in November 1989 (8.5). Each SHA was advised to submit plans to the SHRP-LTPP regional offices outlining specific plans for collection of traffic data at each GPS test section in the state or province. These plans would summarize location, type of equipment, frequency of operation, funds required, persons responsible, and method of transmitting the data. Maps and installation schedules were also included, along with other pertinent information.

Historical Data

The requirements for retrieving and reporting historical data for each GPS test location were specified in Chapter 4 of the LTPP *Data Collection Guide* (8.7). This document provided background information, an explanation of the historical and monitoring traffic data requirements, historical data forms, monitoring data formats, and baseline information about collecting and processing of traffic data.

Historical data were initially retrieved from the files for two sites in each SHA and were submitted to the regional office for review and verification of the output. After receiving feedback from the regional office, the SHA collected the historical data for all other GPS sites in the state. Historical traffic data were received for more than 95% of test locations. These data were an important element in several early analysis studies.

Traffic Data in the LTPP Database

The specific traffic data elements included in the LTPP National Pavement Performance Database (NPPDB) consist of the Level 1 primary loading estimates from the LTPP Central Traffic Database (8.8). These Level 1 records represent the "best estimate" of the traffic loads experienced at each LTPP site for each calendar year since the particular LTPP site was opened to traffic.

The loading estimates are presented as the number of axles by weight range and axle type (i.e., singles, tandems, tridems, and quadrems) to which the LTPP test section was exposed during a given year. Additionally, the combined ESALs for these traffic data are computed based on the current AASHTO ESAL formula. The estimates are also based on the pavement structure identified in the NPPDB and information stored in the two databases. Several supporting variables are also included in the traffic data information stored in the NPPDB.

Maintenance of the pavement loadings by axle load and axle group will provide SHRP-LTPP researchers with the capability to evaluate alternative ESAL computational formulas. On the other hand, the availability of the current AASHTO ESAL values within the NPPDB will provide researchers with a quick, convenient and consistent traffic load estimate for limited, specific analyses.

The NPPDB and the traffic database contain descriptions of the traffic data collected at each LTPP site (8.8). These narratives will be helpful to future researchers by defining the traffic data available in the NPPDB and by identifying the number and type of traffic data used to calculate the annual ESAL loadings. This information is stored in the Data Availability Matrix for each LTPP site. Table 8.1 is a sample matrix.

Table 8.1 Sample Traffic Data Availability Matrix for LTPP Sites

Year	Short Volume Counts	Continuous Volume Counts	Short Vehicle Class Counts	Continuous Vehicle Class Counts	Short WIM Counts	Continuous WIM Counts	Data Availability Code
85	two						2
86	four						2
87	four		one		one		6
88			two				6
89		by lane		by lane		by lane	9
90		by lane		by lane		by lane	9

FHWA Monitoring Standards

One major action taken by the ETG was to recommend the adoption of the FHWA Highway Pavement Management System (HPMS) and Traffic Monitoring Guide (8.9) as basic documents for the development of a SHRP-LTPP traffic database. This resulted in the adoption of the FHWA 13-class vehicle classification system and the standard FHWA formats for reporting traffic volume, classification, and weight data. This provided a standard that was known to all states. With the adoption of the FHWA standards, FHWA committed to provide funding support, personnel support, and assistance at all levels of the organization in the development and implementation of the LTPP traffic data collection program.

Role of the Regional Offices

The traffic database is currently housed at the four regional offices. The data are received, entered, checked, summarized, processed, reported, and stored at the regional level (8.8). The regional representatives work directly with the SHAs in obtaining traffic and load data for the GPS experiments. This includes reviewing and approving data collection plans, verifying the installation of traffic data collection equipment at each site, and receiving and entering traffic data from the SHAs on a monthly basis.

International Traffic Data Requirements

The traffic data requirements for international GPS test locations are expected to be the same as those established for U.S. and Canadian sites. To facilitate an understanding of these requirements by the coordinators from the various countries, an *International Traffic Data Collection Handbook* (8.10) was compiled incorporating the most important technical memoranda, reports, and documents. The handbook was initially distributed at the International Coordinator's meeting in England in November 1990.

Traffic Data Analysis Studies

Data analysis and special studies were conducted in support of the traffic program. In some cases the results were instrumental in transforming the traffic data collection procedures used by the various SHAs. Some of the studies are listed below:

- Evaluation of triple and quadruple axles (8.11)—definition for LTPP studies
- Data Variability (8.12)—procedures for assessing precision of annual traffic estimates
- Piezoelectric cable for vehicle classification (8.13)—development of AVC specifications
- WIM data analysis (8.6, 8.14, 8.15)—identification of traffic load trends and patterns

- ESAL projections for a construction variability study (**8.16 8.17**)

- An assessment of the impact of ESALs and other load/environmental factors on load equivalency factors (LEFs) developed from SHRP-LTPP data (**8.17, 8.18, 8.19**)

Summary

The LTPP traffic database formulated by SHRP will benefit state and federal highway agencies for many years to come. The establishment of the LTPP Central Traffic Database at the Transportation Research Board, in coordination with the NPPDB, will make both readily accessible and usable for research well into the future. At some future date, the relative effect of traffic loading on pavement performance will clearly be known, a process will be available to collect traffic and loading data on a sampling basis, and a method will be developed to project the total cumulative ESALs for a highway over a given time frame in a very accurate and effective manner. Many of the basic objectives of the SHRP-LTPP program will have been met when these events occur.

References

8.1 *Strategic Highway Research Program Research Plans, Final Report*, May 1986. Technical Research Area 2, Long-Term Pavement Performance.

8.2 Elkins, G. E. "Presentation on Traffic Data Requirements." Texas Research and Development Foundation, Austin, Texas, April 30, 1988.

8.3 Elkins G. E. "Background on Traffic Data Considerations for LTPP." Texas Research and Development Foundation, Austin, Texas, May 6, 1988.

8.4 *Traffic Monitoring Guide*. U.S. Department of Transportation, Federal Highway Administration, Washington, DC, June 1985.

8.5 Hallenbeck, M. "Position Paper for Traffic ETG" (unpublished). Washington State Transportation Center (TRAC), Seattle, Washington, July 11, 1988.

8.6 Dahlin, C., P. Harker, and R. Ingberg. "Minnesota WIM Data Analysis Study" (unpublished). Strategic Highway Research Program, National Research Council, Washington, DC, March 1989.

8.7 German, J. L., A. Horosko, M. Hallenbeck, and G. E. Elkins. *SHRP-LTPP Data Collection Guide*, Chapter 4, "Traffic Data Collection for GPS Sections." April 1992.

8.8 German, J. L. "Implementation of the National Traffic Database" (TRDF Technical Memorandum AU-123). Texas Research and Development Foundation, Austin, Texas, April 10, 1990.

8.9 German, J. L. *SHRP-LTPP Traffic Data Collection and Analysis* (Report No. SHRP-P-386). Strategic Highway Research Program, National Research Council, Washington, DC, 1994.

8.10 German, J. L., ed. *SHRP-LTPP International Traffic Data Collection Handbook.* Texas Research and Development Foundation, Austin, Texas, September 1991.

8.11 Hajek, J. and J. Hamrick. "ESALs for Triple and Quadruple Axles." Report prepared for SHRP Expert Task Group on Traffic Data Collection and Analysis. June 1990.

8.12 Wilkinson, J., P. Irick, W. O. Hadley, and J. L. German. "Procedures for Assessing the Precision of Annual Traffic Statistics." SHRP-LTPP. November 1991.

8.13 Laylor, H. M. "Pilot Project: Piezo-Electric Automatic Vehicle Classification System." Oregon Department of Transportation, Salem, Oregon, July 1991.

8.14 Hallenbeck, M. "The SHRP Traffic Database: What It Really Is." Paper prepared for SHRP Midcourse Assessment Meeting in Denver, CO. Washington State Transportation Center (TRAC), Seattle, Washington, August 1990.

8.15 Myers, M. and J. L. German, "Preliminary Weigh-in-Motion Data Analysis for Selected SHRP GPS Sites" (Final Report). Texas Research and Development Foundation, Austin, Texas, July 1992.

8.16 Hadley, W. O. "Construction Variability Studies" (TRDF Technical Memorandum AU-219). Texas Research and Development Foundation, Austin, Texas, October 16, 1992.

8.17 Hadley, W. O. *SHRP-LTPP Data Analysis Studies: Five-Year Report* (Report No. SHRP-P-688). Strategic Highway Research Program, National Research Council, Washington, DC, Forthcoming.

8.18 Hadley, W. O. "Traffic Data Assessment for the SHRP-LTPP Load Equivalence Factor Improvement Study" (TRDF Technical Memorandum AU-217). Texas Research and Development Foundation, Austin, Texas, October 12, 1992.

8.19 Hadley, W. O. "Approach for Improving AASHTO Load Equivalence Factors Using SHRP-LTPP Data" (TRDF Technical Memorandum AU-218). Texas Research and Development Foundation, Austin, Texas, October 13, 1992.

Section 9
International Participation

Introduction

From the beginning, high priority was given to international coordination and cooperation in the conduct of the Strategic Highway Research Program Long-Term Pavement Performance (SHRP-LTPP) program. During the pre-implementation phase, SHRP contacted forty-five individuals in twelve countries to obtain information about concurrent research similar to SHRP and to solicit suggestions for future cooperation.

Initiation of International Cooperation Activities

SHRP hosted a special reception for international attendees at the annual Transportation Research Board (TRB) meeting in 1986 and a SHRP International Workshop in May 1986 to foster future coordination and cooperation between SHRP and the international community. The enthusiasm of the international community for SHRP-LTPP led to the adoption by SHRP's Executive Committee at its meeting in September 1986 of a policy for international cooperation.

As a result of these actions, the Swedish Road and Traffic Research Institute (VTI) and TRB held a joint conference in September 1987 on present and future road research, with special emphasis on SHRP and highway safety research.

The first SHRP International Technical Workshop was held in Bath, England, on September 14, 1988, and involved presentations and discussions concerning implementation of SHRP's data collection procedures in countries planning to establish their own parallel and complementary General Pavement Studies (GPS) or Specific Pavement Studies (SPS) programs.

International Conferences

In September 1989, TRB and VTI held their second jointly organized conference on SHRP and traffic safety in Göteborg, Sweden. A preconference International Long-Term Pavement Performance Workshop was held to demonstrate the levels of participation of overseas countries in the program. A status report on LTPP activities was presented and included the topics of experimental design principles, data collection, information management system, and data analysis.

During SHRP's Midcourse Assessment Meeting of August 1–3, 1990, in Denver, Colorado, a workshop session for international attendees included a brief update on the midcourse status of international LTPP participation. Attendees were alerted to some of the areas where international participation or involvement was needed. Several countries expressed an interest in participating with test sites from their construction programs, including rehabilitation of existing roadways (SPS-5 or SPS-6) as well as construction of new pavements (SPS-1 or SPS-2).

At the International SHRP/Institution of Civil Engineers Conference, Sharing the Benefits, held September 1990 in London, an international SHRP workshop was held to provide an update on international SHRP-related activities and to discuss issues that must be addressed by participating countries that proceed with LTPP studies.

International LTPP experiments were presented by five countries that had committed to establish LTPP test sections. The discussion that followed these presentations addressed several issues, including integrating existing databases, establishing an international database, and developing a European database. Other issues discussed during the workshop were international data handling, data extraction, and condition monitoring. Conformance with International Standard ISO 9000 on quality assurance was also recommended.

An LTPP International Information Management System (I-IMS) workshop was held in conjunction with the annual TRB meeting in January 1991. Workshop participants included coordinators and representatives from Australia, Canada, Denmark, Japan, and the Netherlands; SHRP-loaned staff from Australia, Sweden, and Venezuela; and representatives from the U.S. Federal Highway Administration.

Presentations included updates on the status of the National Information Management System (NIMS), news of the first data release to the public, procedures for requesting data from the NIMS, an update on the status of the traffic database, discussion of quality assurance in the NIMS, and plans for entering data from the I-IMS into the NIMS. A significant outcome of the workshop was the conclusion that a plan for unit conversions in the IMS was necessary to permit the first step in an international data transfer process.

A SHRP-LTPP Traffic Data Collection Workshop was held in Göteborg, Sweden, in September 1991 and focused mainly on establishing traffic data collection and processing guidelines for the international participants in LTPP. The full-day workshop stressed the need for "traffic data compatibility," especially in the determination of equivalent single axle loads (ESALs) that will be needed for pavement-related research.

At the same time, an international conference on SHRP and Traffic Safety on Two Continents, jointly planned by VTI and TRB, was held in Göteborg. The program had parallel sessions, with SHRP information presented in one session and traffic safety information in another. The SHRP session dealt with LTPP in the United States, in Canada, and internationally.

In connection with the conference, an I-IMS User Group Meeting was held. Representatives from Australia, Austria, Canada, the Netherlands, Finland (Nordic countries), the United Kingdom, and the United States were present at the meeting. One major topic discussed was the structure of the I-IMS. The data from all I-IMS users will be forwarded to the United States to be incorporated into the NIMS.

International Data and the LTPP National Information Management System (NIMS)

A link between the NIMS and the I-IMS is an essential element in completing the development of the NIMS. The international participants in LTPP expressed an increasing interest in storing the data from their test sites in the NIMS and acquiring the data from the NIMS. This link would enable researchers worldwide to share and use the data in their research.

Data Flow

At present the data for the international participants will be stored not at the NIMS, but in a separate database. The structure of the NIMS was not altered during SHRP-LTPP, and data from the United States and Canada continue to be entered in American Customary (AC) or foot-pound-second (FPS) units. Researchers who request all the data available in the database would receive the North American data in AC units and the international data in Système Internationale (SI) units. Conversion of existing NIMS data to SI units is a future work activity of the FHWA-LTPP program.

Types of Modifications

The three major modifications necessary for use of the IMS by other countries involve

- Units of measure
- Measurement devices
- Test methods

Modifications to some tables will be required when converting the IMS units. To modify the IMS to suit a given country, it will be important to review the *Data Collection Guide*, IMS schema, and IMS data dictionary to identify tables that require unit conversions. In some cases, new tables will be necessary to accommodate different measurement devices or test methods. In other cases, codes may simply be added to tables to indicate a unique test method. New tables must be created and added to the I-IMS by the individual country.

International Participants

Several countries have recognized the importance of SHRP and its potential benefits and have established or proposed complementary or supplementary SHRP sections. The countries include Australia, Austria, Canada, France, India, Japan, the Netherlands, the Nordic countries (Denmark, Finland, Norway, and Sweden), Poland, Switzerland, and the United Kingdom.

Level of Participation

The international community has embraced SHRP-LTPP at different levels. Some countries, such as the Netherlands, have been involved in SHRP-LTPP almost from the beginning; other countries, such as Australia and Poland, are just now getting their LTPP programs under way.

In addition, the level of involvement in SHRP-LTPP (first 5 years) varied from country to country (see Table 9.1). The Netherlands (264 sites), India (113 sites), Poland (100 sites), and Canada (65 sites) have projected significant participation in the number of supplementary and complementary LTPP sections. Note that the sixty-five sections listed for Canada are a part of their CSHRP program and do not include the Canadian sections identified with SHRP-LTPP.

The international LTPP sites are composed almost totally of flexible pavement sections (504 sites, or 89%). Australia (2 sections), India (39 sections), and the United Kingdom (21 sections) account for the 62 rigid pavement sections. It is important to note that the total of 666 international sites (including the 100 proposed by Poland) almost matches the number of GPS sites (770) included in SHRP-LTPP. The international effort thus represents a significant enhancement to SHRP-LTPP.

Data Collection Activities

The data collection measures and approaches adopted by the international agencies are noteworthy when consideration is given to merging the international community's LTPP results with those of SHRP-LTPP. Differences in data types and form are expected because of the specific equipment adopted SHRP (e.g., PASCO Distress Interpretation, Law Profilometer, Dynatest FWD) to conduct data collection. In general, the international countries attempted to match the SHRP data collection program (see Table 9.2) within budgetary and practical limitations.

The materials testing and deflection programs of the international countries generally matched those of the SHRP program. The French program, however, conducted no tests on subgrade materials; in this instance the properties of the subgrade materials will be obtained from construction records.

Table 9.1. International LTPP Sites

Country	Number of Sites	GPS Sites	SPS Sites	Flexible Pavements	Rigid Pavements
Australia	9	9	0	7	2
Austria	12	12	0	12	0
Canada	65	UNK	UNK	65	0
France	UNK	UNK	UNK	UNK	UNK
India	113	UNK	UNK	74	39
Japan	28	28	0	28	0
Netherlands	264	144	120	264	0
Nordic	38	38	0	38	0
Poland	(110*)	UNK	UNK	UNK	UNK
Switzerland	16	UNK	UNK	16	0
United Kingdom	21	6	15	0	21
	566 (666*)	237	135	504	62

* PROPOSED

Table 9.2. International Data Collection Activities

Country	Materials Testing	Longitudinal Profile	Transverse Profile	Distress	Deflection	Friction	Traffic
Austria	SS	Rod & Level @1′	Planum Cross Profilometer	Manual Photos	FWD	U	U
Canada	SS	Dipstick & Rod & Level @1′	U	Manual	FWD/BB	O	AVC or WIM
France	SS No subgrade testing	SIRANO Profile Analyzer	U	Photos by SIRANO	FWD	SCRIM	Piezo Cables
India	SS	Bump Integrator	Rut Depth Gauge	Manual	BB/FWD	MU-Meter	Manual Census/ Weighing pads
Japan	SS	Manual 3M Profilometer	Manual Profilometer	Manual	FWD	SS	Manual Counts/ Piezofilm mat
Netherlands	SS	ARAN	ARAN	Manual Video	FWD	N	Manual Counts (pneumatic tube)
Nordic Countries							
Norway	U	U	U	Manual	FWD	U	Piezo Cables
Sweden	U	Laser RST	Profilograph Laser RST	Manual	FWD	U	Manual Counts
Switzerland	SS	ARAN	ARAN	U	FWD	Skidometer	U
United Kingdom	SS	TRL Road Monitor	Transverse Profilometer	Manual	FWD	SCRIM	Manual Counts

SS = Similar to SHRP, U = Unknown, O = Optional, N = Not measured

For deflection testing, most countries use falling weight deflectometers (FWDs) only. The exceptions include Canada, which conducts companion benkelman beam (BB) and FWD deflection studies, and India, which currently conducts BB deflection studies but will add an FWD in the future. Most FWDs used in the international LTPP program are manufactured by Dynatest, although Japan uses a Kuab FWD. In two countries (Japan and the United Kingdom) a single load level is used to conduct the deflection program. In addition, FWD sensor locations used in the international programs may differ from the spacings specified in SHRP-LTPP.

The method for developing the longitudinal and transverse profile in the international program differs significantly (Table 9.2) from the PASCO method used in SHRP-LTPP. In most instances the longitudinal profile information is developed at 0.3-m (1-ft) intervals, compared to the 0.15-m 6-in.) intervals in the SHRP program. The transverse profile is obtained by methods ranging from a manual profilometer to an ARAN device. In one country (India) the cross-profile apparently will not be determined; rather, the rut depth will be determined directly with a rut depth gauge.

Distress in the international LTPP sections will be defined in manual/visual distress surveys. Austria and the Netherlands will back up the manual distress information with photos and videos, respectively; France will obtain the distress information principally from photos.

Traffic volumes and loads will be obtained by a variety of techniques (Table 9.2) including automated vehicle classifiers (AVCs) or weigh-in-motion (WIM) equipment, piezoelectric cables and mats, and manual counts. Most of the countries will use manual counting information to develop their traffic information.

Section 10
Expected Results, Products, and Benefits

Introduction

To focus on the expected results, products, and benefits of SHRP-LTPP, it is appropriate to review the initial goals and objectives of the program. The specific objectives developed by the Advisory Committee (**10.1**) were

- Evaluation of existing design methods
- Development of improved design methodologies and strategies for the rehabilitation of existing pavements
- Development of improved design equations for new and reconstructed pavements
- Determination of the effects on pavement distress and performance of (1) loading, (2) environment, (3) materials properties and variability, (4) construction quality, and (5) maintenance levels
- Determination of the effects of specific design features on pavement performance
- Establishment of a national long-term pavement database to support SHRP objectives and future needs

The first 5 years of LTPP have been focused on laying the groundwork for the accomplishment of these goals. Pavement test sections for the General Pavement Studies (GPS) and Specific Pavement Studies (SPS) programs have been established, and standardized monitoring activities have been initiated. Most of the tools for achieving the objectives of SHRP-LTPP are in place.

Most of the goals cannot be fully achieved until SHRP-LTPP has run its course (approximately 2010). However, early data analysis studies conducted during SHRP-LTPP have begun to make great strides in providing useful predictive performance equations from the data collected thus far. The following is a brief outline of the expected results, products, and benefits that have reached fruition over the past 5 years. Readers who wish to gain a greater understanding of the status and progress of SHRP-LTPP after the first 5 years are advised to refer to the various SHRP *Five-Year Reports*.

Initial Results

Results from SHRP-LTPP (i.e., the past 5 years of LTPP) cannot be expressed merely in terms of the specific objectives outlined above. The information and data collected for the

GPS and SPS test sections and entered into the National Pavement Performance Database (NPPDB) represent one step of a continuing process to attain the goals of the program. Products from each area of LTPP may well enhance or fulfill one or more program goals. Many products will be derived from the initial 5 years of these studies; however, the true rewards will only come when long-term performance relationships are established. The GPS test sites will no doubt provide the performance baseline against which the products of other SHRP research will be measured (**10.2**).

The establishment, identification, and monitoring of the GPS test sections are major accomplishments of the first 5 years of LTPP. These baseline studies will provide the initial evaluation of existing design methods as a part of the SHRP Data Analysis contract.

The development of the SPS program is well under way, although some sections have not yet been identified and constructed at this point. Each SPS experiment has been designed to answer specific questions concerning pavement performance (**10.1**):

- What are the proper design and construction procedures for pavement rehabilitation and overlays to provide economical renewed pavement life?
- What are the effects of various types and levels of pavement maintenance on pavement life and performance?
- What are the effects of climatic and environmental variables on pavement life and performance?
- What are the relative effects and interactions of load and environmental (climatic) variables on pavement deterioration, performance, and service life?
- What are the effects of alternative drainage designs on pavement performance and service life (**10.1**)?

The SPS experiments will provide most, if not all, of the answers to these questions. Some will be answered in the short term (for example, maintenance practices); others (for example, climatic effects) will occupy the remaining 15 years of LTPP before sufficient conclusions can be drawn.

A principal by-product of the development of GPS and SPS is the completion of the NPPDB. This database will contain information on the approximately 777 GPS LTPP test sections and 84 SPS test projects. The information in the NPPDB will extend the benefits of LTPP for decades ahead and will allow future researchers to pursue and answer important questions about pavement maintenance, management, rehabilitation, and design.

Along with the development of this database, the development of the National Information Management System (NIMS) to allow access to the data in the database has been achieved. A detailed and extensive quality assurance and quality control (QA/QC) program was implemented for the NIMS to ensure the quality of the various data elements residing in the database through appropriate validation and verification actions.

The traffic issues considered and traffic monitoring activities pursued during SHRP-LTPP could themselves be considered products of the program. The dialogue and cooperation developed among the traffic/highway groups of the states and provinces included within SHRP-LTPP have led to the development of standard specifications, methods, and protocols for all phases of traffic monitoring, including weigh-in-motion (WIM) devices, automated traffic classification, and data interpretation techniques. More definitive traffic-related products are anticipated in future LTPP activities as more states and provinces become more involved in traffic monitoring activities and comprehensive traffic volume and vehicular loading data are obtained.

The collection of SHRP-LTPP techniques developed in materials characterization, visual distress, profile, deflection, and instrumentation will lead to the adoption of more standard and fundamental pavement evaluation diagnostic techniques. The SHRP-LTPP standards, specifications, and protocols, when considered as companion documents to the NPPDB data, offer a great opportunity for national and international standardization.

Analysis of the NPPDB data will yield improved pavement design equations, improved design and analysis techniques, distress-specific performance models, construction variability, factors important in the initiation of rutting, and a technique for reevaluating load equivalency factors. These initial efforts offer a baseline for launching future research efforts.

Finally, a product of SHRP-LTPP is the national and international focus generated by the interest in long-term pavement performance. This focus opened the door to widespread cooperative studies and research efforts. The NPPDB data, similar information gathered in Canadian SHRP, and other international efforts will foster the development of a variety of standardized specifications, techniques, and protocols.

Summary

The products or results gained from the capture and analysis of these data are expected to be gleaned from equations that describe the relationships among various data elements in the NPPDB. These 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 into design equations or transformed into nomographs for design of pavements or overlays (**10.1**). The dependent variables in these equations 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. Among these elements are materials characteristics, environmental data, traffic data, and pavement structure data.

Implicitly, these developments will yield the answers to such questions as "What is the cost of deferred maintenance and the ultimate effect on the life of the highway?" or "What is the load-carrying capacity of a pavement when the design life is reached?" This information in turn could, and will, lead to improved cost allocation analysis and more accurate pavement needs estimates, among other things.

In summary, over its first 5 years, LTPP has produced the following usable results:

1. Standardized data collection procedures
2. Establishment of the NPPDB to realize the goals of the program
3. Improved understanding of pavements in general

These results and accomplishments must be carried on for at least the next 15 years to reap all the benefits of the building blocks established over the first 5 years of SHRP. Through the experience of the research teams currently in place and the cooperation of all participating agencies, SHRP-LTPP has provided the direction necessary for achieving all the goals originally set forth by the Pavement Performance Advisory Committee and the SHRP Executive Committee.

References

10.1 *Strategic Highway Research Program Research Plans, Final Report*. Transportation Research Board, National Research Council, Washington, D.C., May, 1986.

10.2 Hawks, N. F. "Future of LTPP." White paper prepared for the AASHTO Task Force on the Future of LTPP. Strategic Highway Research Program, National Research Council, Washington, D.C., July 18, 1989.

SELECT BIBLIOGRAPHY

MISCELLANEOUS REPORTS AND MANUALS

A Review of the Technical Analysis for the Canadian Long-Term Pavement Performance (C-LTPP) Project. Clayton, Sparks and Associates Ltd. and Decision Focus Incorporated. Draft. August 1990.

"American's Highway, Accelerating the Search for Innovation." Special Report 2020, Strategic Transportation Research Study: Highways, pp. 93-94, Transportation Research Board, National Research Council, Washington, D.C., 1984.

AASHTO Pavement Design Guide (1986), Appendix D.

Benson, K., H. Castedo, and D. Goulias. "Distress Identification Manual for the Long-Term Pavement Performance (LTPP) Studies." Operational Guide No. SHRP-LTPP-OG-002, October 1990.

Benson, K., H. Castedo, et. al. "Manual for Field Distress Survey of Pavements with Asphalt Concrete Surfaces I, II, III." Operational Guide No. SHRP-LTPP-OG-008, June 1989.

Brent Rauhut Engineering Inc. and ERES Consultants, Inc. *Data Analysis Work Plan, Long-Term Pavement Performance Studies, SHRP Projects P020A*. September 1990.

Brent Rauhut Engineering, Inc. and ERES Consultants, Inc. "Technical Research Area 2, Long-Term Pavement Performance." prepared for the *Strategic Highway Research Program's Research Plans* p. TRA2-14. January 1986.

Data Analysis - A Revised Research Plan - SHRP Project P-020B. Michigan State University. September, 1990.

Database Structure Reference Manual, Long-Term Pavement Performance Information Management System. January 1990.

"Discussion of Initial SHRP Database Design." April 1989.

EARTHINFO, Inc. "DRAFT Documents for SHRP-LTPP Environmental Database." September 5, 1991.

"Environmental Data Collected For LTPP Study." July 15, 1989.

Gardner, M., and Rauhut, J., "Material Sampling and Testing Guide for Long-Term Pavement Performance Studies, Draft. "Brent Rauhut Engineering, Inc. October, 1987.

Hadley, W.O. and J.L. Groeger, "An Introduction to the SHRP-LTPP Asphalt Concrete Resilient Modulus Testing Program", paper No. 920898, Transportation Research Board, 71st Annual Meeting. January, 1992.

Hadley, W.O. and J.L. Groeger, "The SHRP-LTPP Asphalt Concrete Resilient Modulus Pilot Study." A Paper Prepared for Presentation at the ASCE Materials Specialty Conference, Texas Research and Development Foundation. August, 1992.

Hadley, W.O., W.R. Hudson, and T.W. Kennedy, "A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension." Research Report 98-2, Center for Highway Research, the University of Texas. September, 1970.

Hondros, G., "The Evaluation of Poisson's Ratio and the Modulus of Materials of a Low Tensile Resistance by the Brazilian (Indirect Tensile) Test with Particular Reference to Concrete." Australian Journal of Applied Science, Volume 10, No.3.

"LTPP IMS Data Quality Assurance Checks." Long-Term Pavement Performance Information Management System, Draft. May 1992.

NIMS Users Manual, Long-Term Pavement Performance Information Management System. March 1990.

Operations and Quality Assurance Manual, Long-Term Pavement Performance Informational Management System. April 1990.

"Operations Manual" for Roadrecon Pavement Condition Monitoring Methods and Equipment, PASCO USA. January 1989.

Paterson, William D.O. "Road Deterioration and Maintenance Effects: Models for Planning and Management." the John Hopkins University Press. December 1987.

Pelzner, Adrian, "SHRP-LTPP Pavement Materials Characterization, SHRP-LTPP Interim Report (Unpublished)." Strategic Highway Research Program. April, 1990.

PROGRAMMER'S REFERENCE MANUAL, Long-Term Pavement Performance Information Management System. July 1989.

"Procedures for Manipulating SHRP LTPP Traffic Data." June 1989.

RIMS Users Manual. Long-Term Pavement Performance Information Management System. January 1990.

Strategic Highway Research Program. "A Video Guide for Obtaining SHRP-LTPP Pavement Material Samples." (VHS Videocassette). May, 1989.

Strategic Highway Research Program. "Data Collection Guide for Long-Term Pavement Performance Studies." Draft. Revised January 17, 1990.

Strategic Highway Research Program. "Framework for Traffic Data Collection at GPS Test Locations." January 1989.

Strategic Highway Research Program. "Guidelines for Maintenance of General Pavement Studies (GPS) Test Sections." Operational Memorandum SHRP-LTPP-OM-001. July 1988.

Strategic Highway Research Program. "IMS Researchers Guide." January, 1991.

Strategic Highway Research Program. "Long-Term Pavement Performance Information Management Researchers Guide." SHRP-NRC. July 1991.

Strategic Highway Research Program. "PASCO Film Interpretation Manual (PASCO-FMA)." Operational Guide No. SHRP-LTPP-OG-0024. May 1990.

"Strategic Highway Research Program, Research Plans, Final Report." pp. TRA2-6. Transportation Research Board. National Research Council. Washington, D.C.. May 1986.

Strategic Highway Research Program. "SHRP LTPP Development of Specific Pavement Studies." September 1988.

Strategic Highway Research Program. "SHRP LTPP Guide for Field Materials Sampling, Testing, and Handling, Version 1.0 (A guide for Drilling and Sampling)." January 20, 1991.

Strategic Highway Research Program. "SHRP LTPP Guide for Field Materials Sampling, Testing, and Handling, Version 1.0." Operational Guide No. SHRP-LTPP-OG-006. May 1990.

Strategic Highway Research Program. "SHRP LTPP Guidelines for Signing and Marking of General Pavement Studies' (GPS) Test Sections (SHRP-LTPP-OM-002)." July 1988.

Strategic Highway Research Program. "SHRP-LTPP Interim Guide for Laboratory Materials Handling and Testing (PCC, Bituminous Materials, Aggregates and Soils)." Operational Guide No. SHRP-LTPP-OG-004. November 1989.

Strategic Highway Research Program. "SHRP-LTPP Manual for FWD Testing (SHRP-LTPP-OG-002)." Operational Guide No. SHRP-LTPP-OG-007. January 1989.

Strategic Highway Research Program. "SHRP-LTPP Manual for Profile Measurements." Operational Field Guidelines Version 1.0." Operational Guide No. SHRP-LTPP-OG-005. December 1989.

Strategic Highway Research Program. "SHRP-LTPP Traffic Database Design." June 1989.

Strategic Highway Research Program. "SHRP Operational Guidelines on Test Pits." (SHRP-LTPP-OM-004). January 1989 (Revised March 17, 1989.

Strategic Highway Research Program. "SHRP Program Announcement for Fourth Quarter of FY '88." June, 1988.

Strategic Highway Research Program. "Skid Data Collection for SHRP Test Sections." May 22, 1989.

Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-1: Strategic Study of Structural Factors for Flexible Pavements." SHRP-LTPP-OM-021. February 1991.

Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-1: Rehabilitation of Jointed Portland Cement Concrete Pavements." Operational Memorandum No. SHRP-LTPP-OM-023. December 1991.

Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-1: Study of Structural Factors for Flexible Pavements." Operational Memorandum No. SHRP-LTPP-OM-026. December 1991.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-1) Strategic Study of Structural Factors for Flexible Pavements: Experimental Design and Research Plan." February 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-1) Strategic Study of Structural Factors for Flexible Pavements: Guidelines for Nomination and Evaluation of Candidate Projects." SHRP-LTPP-OM-008. February 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-1) - Strategic Study of Structural Factors for Flexible Pavements: Construction Guidelines." February 1990.

Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-2: Strategic Study of Structural Factors for Rigid Pavements." SHRP-LTPP-OM-022. April 1991.

Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment (SPS-2) Strategic Study of Structural Factors for Rigid Pavements." Operational Memorandum No. SHRP-LTPP-OM-028. February 1992.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-2) Strategic Study of Structural Factors for Rigid Pavements: Construction Guidelines." April 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-2) Strategic Study of Structural Factors for Rigid Pavements: Experimental Design and Research Plan." April 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-2) Strategic Study of Structural Factors for Rigid Pavements: Guidelines for Nomination and Evaluation of Candidate Projects." SHRP-LTPP-OM-009. April 1990.

Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiments SPS-5: Rehabilitation of Hot Mix Asphalt Concrete Pavements." Operational Memorandum No. SHRP-LTPP-OM-015. October 1990.

Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-5: Rehabilitation of Asphalt Concrete Pavements." SHRP-LTPP-OM-014. October 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-5) Rehabilitation of Asphalt Concrete Pavements: Experimental Design and Implementation Plan." April 1989.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-5) Rehabilitation of Asphalt Concrete Pavements: Construction Guidelines." SHRP-LTPP-OM-012. June 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-5) Rehabilitation of Asphalt Concrete Pavements: Guidelines for Nomination and Evaluation of Candidate Projects." SHRP-LTPP-OM-006. November 1989.

Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-6, Rehabilitation of Jointed Portland Cement Concrete Pavements." January 1991.

Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-6, Rehabilitation of Jointed Portland Cement Concrete Pavements." Operational Memorandum No. SHRP-LTPP-OM-023. May 1991.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-6) Rehabilitation of Jointed Portland Cement Concrete Pavements: Experimental Design and Research Plan." March 20, 1989.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-6) Rehabilitation of Jointed Portland Cement Concrete Pavements: Guidelines for Nomination and Evaluation of Candidate Projects." SHRP-LTPP-OM-007. November 1989.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-6) Rehabilitation of Jointed Portland Cement Concrete Pavements: Construction Guidelines." SHRP-LTPP-OM-013. July 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-7) Bonded Portland Cement Concrete Overlays: Experimental Design and Research Plan." February 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-7) Bonded Portland Cement Concrete Overlays: Guidelines for Nomination and Evaluation of Candidate Projects." SHRP-LTPP-OM-011. June 1990.

Strategic Highway Research Program. "Specific Pavement Studies Materials Sampling and Testing Requirements for Experiment SPS-7, Bonded Portland Cement Concrete Overlays." SHRP-LTPP-OM-020. January 1991.

Strategic Highway Research Program. "Specific Pavement Studies Data Collection Guidelines for Experiment SPS-7, Bonded Portland Cement Concrete Overlays." Operational Memorandum No. SHRP-LTPP-OM-024. July 1991.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-7) Bonded Portland Cement Concrete Overlays: Construction Guidelines." February, 1990.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-8) Environmental Factors: Experimental Design and Research Plan." February 1992.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-8) Environmental Factors: Construction Guidelines." February 1992.

Strategic Highway Research Program. "Specific Pavement Studies (SPS-8) Environmental Factors: Data Collection Guidelines." February 1992.

Strategic Highway Research Program. "Specific Pavement Studies: Experimental Design and Participation Requirements." November 1989.

Strategic Highway Research Program. "Technical Provisions and Fee Schedules for Field Sampling and Field Testing." May 6, 1988.

Strategic Highway Research Program. "Technical Provisions and Fee Schedules for Laboratory Testing of Portland Cement Concrete Pavement Materials." May 6, 1988.

Strategic Highway Research Program. "Technical Provisions and Fee Schedules for Laboratory Testing of Soils and Bituminous Materials." May 6, 1988.

Texas Research and Development Foundation. "Final Development of General Pavement Studies Sampling Plan." Prepared for the Strategic Highway Research Program by the June 1988.

Texas Research and Development Foundation. "Guidelines for Initial State Visits Section Selection and Section Verification." Prepared for the Strategic Highway Research Program's Long-Term Pavement Performance. July 6, 1988.

Texas Research and Development Foundation. "Recruitment Guidelines for Additional GPS Candidate Projects." Prepared for the Strategic Highway Research Program's Long-Term Pavement Performance. October 1988.

Texas Research and Development Foundation. "Report on the Evolution and Development of GPS." Prepared for the Strategic Highway Research Program's Long-Term Pavement Performance. December 1990.

Texas Research and Development Foundation. "SHRP Field Operations Guidelines for Dipstick Measurements." Prepared for the Strategic Highway Research Program's Long-Term Pavement Performance. July 1989.

Texas Research and Development Foundation. "SHRP Traffic Data Collection and Analysis Expert Task Group Meeting Notebook." Prepared for the Strategic Highway Research Program's Long-Term Pavement Performance. May 1992.

"The AASHO Road Test Report 5, Pavement Research." Highway Research Board Special Report 61E, NAS, NRC, 1962.

"Traffic Monitoring Guide." U.S. Department of Transportation, Federal Highway Administration. June, 1985.

Welch, William J. "Algorithms for the Construction of Experimental Designs." Version 1.6.1. University of Waterloo.

MATERIALS DIRECTIVES

Strategic Highway Research Program. "Bulk Sample Handling and Testing Requirements for Unbound Materials." SHRP-LTPP Materials Directive No. 7. May 26, 1989.

Strategic Highway Research Program. "Change in GPS Experiment No. 5 Sampling Plans." SHRP-LTPP Materials Directive No. 4. April 26, 1989.

Strategic Highway Research Program. "Field Material Sampling Layout Plans for GPS-6 and GPS-7 Pavements." SHRP-LTPP Materials Directive No. 13. August 21, 1989.

Strategic Highway Research Program. "Information and Forms for SHRP Laboratory Material Testing Contractors." SHRP-LTPP Materials Directive No. 3. March 23, 1989.

Strategic Highway Research Program. "Laboratory Identification Code Numbering Scheme." SHRP-LTPP Materials Directive No. 23. December 3, 1990.

Strategic Highway Research Program. "Laboratory Sample Tracking Tables." SHRP-LTPP Materials Directive No. 12. August 2, 1989.

Strategic Highway Research Program. "Materials Testing Quarterly Reporting Requirements." SHRP-LTPP Materials Directive No. 10. June 30, 1989.

Strategic Highway Research Program. "National Verification of Nuclear Moisture Density Equipment Used by SHRP Drilling and Sampling Contractors." SHRP-LTPP Materials Directive No. 15. October 5, 1989.

Strategic Highway Research Program. "Obtaining 12 Inch Cores for Use in A-001 Testing." SHRP-LTPP Materials Directive No. 8. May 24, 1989.

Strategic Highway Research Program. "Obtaining AC and PCC Cores for Use in the H-210, H-202, H-203 and H-204 Contracts from the North Central and North Atlantic Regions." SHRP-LTPP Materials Directive No. 11. July 26, 1989.

Strategic Highway Research Program. "Reduction in LTPP Sampling and Testing." SHRP-LTPP Materials Directive No. 1. March 1, 1989.

Strategic Highway Research Program. "Reduction in LTPP Sampling and Testing." SHRP-LTPP Materials Directive No. 2. March 14, 1989.

Strategic Highway Research Program. "Resilient Modulus Testing Protocols." SHRP-LTPP Materials Directive No. 14. September 26, 1989.

Strategic Highway Research Program. "Revised Field Data Collection Forms and Guidelines for Bulk Sample Retrieval from BA..-type Boreholes." SHRP-LTPP Materials Directive No. 16. February 5, 1990.

Strategic Highway Research Program. "Revised Laboratory Data Sheets L05A and L05B. Summary of Pavement Layers." SHRP-LTPP Materials Directive No. 30. May 19, 1992.

Strategic Highway Research Program. "Revised SHRP-LTPP Guide for Laboratory Material Handling and Testing, Revised February, 1991." SHRP-LTPP Materials Directive No. 25. March 22, 1990.

Strategic Highway Research Program. "Revised SHRP Protocol P04." SHRP-LTPP Materials Directive No. 24. December 3, 1990.

Strategic Highway Research Program. "Revised SHRP Protocols P04 and P42." SHRP-LTPP Materials Directive No. 18. March 29, 1990.

Strategic Highway Research Program. "Revised SHRP Protocol P43." SHRP-LTPP Materials Directive No. 19. April 19, 1990.

Strategic Highway Research Program. "Revised SHRP Protocols P47 and P52." SHRP-LTPP Materials Directive No. 17. March 20, 1990.

Strategic Highway Research Program. "Revised Table C.2, Version 2.0 of the SHRP-LTPP Guide for Field Materials Sampling, Handling and Testing. May, 1990." SHRP-LTPP Materials Directive No. 21, June 5, 1990.

Strategic Highway Research Program. "Revised Version of SHRP Protocols P14 and P51." SHRP-LTPP Materials Directive No. 22. June 19, 1990.

Strategic Highway Research Program. "Revised Version of Appendix D (Pages 1-11) of the SHRP-LTPP Guide for Laboratory Materials Handling and Testing." SHRP-LTPP Materials Directive No. 27. October 30, 1991.

Strategic Highway Research Program. "Revised Version of SHRP Protocols P47 (GPS) and Protocol P47 (SPS)." SHRP-LTPP Materials Directive No. 26. August 12, 1991.

Strategic Highway Research Program. "Revisions to the SHRP-LTPP Guide for Laboratory Materials Handling and Testing." SHRP-LTPP Materials Directive No. 20. May 24, 1990.

Strategic Highway Research Program. "SHRP Protocols for SPS Laboratory Materials Testing and Related Revisions to the SHRP-LTPP Guide for Laboratory Materials Handling and Testing." SHRP-LTPP Materials Directive No. 28. November 5, 1991.

Strategic Highway Research Program. "SHRP Protocols for SPS Laboratory Materials Testing and Related Revisions to the SHRP-LTPP Guide for Laboratory Materials Handling and Testing." SHRP-LTPP Materials Directive No. 29. January 23, 1992.

Strategic Highway Research Program. "Testing Requirements for Layers Within AC Cores." SHRP-LTPP Materials Directive No. 5. May 4, 1989.

Strategic Highway Research Program. "Testing Requirements for Treated Base and Subbase Materials and Treated Subgrade." SHRP-LTPP Materials Directive No. 9. June 13, 1989.

Strategic Highway Research Program. "Transmittal of Protocols P41, P42, P47, P51, and P52." SHRP-LTPP Materials Directive No. 6. May 16, 1989.

REM NOTES

Hadley, W.O. "SHRP Rem Notes Issue No. 1 - Resilient Modulus Testing for Asphalt Concrete." Strategic Highway Research Program. April, 1990.

Hadley, W. O. "SHRP Rem Notes Issue No. 3 - Alignment and Measurement Issues Associated with SHRP Protocol P07." Strategic Highway Research Program. June, 1990.

Hadley, W. O. "SHRP Rem Notes Issue No. 4 - Alignment and Measurement Issues Associated with SHRP Protocol P07, continued." Strategic Highway Research Program. July, 1990.

Hadley, W.O., "SHRP Rem Notes Issue No. 6 - SHRP Protocol P46 Familiarization Testing." Strategic Highway Research Program. November, 1990.

Pelzner A., and Groeger, J. "SHRP Rem Notes Issue No. 7 - Observation of SHRP Laboratories and Revisions to the SHRP Laboratory Materials Testing Guide." Strategic Highway Research Program. April, 1991.

Steele, Garland. "SHRP Rem Notes Issue No. 2 - SHRP Proficiency Testing." Strategic Highway Research Program. May, 1990.

Steele, Garland. "SHRP Rem Notes Issue No. 5 - SHRP Proficiency Sample Testing Programs." Strategic Highway Research Program. August, 1990.

TECHNICAL MEMORANDA

NOTE: All Technical Memoranda listed below were prepared for the Strategic Highway Research Program's Long-Term Pavement Performance project - unless otherwise stated.

Anderson, V. "A Short Discussion of Algorithms for the Construction of Experimental Designs (ACED)." TRDF Technical Memorandum VA-1. February 8, 1988.

Anderson, V. "Analysis of GPS Data." TRDF Technical Memorandum AU-15. March 18, 1988.

Anderson, V. "Analysis of the Material Testing Sampling Design." TRDF Technical Memorandum AU-108. January 31, 1990.

Anderson, V. "An Analysis of Variance Method to Estimate ESAL's for a Year." TRDF Technical Memorandum AU-199. January 20, 1992.

Anderson, V. "Crucial Analyses for SPS-1." TRDF Technical Memorandum AU-162. September 10, 1990.

Anderson, V. "Error Variation for GPS and SPS." TRDF Technical Memorandum AU-171. October 25, 1990.

Anderson, V. "A Few Analyses of LTPP Data from the North Atlantic Region." TRDF Technical Memorandum AU-211. September 15, 1992.

Anderson, V. "A Few Analyses of LTPP Data from the Southern Region." TRDF Technical Memorandum AU-210 (Revised). August 14, 1992.

Anderson, V. "Fractional Factorials for Designs that have Classification and Treatment Factors in the Same Experiment." TRDF Technical Memorandum AU-9. February 17, 1988.

Anderson, V. "GPS (1-5) Simulated data Analyses for the Initial Recruitment." TRDF Technical Memorandum AU-49. April 7, 1989.

Anderson, V. "Method to Compare Predictability of Y called "closeness"." TRDF Technical Memorandum AU-28. September 16, 1988.

Anderson, V. "M_r (Calculated Resilient Modulus) Analysis of Variance (ANOVA) for Five Sections." TRDF Technical Memorandum AU-202. March 17, 1992.

Anderson, V. "One Method to Estimate Construction Variability on Pavement Distress." TRDF Technical Memorandum AU-201. February 28, 1992.

Anderson, V. "Philosophy of Sampling (Allocating Observations)." TRDF Technical Memorandum AU-17. March 28, 1988.

Anderson, V. "Possible Influence of Unequal Frequencies on Two Factor Interactions in GPS-5, 4, 3, 2." TRDF Technical Memorandum AU-151. August 2, 1990.

Anderson, V. "A Recapitulation of the Design of GPS and Regression Analyses." TRDF Technical Memorandum AU-178. March 1, 1991.

Anderson, V. "Rut Depth Analyses for Six Section." TRDF Technical Memorandum AU-206. May 15, 1992.

Anderson, V. "Selecting Sections for GPS (P-001)." TRDF Technical Memorandum AU-3. January 6, 1988.

Anderson, V. "Some Essential Data Enhancement Techniques." TRDF Technical Memorandum AU-117. March 22, 1990.

Anderson, V. "SPS Designs." TRDF Technical Memorandum AU-14. March 16, 1988.

Anderson, V. "Statistical Design (Split Plot) and Inference Space for SPS (Rationale for using at least 2 error terms)." TRDF Technical Memorandum AU-173. December 3, 1991.

Anderson, V. "Statistical Design (Completely Randomized) and Inference Space for GPS (Rational for using residual mean square for the estimate of the error variance in regression analyses)." TRDF Technical Memorandum AU-172. November 21, 1990.

Anderson, V. "Suggested Verification Procedure in South Carolina as a GPS Pilot Study." TRDF Technical Memorandum AU-13. March 15, 1988.

Anderson, V. "Three factor Interactions (3 f.i.) Confounded with 4 f.i. and Higher From 1/4th replicate of 2^8." TRDF Technical Memorandum AU-19. April 17, 1988.

Anderson, V. "Trial Analyses for GPS 1-5 Using Simulated Data." TRDF Technical Memorandum TW-2. September 19, 1988.

Anderson, V. and R. High. "Sampling Within Sections." TRDF Technical Memorandum AU-4. January 29, 1988.

Anderson, V. and R. High. "Value of Fractional Factorials for the SPS-1 and SPS-2 Experimental Designs." TRDF Technical Memorandum AU-56. March 14, 1989.

Benson, K. "Collection of Skid Measurements for SPS Test Sections." TRDF Technical Memorandum AU-96. December 12, 1989.

Benson, K. "Existing AC Overlay of PCC Pavements." TRDF Technical Memorandum AU-47. February 9, 1989.

Benson, K. "Extension of Tech Memo AU-23, Surface Distresses for LTPP Test Sections." TRDF Technical Memorandum AU-25. September 14, 1988.

Benson, K. "Florida Limerock Sections." TRDF Technical Memorandum AU-43. January 19, 1989.

Benson, K. "GPS New AC Overlay Studies (GPS-6B/7B)." TRDF Technical Memorandum AU-50. February 14, 1989.

Benson, K. "GPS Unbonded PCC Overlay of PCC Study." TRDF Technical Memorandum AU-51. February 15, 1989.

Benson, K. "Guidelines for Routine Monitoring Measurements." TRDF Technical Memorandum AU-93. December 6, 1989.

Benson, K. "Magnetic Pavement Marking System (DRAFT)." TRDF Technical Memorandum AU-33. January 9, 1989.

Benson, K. "Quality Control Plan for Rehabilitation Data Collection." TRDF Technical Memorandum AU-80. September 26, 1989.

Benson, K. "Recommended Certification Procedures for the Manual Distress Surveys." TRDF Technical Memorandum AU-157. August 23, 1990.

Benson, K. "Recommended Quality Control of the Manual Distress Survey Data." TRDF Technical Memorandum AU-158. August 15, 1990.

Benson, K. "Recommended System of Inter-Region Quality and Consistency for Distress Data." TRDF Technical Memorandum AU-71. August 6, 1989.

Benson, K. "Rehabilitation Sheets 1-64." TRDF Technical Memorandum AU-115. March 16, 1990.

Benson, K. "Site Verification Recommendations." TRDF Technical Memorandum AU-10. February 16, 1988.

Benson, K. "Update of Tech Memo AU-22, Surface Distresses for LTPP Pavement Test Sections." TRDF Technical Memorandum AU-23. August 15, 1988.

Benson, K. and R. High. "Existing AC Overlay of PCC Pavements." TRDF Technical Memorandum AU-46. January 31, 1989.

Benson, K. and E. Pensock. "Quality Control Plan for Skid Data." TRDF Technical Memorandum AU-75. October 24, 1989.

Benson, K. and H. Roper. "Review of PASCO's January 1989 Operation Manual." TRDF Technical Memorandum AU-48. February 7, 1989.

Bertrand, Carl and G. Claros. "Class I Rod Profiling Techniques." TRDF Technical Memorandum UT-38. March 30, 1990.

Castedo, H. "Consideration of Data Collection Needs for Evaluating Existing Pavement Design Methods (Revision of the Data Collection Guide for LTPP)." TRDF Technical Memorandum UT-4. February 17, 1988.

Castedo, H. "Environmental Data for LTPP." TRDF Technical Memorandum UT-6. April 29, 1988.

Castedo, H. "Evaluation and Comments of Proposed AC Hot Mix Recycling (SPS-3) and JCP Restoration (SPS-4) Experiments (Refer to Tech Memo No. PI-03)." TRDF Technical Memorandum UT-5. April 6, 1988.

Castedo, H. "List of "Available" Computer Programs for Pavement Design, Condition Survey and Pavement Structures in General." TRDF Technical Memorandum UT-2. February 16, 1988.

Castedo, H. "Literature on Pavement Design Methods." TRDF Technical Memorandum UT-3. February 19, 1988.

Castedo, H. "Long-Term PASCO Film Storage at TRDF." TRDF Technical Memorandum UT-17. June 29, 1989.

Castedo, H. "P-001 Project." TRDF Technical Memorandum UT-1. December 23, 1987.

Castedo, H. "Recommendations for the Implementation of the Environmental Data Collection to be Used in LTPP. (Refer to TMs No. UT-06 and 07)." TRDF Technical Memorandum UT-8. May 6, 1988.

Castedo, H. "Sources of Information and References for Environmental Data to be Used in LTPP (Refer to TM no. UT-06)." TRDF Technical Memorandum UT-7. May 4, 1988.

Castedo, H. "Status Report on: Surface Distress Manual - PASCO Film Data Reduction." TRDF Technical Memorandum UT-9. July 7, 1988.

Castedo, H. and K. Benson. "Recommended Distresses to be Collected on LTPP Test Sections." TRDF Technical Memorandum AU-26. September 14, 1988.

Castedo, H., K. Benson and L. Moser. "Surface Distresses for LTPP Pavement Test Sections." TRDF Technical Memorandum AU-22. July 21, 1988.

Castedo, H., J. Semrau and K. Benson. "Summary and Review of Pavement Condition Survey Manuals from Various States and Provinces." TRDF Technical Memorandum AU-24. August 19, 1988.

Claros, G. "Additional Comments Regarding the PADIAS-SHRP Manual." TRDF Technical Memorandum UT-36. March 19, 1990.

Claros, G. "Comments to the PADIAS-SHRP Manual Revision." TRDF Technical Memorandum UT-35. March 9, 1990.

Claros, G. "Comments to the Procedure for Testing Synthetic Samples." TRDF Technical Memorandum UT-34. February 26, 1990.

Claros, G. "Proficiency and Calibration Tests for Task 3." TRDF Technical Memorandum UT-33. February 22, 1990.

Claros, G. "Protocols for SPS Experiments." TRDF Technical Memorandum UT-46. May 23, 1990.

Claros, G. "Task 2, Protocol P-07." TRDF Technical Memorandum UT-28. January 22, 1990.

Claros, G. and H. deSolminihac. "Comments to Tech Memo AU-101." TRDF Technical Memorandum UT-29. January 25, 1990.

Claros, G. and H. deSolminihac. "Preliminary Analysis of the SHRP Profilometer Workshop." TRDF Technical Memorandum UT-31. February 15, 1990.

Copeland, C. "SHRP Regional IMS Computer Equipment Configuration." TRDF Technical Memorandum AU-103. January 26, 1990.

Copeland, C. and J. German. "Traffic Data Tracking System." TRDF Technical Memorandum AU-105. January 31, 1990.

Copeland, C. and J. German. "Automated NTDB Traffic Data Edit." TRDF Technical Memorandum AU-106. January 31, 1990.

Coplantz, J. "Alternatives for Revision of GPS Experiment 2." TRDF Technical Memorandum AU-6. February 1, 1988.

Coplantz, J. "Investigation of Quality Control Procedures for Use of Nuclear Moisture/Density Gauges." TRDF Technical Memorandum AU-11. February 18, 1988.

Coplantz, J. "Proposed Revision of GPS Experiment 2 to be Presented to the ETG on May 9th and 10th." TRDF Technical Memorandum AU-18. April 19, 1988.

Coplantz, J. and P. Irick. "Recommendations on Approach to GPS Experiments 6, 7, and 9." TRDF Technical Memorandum AU-8. February 10, 1988.

deSolminihac, H. "Acceptance Criteria for the PASCO Films and Results of the First Film Revision." TRDF Technical Memorandum UT-52. June 25, 1990.

deSolminihac, H. "Certification Procedures for Manual Condition Survey Personnel." TRDF Technical Memorandum UT-49. June 4. 1990.

deSolminihac, H. "Certification Procedures for the PADIAS Operator." TRDF Technical Memorandum UT-45. June 27, 1990.

deSolminihac, H. "Manual Procedure for Faulting Measurement." TRDF Technical Memorandum UT-55. July 27, 1990.

deSolminihac, H. "Organization of the Distress Identification Manual for PASCO Films." TRDF Technical Memorandum UT-30, January 25, 1990.

deSolminihac, H. "Preliminary Proposition for the Quality Assurance Plan of the Manual Condition Survey." TRDF Technical Memorandum UT-32. February 20, 1990.

deSolminihac, H. "Quality Assurance Plan for Film Interpretation." TRDF Technical Memorandum UT-47. June 27, 1990.

deSolminihac, H. "Quality Assurance Plan for the Manual Condition Survey." TRDF Technical Memorandum UT-50. June 27. 1990.

deSolminihac, H. and G. Claros. "Statistical Analysis of the February 1990 SHRP Profilometer Workshop." TRDF Technical Memorandum UT-39. March 26, 1990.

Elkins, G. "Additions to Traffic Presentation on Review of Continuously Collected Data." TRDF Technical Memorandum AU-63. May 1, 1989.

Elkins, G. "Acceptance Recommendation on SPS-6 Project in Texas." TRDF Technical Memorandum EC-48. April 19, 1990.

Elkins, G. "Data Collection and Storage Consideration for SPS Sections." TRDF Technical Memorandum EC-44. February 5, 1990.

Elkins, G. "Executive Summary of LTPP Technical Overview Workshop." TRDF Technical Memorandum EC-16. May 14, 1989.

Elkins, G. "Manual measurement of transverse profile using the Dipstick." TRDF Technical Memorandum EC-39. January 15, 1990.

Elkins, G. "Material Sampling Plan for SPS-5 Manitoba Project." TRDF Technical Memorandum EC-19. June 27, 1989.

Elkins, G. "Nominated SPS-6 Project on US-31." TRDF Technical Memorandum EC-68. August 10, 1990.

Elkins, G. "Notes to Reviewers of Preliminary SPS-1 Construction Guidelines." TRDF Technical Memorandum EC-66. August 7, 1990.

Elkins, G. "Pavement Condition Index for LTPP." TRDF Technical Memorandum AU-69. June 15, 1989.

Elkins, G. "Policy for Pavement Maintenance on GPS Sections." Texas Research and Development Memorandum T-001. May 26, 1988.

Elkins, G. "Potential Modification to SPS 1 Design." TRDF Technical Memorandum EC-37. January 4, 1990.

Elkins, G. "Recommendation on Montana's Request to Omit the Control Section on their SPS-5 Project." TRDF Technical Memorandum EC-59. June 20, 1990.

Elkins, G. "Recommendation on Nominated SPS-2 Site on I-80, Iowa." TRDF Technical Memorandum EC-70. August 10, 1990.

Elkins, G. "Recommendation on Nominated SPS-5 project from Texas, US-175." TRDF Technical Memorandum EC-64. August 8, 1990.

Elkins, G. "Recommendation on Nominated SPS-7 Project from Minnesota on I-94." TRDF Technical Memorandum EC-65. August 8, 1990.

Elkins, G. "Recommendation on SPS-5 Project in Florida." TRDF Technical Memorandum EC-54. May 23, 1990.

Elkins, G. "Recommendations on Arizona SPS-1 Project." TRDF Technical Memorandum EC-57. May 30, 1990.

Elkins, G. "Recommendations on Nominated SPS-5 Project in Maryland." TRDF Technical Memorandum EC-52. June 13, 1990.

Elkins, G. "Recommendations on Organization to Interpret Distress Photographs." TRDF Technical Memorandum AU-44. January 27, 1989.

Elkins, G. "Recommendations on SPS-1 project in California." TRDF Technical Memorandum EC-56. May 30, 1990.

Elkins, G. "Recommended Design and Construction Details for Manual Rut Depth Gauge." TRDF Technical Memorandum EC-14. May 11, 1989.

Elkins, G. "Recruitment Plan for SPS Test Sections." TRDF Technical Memorandum EC-31. September 25, 1989.

Elkins, G. "Review & Recommendations on nominated SPS-5 Project on I-75 in TRDF Technical Memorandum EC-60. June 25, 1990.

Elkins, G. "Review of Nominated SPS 5 & 6 Projects in Connecticut." TRDF Technical Memorandum EC-47. February 19, 1990.

Elkins, G. "Review of Nominated SPS 6 Project in Pennsylvania." TRDF Technical Memorandum EC-41. January 19, 1990.

Elkins, G. "Review of Nomination Form for SPS-7 on US-67 in Missouri." TRDF Technical Memorandum EC-67. August 10, 1990.

Elkins, G. "Review of SPS-6 Nomination Forms." TRDF Technical Memorandum EC-26. August 9, 1989.

Elkins, G. "Review of SPS-6 Nomination from Ohio." TRDF Technical Memorandum EC-63. July 27, 1990.

Elkins, G. "Revised Survival Estimates for Revised SPS-1 Test Sections Structures." TRDF Technical Memorandum EC-34. December 29, 1989.

Elkins, G. "Site Specific Environmental Data Collection." TRDF Technical Memorandum EC-58. May 31, 1990.

Elkins, G. "SPS-8 Strawman Experiment Design." TRDF Technical Memorandum EC-51. June 13, 1990.

Elkins, G. "SPS Recruitment Plan and Schedule." TRDF Technical Memorandum EC-32. November 13, 1989.

Elkins, G. "SPS Test Section Numbering Scheme." TRDF Technical Memorandum EC-29. September 7, 1989.

Elkins, G. "Status of Data Base and Available LTPP Data." TRDF Technical Memorandum EC-50. February 26, 1990.

Elkins, G. "Survival Estimates for SPS-1 Test Sections." TRDF Technical Memorandum EC-33. December 19, 1989.

Elkins, G. "Traffic Data Collection Needs for Specific Pavement Studies Test Sections." TRDF Technical Memorandum AU-72. September 21, 1989.

Elkins, G. "Use of SPS 3, 4, 5, and 6 Data in P-020 Analysis." TRDF Technical Memorandum EC-49. May 11, 1990.

Elkins, G. "Work Items and Development Topics for SPS Experiments." TRDF Technical Memorandum EC-17. May 13, 1989.

Elkins, G. and K. Benson. "REVISED - Guidelines for Before and After Overlay and Seal Coat Monitoring Measurements (Update of the May 13, 1989 version)." TRDF Technical Memorandum EC-15. November 10, 1989.

Elkins, G. and C. Copeland. "Traffic Data Summary Statistics in the SHRP NPDB." TRDF Technical Memorandum EC-43. January 30, 1990.

Elkins, G. and J. German. "Draft Material for Traffic Executive Summary Report." TRDF Technical Memorandum AU-40. December 30, 1988.

Elkins, G. and J. Groeger. "Recommended Materials Sampling Plan for SPS-6 Site in Iowa." TRDF Technical Memorandum EC-21. June 30, 1989.

Elkins, G. and J. Groeger. "Review of SPS-5 Nomination Forms." TRDF Technical Memorandum, EC-28. August 21, 1989.

Elkins, G., R. Haas and P. Irick. "Draft Report on Further Development of SPS-5." TRDF Technical Memorandum EC-10. January 24, 1989.

Elkins, G. and P. Stephanos. "Comparison of Rut Depths from Dipstick and PASCO Transverse Profile Measurements." TRDF Technical Memorandum EC-42. January 30, 1990.

German, J. "Algorithms for the Estimation of Traffic Variability." TRDF Technical Memorandum AU-176. January 24, 1991.

German, J. "Computer Capability at Regional Level." TRDF Technical Memorandum AU-122. March 28, 1990.

German, J. and W. O. Hadley. "Determination of Cumulative Loading Estimates from Historical Data." TRDF Technical Memorandum AU-175. January 4, 1991.

German, J. "Final Draft of Data Collection Guide Chapter 3: Traffic Data Collection." TRDF Technical Memorandum AU-52. August 9, 1989.

German, J. "Implementation of the National Traffic Data Base." TRDF Technical Memorandum AU-123. March 29, 1990.

German, J. "Incorporating FHWA Truck Weight Data into GPS Traffic Database." TRDF Technical Memorandum AU-177. February 15, 1991.

German, J. "Procedures for Assessing the Precision of Annual Traffic Estimates." TRDF Technical Memorandum AU-193. October 29, 1991.

German, J. "Site Related Code for Traffic Data." TRDF Technical Memorandum AU-134. June 1, 1990.

German, J. "Standards for Profile Measurements at WIM Locations."TRDF Technical Memorandum AU-192. October 25, 1991.

German, J. "Traffic Data Collection Plan Guidelines." TRDF Technical Memorandum AU-88. November 16, 1989.

German, J. "Traffic Data Collection Requirements for SPS-8." TRDF Technical Memorandum AU-161. August 31, 1990.

German, J. "WIM Data Analyses for the SHRP LTPP Traffic ETG." TRDF Technical Memorandum AU-205. May 8, 1992.

German, J. and W. Cunagin. "Measures of Traffic Data Variability." TRDF Technical Memorandum AU-128. April 30, 1990.

German, J. and E. Pensock. "Selection Criteria for Regional Weigh-in-Motion Sites." TRDF Technical Memorandum AU-147. June 29, 1990.

Gibson, S. "Additional Revisions to the PADIAS Distress Analysis System." TRDF Technical Memorandum AU-143. June 25, 1990.

Gibson, S. "PASCO Film Acceptance Review." TRDF Technical Memorandum AU-165. August 31, 1990.

Gibson, S. "PASCO Film Acceptance Review." TRDF Technical Memorandum AU-148. July 13, 1990.

Gibson, S. "PASCO Film Acceptance Review." TRDF Technical Memorandum AU 150. July 16, 1990.

Gibson, S. "Recommended Certification Criteria for PASCO FMA Interpretation Technician." TRDF Technical Memorandum AU-149. July 13, 1990.

Gibson, S., H. Roper and W. O. Hadley. "Pilot Study for PASCO Distress Interpretation." TRDF Technical Memorandum AU-164. September 10, 1990.

Goulias, D. "Anticipated SHRP-LTPP General Revisions of AASHTO Pavement Design Guide." TRDF Technical Memorandum UT-41. April 2, 1990.

Goulias, D. "Conversion of Asphalt Pavement Field Distress Data Collected During the Preliminary "Before Overlay or Seal Coat Application" Condition Surveys to the Descriptions Included in the "Distress Identification Manual for the LTPP Studies." TRDF Technical Memorandum UT-22. September 25, 1989.

Goulias, D. "Conversion of Rigid Pavement Field Distress Data Collected from the Preliminary Before Overlay or Seal Coat Application" Condition Surveys to the Descriptions included in the "Distress Identification Manual for the LTPP Studies." TRDF Technical Memorandum UT-23. September 25, 1989.

Goulias, D. "Evaluation of the Input Parameters of the 1986 AASHTO Design Equation for Rigid Pavements from the LTPP Data Base." TRDF Technical Memorandum UT-48. May 29, 1990.

Goulias, D. "Evaluation of the Input Parameters of the 1986 AASHTO Design Equation for Flexible Pavements from the LTPP Data Base." TRDF Technical Memorandum UT-27. January 30, 1990.

Goulias, D. "Evaluation of Input Variables of Existing Pavement Design Equations from LTPP Data." TRDF Technical Memorandum UT-26. November 6, 1989.

Goulias, D. "Input/Output Variables at the 1986 AASHTO Design Guide for Flexible Pavements and their Evaluation from the LTPP Data Collection Set." TRDF Technical Memorandum UT-15. June 19, 1989.

Goulias, D. "Pavement condition Indices Based on Distress Data and Other Pavement Condition Measurements." TRDF Technical Memorandum UT-10. June 5, 1989.

Goulias, D. "Possible Improvements to Chapters 2 and 3 of Part II of the 1986 AASHTO Design Guide from the SHRP/LTPP Study." TRDF Technical Memorandum UT-37. March 16, 1990.

Goulias, D. "Procedures for evaluating the ESAL's (of non-overlayed sections) from the traffic data of the LTPP test sections." TRDF Technical Memorandum "Status of "INV_PCC_STRENGTH Portland Concrete Layers Strength Data ...." TRDF Technical Memorandum UT-56. June 13, 1990.

Goulias, D. "Flowchart of distress data collection and monitoring for the LTPP studies." TRDF Technical Memorandum UT-21. September 11, 1989.

Goulias, D. "Input/Output Variables at the 1986 AASHTO Design Guide for Flexible Pavements and their Evaluation from the LTPP Data Collection Set." TRDF Technical Memorandum UT-15. June 19, 1989.

Goulias, D. "Modeling Approach for Developing Pavement Performance Prediction Models." TRDF Technical Memorandum UT-25. November 3, 1989.

Goulias, D. "Pavement condition Indices Based on Distress Data and Other Pavement Condition Measurements." TRDF Technical Memorandum UT-10. June 5, 1989.

Goulias, D. "Possible Improvements to Chapters 2 and 3 of Part II of the 1986 AASHTO Design Guide from the SHRP/LTPP Study." TRDF Technical Memorandum UT-37. March 16, 1990.

Goulias, D. "Procedures for evaluating the ESAL's (of non-overlayed sections) from the traffic data of the LTPP test sections." TRDF Technical Memorandum "Status of "INV_PCC_STRENGTH Portland Concrete Layers Strength Data ...." TRDF Technical Memorandum UT-56. June 13, 1990.

Goulias, D. "Proposed Procedures for Rating LTPP Test-Sections Prior to Placement of Overlays and Seal Coats for Classifying the Sections in the "Good" or "Bad" Category of the GPS 6B and 7B Factorial Analysis." TRDF Technical Memorandum UT-24. October 13, 1989.

Goulias, D. "Recommendations for Distress Measurements on the SPS-5 & 6 Sections." TRDF Technical Memorandum UT-42. April 19, 1990.

Goulias, D. "Recommended Pavement Condition Indices based on Distress Data for use in the LTPP Test Sections." TRDF Technical Memorandum UT-11. June 5, 1989.

Goulias, D. "Review and Comparison of Techniques for Developing Pavement Performance Prediction Models." TRDF Technical Memorandum UT-20, 1989.

Goulias. "Status of "INV_GENERAL Geometric, Drainage, and other General Information Requiring the Construction Number (Data Sheets 1, 2, & 3) ...." TRDF Technical Memorandum UT-51. June 8, 1990.

Goulias, D. "Status of 'INV_LAYER Layer Descriptions (Data Sheet: Inventory 3)" and "INV_AGE of Pavement Data (Data Sheets: Inventory 4)." TRDF Technical Memorandum UT-53. June 12, 1990.

Goulias, D. "Status of "INV_MAJOR_IMP Major Improvement Data (Data Sheet: Inventory 4)" and INV_PCC_STEEL Portland Concrete Layers Reinforcing Steel (Data Sheets: Inventory 7)." TRDF Technical Memorandum UT-54. June 14, 1990.

Goulias, D. "Use of Markov Chains in Developing Pavement Performance Prediction Models." TRDF Technical Memorandum UT-19. August 18, 1989.

Goulias, D. "Use of Statistical Concepts in Developing Probabilistic Performance Prediction Models." TRDF Technical Memorandum UT-18. July 17, 1989.

Goulias, D. and H. Castedo. "Pavement Condition Rating Procedure for LTPP Asphalt Test Sections (Before Overlay or Seal Coat Application." TRDF Technical Memorandum UT-14. June 22, 1989.

Goulias, D. and H. Castedo. "Preliminary Rating of LTPP Asphalt Test Sections." TRDF Technical Memorandum UT-12. June 8, 1989.

Goulias, D. and H. Castedo. "Preliminary Rating of LTPP Portland Cement Concrete Test Sections." TRDF Technical Memorandum UT-13. June 14, 1989.

Goulias, D. and H. Castedo. "Pre-Overlay Pavement Condition Rating Procedure for LTPP Portland Cement Concrete." TRDF Technical Memorandum UT-16. June 26, 1989.

Goulias, D. and H. deSolminihac. "Preliminary Recommendations for Distress Measurements on the SPS 5 & 6 Sections." TRDF Technical Memorandum UT-40. March 26, 1990.

Groeger, J. "Comparative Laboratory Testing Costs." TRDF Technical Memorandum EC-40. January 18, 1990.

Groeger, J. "Materials Sampling & Testing - Laboratory Identification Code Numbering Scheme." TRDF Technical Memorandum EC-62. July 24, 1990.

Groeger, J. "Proof Testing of P07 M_r Test System with an Aluminum Specimen." TRDF Resilient Modulus Technical Memorandum AURES-3. May 12, 1992.

Groeger, J. "Recommendations for the Revision of SHRP Protocol P51." TRDF Technical Memorandum EC-46. April 19, 1990.

Groeger, J. "Section 4 of the SHRP-LTPP Field Drilling & Sampling Guide Quality Control & Quality Assurance." TRDF Technical Memorandum EC-45. April 16, 1990.

Groeger, J. "SPS Field Sampling & Lab Testing Protocols." TRDF Technical Memorandum EC-61. June 21, 1990.

Groeger, J. "Summaries of ETG Comments and Possible Cost Savings from Elimination of Selected Laboratory Material Tests." TRDF Technical Memorandum EC-11. February 1, 1989.

Groeger, J. and G. Elkins. "Arizona Drilling, Sampling and Testing Plan for SPS-6 Project." TRDF Technical Memorandum EC-38. January 22, 1990.

Groeger, J. and G. Elkins. "California and Arizona Drilling, Sampling, and Testing Plan for SPS-5 Projects." TRDF Technical Memorandum EC-35. December 29, 1989.

Groeger, J.and G. Elkins. "Comments on Proposed Sampling Plan for SPS-5 Westbound Trunk Highway 2 West of Bemidji, MN." TRDF Technical Memorandum EC-55. May 31, 1990.

Groeger, J. and W. O. Hadley. "Field Drilling and Sampling of GPS-6B and GPS-7B Pavements." TRDF Technical Memorandum AU-212. September 23, 1992.

Haas, R. "Design for SPS-1 (Particularly the Thin-thin Section Combination)." TRDF Technical Memorandum RH-2. December 23, 1989.

Haas, R. "Potential Benefits from LTPP Models Incorporating Environmental Factors and Environment-Load Interactions." TRDF Technical Memorandum RH-03. July 21, 1989.

Haas, R., T. White, W. Uddin and W. R. Hudson. "Potential Benefits from LTPP." TRDF Technical Memorandum AU-74. October 15, 1989.

Hadley, W. O. "An Approach to Improvements of Load Equivalence Factors from SHRP LTPP Data." TRDF Technical Memorandum AU-190. October 15, 1991.

Hadley, W. O. "Classification of Pavement Types (Revised)." TRDF Technical Memorandum AU-166. November 5, 1990.

Hadley, W.O. "Equivalent Thickness for GPS-LTPP Overlay Sections (Revised)." TRDF Technical Memorandum AU-169. November 5, 1990.

Hadley, W.O. "Fingerprinting Comparisons Between Round Robin Laboratories, Southwestern Laboratories and Arizona State University." TRDF Resilient Modulus Technical Memorandum AURES-1. April 23, 1992.

Hadley, W.O. "General Review of Computer Printouts/Results." TRDF Technical Memorandum AU-194. December 3, 1991.

Hadley, W. O. "General Review of Computer Printout/Results - Second Report." TRDF Technical Memorandum AU-196. January 2, 1992.

Hadley, W. O. "Initial Report - General Review of Computer Printouts/ Results - Protocol P46 - Law Engineering." TRDF Technical Memorandum AU-198. January 13, 1992.

Hadley, W. O. "Initial Statistical Analysis of the February 1990 SHRP Profilometer Workshop Results." TRDF Technical Memorandum AU-131. May 4, 1990.

Hadley. W.O. "Instantaneous Deformation Data Extraction Procedure for P07 Resilient Modulus Test." TRDF Resilient Modulus Technical Memorandum AURES-11. July 31, 1992.

Hadley, W. O. "Load Equivalency Factor (LEF) Estimates for GPS-LTPP Rigid Pavements Based on the SHRP LTPP IMS Inventory Data (Revised)." TRDF Technical Memorandum AU-168. November 26, 1990.

Hadley, W. O. "Logical Review and Acceptable Range Values of LTPP Maintenance Data." (DRAFT)." TRDF Technical Memorandum AU-107. January 29, 1990.

Hadley, W.O. "North Central Region Modulus Testing." TRDF Resilient Modulus Technical Memorandum AURES-9. July 2, 1992.

Hadley, W.O. "P07 Proof Testing with Aluminum Specimen." TRDF Resilient Modulus Technical Memorandum AURES-7. May 29, 1992.

Hadley, W. O. "Pilot Studies of Effects of Materials and Construction Variabilities on Pavement and Performance." TRDF Technical Memorandum AU-203. April 6, 1992.

Hadley, W. O. "Possible Revisions to the Resilient Modulus Test Procedures (P-07)." TRDF Technical Memorandum AU-110. January 12, 1990.

Hadley, W.O. "Preliminary Evaluation of the "Fingerprinting" Testing of the Synthetic Specimens." TRDF Resilient Modulus Technical Memorandum AURES-4. May 12, 1992.

Hadley, W. O. "Proposed Decision Criteria for Establishing Representative Thickness of a Flexible Pavement with Variable Structural Sections." TRDF Technical Memorandum AU-159. September 29, 1990.

Hadley, W. O. "Proposed Method for Measurement of PCC Slab Faulting." TRDF Technical Memorandum AU-141. June 21, 1990.

Hadley, W. O. "Quality Assurance Checks on FWD Data." TRDF Technical Memorandum AU-207. May 18, 1992.

Hadley, W. O. "Recommended PC Concrete Pilot Studies." TRDF Technical Memorandum AU-190a. September 30, 1991.

Hadley, W. O. "REM Notes." TRDF Technical Memorandum AU-121. March 28, 1990.

Hadley, W. O. "Resilient Modulus Testing." TRDF Technical Memorandum AU-112, March 7, 1990.

Hadley, W.O. "Review of Law Engineering M_r Test Data for Round Robin Synthetic Samples." TRDF Resilient Modulus Technical Memorandum AURES-8, June 22, 1992.

Hadley, W.O. "Review of Initial Braun M_r "Fingerprinting" of Test System with Synthetic Specimens." TRDF Resilient Modulus Technical Memorandum AURES-5. May 15, 1992.

Hadley, W. O. "Revision of SHRP Protocol P51." TRDF Technical Memorandum AU-114. March 15, 1990.

Hadley, W. O. "Rut Depth Estimates from PASCO Cross Profile." TRDF Technical Memorandum AU-185. June 28, 1991.

Hadley, W. O. "Technical Review of Initial Statistical Analysis & Analysis of Results & Recommendations for Future Analyses: Feb. 1990 SHRP Profilometer Workshop." TRDF Technical Memorandum AU-132. May 7, 1990.

Hadley, W.O. and J.L. Groeger. "Interim Results - SHRP Resilient Modulus Pilot Study." TRDF Resilient Modulus Technical Memorandum AURES-2. June 15, 1992.

Hadley, W.O. and J.L. Groeger. "Revised Modification of SHRP Diametral Load Guide Device." TRDF Resilient Modulus Technical Memorandum AURES-6 (Revised). June 30, 1992.

Hadley, W.O. and S. Heinberg. "Review of Results from the ITVIEW Software Package." TRDF Resilient Modulus Technical Memorandum AURES-10. July 15, 1992.

Hadley, W. O. and P. Irick. "An Approach to Improvements of Load Equivalence Factors from SHRP LTPP Data." TRDF Technical Memorandum AU-204. May 7, 1992.

Hadley, W. O., E. Pensock, and D. Goulias. "Flexible Pavement Load Equivalency Factors, LEFs, Based on Structural Number Estimates Using the SHRP-LTPP IMS Inventory Data." TRDF Technical Memorandum AU-167. November 26, 1990.

High, R. "Algorithm for Cell Numbers of Factorial Designs." TRDF Technical Memorandum AU-189. September 3, 1991.

High, R. "Analysis of Pavement Condition Measurements with Zero Response." TRDF Technical Memorandum AU-187. August 21, 1991.

High, R. "Analysis of Type I Base Course Aggregates Test Data." TRDF Technical Memorandum AU-208. July 7, 1992.

High, R. "Analysis of Type II Cohesive Subgrade Soil Test Data." TRDF Technical Memorandum AU-209. July 7, 1992.

High, R. "Censored Regression Analysis Applied to the AASHO Road Test Equation for Rigid Pavement." TRDF Technical Memorandum AU-113. March 15, 1990.

High, R. "Data Analysis Plan for LTPP Studies." TRDF Technical Memorandum AU-36. March 29, 1989.

High, R. "Dipstick Data Analysis." TRDF Technical Memorandum AU-94, December 1, 1989.

High, R. "Effectiveness Computations Using Prediction Variances." TRDF Technical Memorandum AU-183. June 17, 1991.

High, R. "The Effectiveness of the GPS Sampling Designs for Predictions from Linear Regression Relationships." TRDF Technical Memorandum AU-60. March 29, 1989.

High, R. "Evolution of the Number of Test Sections for the LTPP." TRDF Technical Memorandum AU-31. November 9, 1988.

High, R. "Example of Preliminary GPS Simulated Data Analyses." TRDF Technical Memorandum AU-34, prepared for SHRP. January 3, 1989.

High, R. "Expected Types of Improvements for LTPP Pavement Design Equations." TRDF Technical Memorandum AU-62. May 1, 1989.

High, R. "Experimental Plan for the Comparison of SHRP Profilometers." TRDF Technical Memorandum AU-100. January 26, 1990.

High, R. "Frequency Distribution of Layer Thicknesses by Layer Descriptions for GPS Candidate Projects." TRDF Technical Memorandum AU-2. December 21, 1987.

High, R. "Frequency Distribution of Layer Thicknesses Material Type Codes for GPS Candidate Projects." TRDF Technical Memorandum AU-1. December 21, 1987.

High, R. "Guidelines for the Classification of GPS Test Sections as Released or Out-of-Study." TRDF Technical Memorandum AU-188. August 26, 1991.

High, R. "Initial GPS Project Selections." TRDF Technical Memorandum AU-12. March 2, 1988.

High, R. "LTPP Quality Control & Assurance Procedures." TRDF Technical Memorandum AU-146. June 29, 1990.

High, R. "LTPP Section Reference Guide." TRDF Technical Memorandum AU-145, June 29, 1990.

High, R. "Materials Testing Sampling Designs." TRDF Technical Memorandum AU-95. December 28, 1989.

High, R. "Notes on Environmental Data Collection." TRDF Technical Memorandum RH-1. April 1, 1989.

High, R. "Proposed Modifications to GPS Experimental Design Number 1: AC on Granular Base." TRDF Technical Memorandum AU-5. February 2, 1988.

High, R. "Quality Control & Assurance Procedures for LTPP Data." TRDF Technical Memorandum AU-119. March 23, 1990.

High, R. "Quality Control Processing of LTPP Data." TRDF Technical Memorandum AU-160. August 3, 1990.

High, R. "SPS-2 Experimental Design." TRDF Technical Memorandum AU-90, November 17, 1989.

High, R. "Statistical Analyses of IRI from SHRP Profilometers." TRDF Technical Memorandum AU-66. June 1, 1989.

High, R. "Statistical Software for VAX Computer." TRDF Technical Memorandum AU-125. March 30, 1990.

High, R. "Status of General Pavement Studies." TRDF Technical Memorandum AU-37. December 22, 1988.

High, R. "Strategic pavement Design Initiatives for SPS-1 and SPS-2." TRDF Technical Memorandum AU-35. February 10, 1989.

High, R. "Variance Component Estimates of Resilient Modulus Tests for Type II Soils." TRDF Technical Memorandum AU-184. June 17, 1991.

High, R. "Variance Component Estimates of Resilient Modulus Tests for Type I Materials." TRDF Technical Memorandum AU-186. August 21, 1991.

High, R. "Variance Components and Bias Estimation for SHRP Moisture Content Proficiency Sample Program." TRDF Technical Memorandum AU-181. June 12, 1991.

High, R. and V. Anderson. "A Note on Centering Data." TRDF Technical Memorandum AU-144. June 26, 1990.

High, R. and W.O. Hadley. "Variance Component Analysis of SHRP Portland Cement Concrete Core Proficiency Sample Program." TRDF Technical Memorandum AU-127. May 21, 1990.

High, R., P. Irick and V. Anderson. "Data Analysis Plan to Meet LTPP Objectives." TRDF Technical Memorandum AU-68. July 13, 1989.

Hudson, W.R. "Evaluation of PRORUT." TRDF Technical Memorandum AU-39, January 1, 1989.

Hudson, W. R. "GPS Test Site Status as of 1 February 1989." TRDF Technical Memorandum AU-38. February 29, 1989.

Hudson, W.R. and P. Irick. "Draft Report on Further Development of SPS-6." TRDF Technical Memorandum AU-45. January 24, 1989.

Irick, P. "AASHTO Design Guide Modifications." TRDF Technical Memorandum AU-120. March 26, 1990.

Irick, P. "Data simulation and Trial Analyses for GPS Experimental Designs (DRAFT)." TRDF Technical Memorandum PI-4. April 27, 1988.

Irick, P. "GPS Section Length and Sampling Plans for Inventory Data." TRDF Technical Memorandum PI-2. February 20, 1988.

Irick, P. "Rationale for Further Development and Implementation of Experimental Designs for SHRP LTPP Studies." TRDF Technical Memorandum PI-1. January 6, 1988.

Irick, P. "SPS Experimental Design Development and Implementation." TRDF Technical Memorandum PI-3. February 20, 1988.

Irick, P and R. High. "Evaluation and Calibration of Pavement Design Equations." TRDF Technical Memorandum AU-89. December 29, 1989.

Irick, P. and R. High. "Expected Economic Benefits from Increased Precision in LTPP Prediction Equations." TRDF Technical Memorandum AU-79. September 29, 1989.

Irick, P. and R. High. "LTPP Data Base Gaps & Biases." TRDF Technical Memorandum AU-136. June 11, 1990.

Linder, S. "PASCO Film Data Reduction Possibilities." TRDF Technical Memorandum AU-7. February 2, 1988.

Myers, M. "Rehabilitation Intra-Module Checks." TRDF Technical Memorandum AU-174. January 2, 1991.

Moser, L. "Surface Distress." TRDF Technical Memorandum AU-20. June 21, 1988.

Moser, L. "TRDF Staff (DRAFT)." TRDF Technical Memorandum AU-21. June 22, 1988.

Myers, M. "Identification of GPS Sites where FHWA Traffic Data can be used to Calculate Site Specific." TRDF Technical Memorandum AU-180. May 13, 1991.

Myers, M. "Literature Search for Pertinent Past Research on Deriving Load Equivalency Factors." TRDF Technical Memorandum AU-200. February 13, 1992.

Myers, M. and J. German. "Definition of Truck for SHRP." TRDF Technical Memorandum AU-182. June 12, 1991.

Myers, M. and J. German, "Research Plan for Studying WIM Data From Selected SHRP GPS Sites." TRDF Technical Memorandum AU-197. January 7, 1992.

Myers, M. and W. O. Hadley. "Rut Depth Estimates Developed." TRDF Technical Memorandum AU-179. April 1, 1991.

Pensock, E. "Historical Traffic Data Profile." TRDF Technical Memorandum AU-87. November 16, 1989.

Pensock, E. "Logical Review of LTPP Maintenance Data." TRDF Technical Memorandum AU-84. September 27, 1989.

Pensock, E. "LTPP International Test Section Numbering." TRDF Technical Memorandum AU-163. September 10, 1990.

Pensock, E. "Maintenance Construction Data Guidelines for SPS-5." TRDF Technical Memorandum AU-118. March 22, 1990.

Pensock, E. "Maintenance Data Collection Quality Control and Quality Assurance." TRDF Technical Memorandum AU-70. June 30, 1989.

Pensock, E. "Proposed LTPP Data collection Guide Revisions." TRDF Technical Memorandum AU-129. May 1, 1990.

Pensock, E. "Rehabilitation Construction Data for SPS-5." TRDF Technical Memorandum AU-124. March 30, 1990.

Pensock, E. "Review of Proposed Australian GPS Projects." TRDF Technical Memorandum AU-111. March 1990.

Pensock, E. "Summary of LTPP Projects." TRDF Technical Memorandum AU-65, June 29, 1989.

Rabinow, S., M. Witczak and W. Uddin. "FWD Test Sequence and Data Collection Recommendation." TRDF Technical Memorandum EC-6. May 5, 1988.

Roper, H. "Dipstick Data Handling Plan." TRDF Technical Memorandum AU-153, August 13, 1990.

Roper, H. "Dipstick Evaluation." TRDF Technical Memorandum AU-57. March 22, 1989.

Roper, H. "Evaluation Plan for the Datalogger Mode of Dipstick." TRDF Technical Memorandum AU-64. May 15, 1989.

Roper, H. "Evaluation Plan for the Manual Mode of Dipstick." TRDF Technical Memorandum AU-59. April 6, 1989.

Roper, H. "Evaluation Report Using the Manual Mode of Dipstick." TRDF Technical Memorandum AU-61. May 15, 1989.

Roper, H. "FHWA Profilometer Data Analysis." TRDF Technical Memorandum AU-77. October 29, 1989.

Roper, H. "Guidelines of Profile Data Processing." TRDF Technical Memorandum AU-98. December 31, 1989.

Roper, H. "Initial Evaluation of the Pre-Processor for Profile Data Processing." TRDF Technical Memorandum AU-156. August 14, 1990.

Roper, H. "Initial Review of the PADIAS Distress Analysis System." TRDF Technical Memorandum AU-130. May 2, 1990.

Roper, H. "Measurement Error Associated with GPS Test Section Data." TRDF Technical Memorandum AU-137. June 13, 1990.

Roper, H. "PASCO Rut Depth Data for H101 Contractor." TRDF Technical Memorandum AU-152. August 11, 1990.

Roper, H. "PASCO Distress Interpretation Procedure." TRDF Technical Memorandum AU-154. August 13, 1990.

Roper, H. "Personnel/Operator Requirements for the SHRP KJ Law Profilometers." TRDF Technical Memorandum AU-54. February 28, 1989.

Roper, H. "Plan for Evaluation and Acceptance of the KJ Law Profilometer." TRDF Technical Memorandum AU-53. February 28, 1989.

Roper, H. "Preliminary Profilometer Data Analysis." TRDF Technical Memorandum AU-67. May 3, 1989.

Roper, H. "Profile Data Collection Quality Control and Quality Assurance." TRDF Technical Memorandum AU-82. September 29, 1989.

Roper, H. "Profile Field Q.C. Procedure." TRDF Technical Memorandum AU-83, October 6, 1989.

Roper, H. "Profile Quality Assurance Software." TRDF Technical Memorandum AU-138. June 15, 1990.

Roper, H. "Profile Q.C. Procedures for Data Collection Assurance." TRDF Technical Memorandum AU-85. October 7, 1989.

Roper, H. "Profilometer Test Plan." TRDF Technical Memorandum AU-101, January 29, 1990.

Roper, H. "Recommendations to Interpret PASCO Distress Photographs." TRDF Technical Memorandum AU-73. September 19, 1989.

Roper, H. "Recommendations for Modification of the FHWA Profilometer." TRDF Technical Memorandum AU-55. March 15, 1989.

Roper, H. "Recommendations for Profilometers for SPS 5 & 6." TRDF Technical Memorandum AU-116. March 21, 1990.

Roper, H. "Recommendations on the Specifications for the Purchase of Dipstick." TRDF Technical Memorandum AU-76. October 29, 1989.

Roper, H. "Recommended Acceptance Test Plan for the SHRP-LTPP Dipsticks." TRDF Technical Memorandum AU-86. November 9, 1989.

Roper, H. "Recommended Acceptance Testing Plan for the Southern Region SHRP-LTPP Dipstick." TRDF Technical Memorandum AU-133. May 15, 1990.

Roper, H. "Recommended Plan for Completion of PASCO Distress ID Manual." TRDF Technical Memorandum AU-78. September 13, 1989.

Roper, H. "Review of the Revisions to PADIAS Distress Analysis System." TRDF Technical Memorandum AU-135. June 5, 1990 .

Roper, H. "Rod and Level Survey Procedures for Profilometer Acceptance Testing." TRDF Technical Memorandum AU-58. March 27, 1989.

Roper, H. "Rod and Level Survey Procedures for Profilometer Testing." TRDF Technical Memorandum AU-102. January 22, 1990.

Roper, H. "Rut Depth Quality Control Recommendations." TRDF Technical Memorandum AU-155. August 13, 1990.

Roper, H. "SHRP-LTPP Dipstick Acceptance Testing." TRDF Technical Memorandum AU-92. November 22, 1989.

Roper, H. "SHRP-LTPP Dipstick Acceptance Testing for Southern Region." TRDF Technical Memorandum AU-142. June 22, 1990.

Roper, H. "Simplifying Profile Measurements on SPS Sections." TRDF Technical Memorandum AU-97. December 19, 1989.

Roper, H. "Simulated Data Analysis GPS (Simple Case)." TRDF Technical Memorandum AU-16. March 28,1988.

Roper, H. "Specifications for Interpretation of Distress from PASCO Photographs." TRDF Technical Memorandum AU-42. February 23, 1989.

Smith, H. "Field Sampling and Testing." TRDF Technical Memorandum EC-3, January 20, 1988.

Smith, H. "State Implementation of LTPP Results." TRDF Technical Memorandum EC-1. January 6, 1988.

Smith, H. "Suggested Revisions of GPS Experiment 1 and 2." TRDF Technical Memorandum EC-4. March 4, 1988.

Smith, H. "Visits with SHRP State Coordinators and LTPP Contacts." TRDF Technical Memorandum EC-2. January 20, 1988.

Stephanos, P. "Appendixes of Data and Figures for Comparison of Rut Depth from Dipstick and PASCO Measurements." TRDF Technical Measurements EC-47a. February 19, 1990.

Stephanos, P. and G. Elkins. "Model Construction Specification for Crack and Seat and Break and Seat Operations on SHRP SPS-6 Test Sections." TRDF Technical Memorandum EC-36. January 40, 1990.

Uddin, W. "Analysis of SHRP FWD Acceptance Tests Data." TRDF Technical Memorandum EC-8. June 21,1988.

Uddin, W. "Harold Von Quintus' Memo of 13 June 1989, Confusion with Layer Numbers." TRDF Technical Memorandum EC-22. July 5, 1989.

Uddin, W. "Material Sampling and Testing Data" Chapter for the LTPP Data Collection Guide." TRDF Technical Memorandum EC-29a. September 25, 1989.

Uddin, W. "Pavement Temperature Measurement Procedure." TRDF Technical Memorandum EC-9. July 15, 1988.

Uddin, W. "Quality Control and Quality Assurance of LTPP Field Material Sampling, Handling, and Laboratory Material Testing Activities." TRDF Technical Memorandum EC-23. July 5, 1989.

Uddin, W. "Reduction of Bulk Sample to Test Sample Sizes." TRDF Technical Memorandum EC-18. June 6, 1989.

Uddin, W. "Remote Pavement Temperature Gradient Data Collection During FWD Testing." TRDF Technical Memorandum EC-12. March 15, 1989.

Uddin, W. "Resilient Modulus Testing of Unbound Granular Base and Subbase Materials and Subgrade Soils - Protocol P46." TRDF Technical Memorandum EC-13. May 10, 1989.

Uddin, W. "Response to Tony's Memo (Dated June 28, 1989) to Waheed Materials Testing." TRDF Technical Memorandum EC-27. August 9, 1989.

Uddin, W. "Review of Nominated SPS-7 Project on I-35, Iowa." TRDF Technical Memorandum EC-69. August 10, 1990.

Uddin, W. "Sensor Configuration for Falling Weight Deflectometers." TRDF Technical Memorandum EC-5. March 16, 1988.

Uddin, W. "Summarizing Resource Materials Used in Version 1.0 of the LTPP Laboratory Material Testing Guide." TRDF Technical Memorandum EC-30. September 22, 1989.

Uddin, W. "Testing of Asphaltic Concrete Layers, Harold Von Quintus' Memo of 29 August 1989." TRDF Technical Memorandum EC-31a. September 25, 1989.

Uddin, W. and J. Groeger. "Consideration of Treated Subgrade Soil in the LTPP Field Material Sampling, Handling and Laboratory Material Testing Programs." TRDF Technical Memorandum EC-24. August 1, 1989.

Uddin, W. and J. Groeger. "Laboratory Sample Tracking Tables for the GPS Sampling and Testing Program." TRDF Technical Memorandum EC-25. August 1, 1989.

Uddin, W., M. Witczak, and S. Rabinow. "Acceptance Testing of SHRP-FWDs." TRDF Technical Memorandum EC-7. May 10, 1988.

Uddin, W. and D. Wagner. "Pavement Temperature Measurement for FWD (Final Revision of Tech Memo No. EC-09)." TRDF Technical Memorandum AU-27. September 8, 1988.

Wagner, D. "PRORUT Evaluation Trip Report to Purdue University West Lafayette, Indiana." TRDF Technical Memorandum AU-32. December 2, 1988.

Wagner, D. "Suggested Acceptance Tests and Operations Manual Procedures for PASCO." TRDF Technical Memorandum AU-29. October 20, 1988.

Wagner, D. and L. Moser. "Interpretation of PASCO Distress Photos." TRDF Technical Memorandum AU-30. October 25, 1988.

White, T. "Digitalizing Pavement Photo Logs." TRDF Technical Memorandum TW-2. July 30, 1989.

White, T. "SHRP Products." TRDF Technical Memorandum TW-1. July 23, 1989.

IMS MESSAGES

Copeland, C. "Comments Table Review and Usage Recommendations for Regions." IMS Message Number TRDF-58. May 3, 1991.

Copeland, C. and W.O. Hadley. "COMMENTS Table Usage Recommendations for Regions." IMS Message Number TRDF-64. May 16, 1991.

Copeland, C. "Concerns with Newly Revised Climatic Data to be Stored in NIMS." TRDF-125. May 29, 1992.

Copeland, C. "EXPERIMENT_SECTION Table Changes." TRDF-133. August 17, 1992.

Copeland, C. "EXPERIMENT_SECTION Table Changes." TRDF-132. August 17, 1992.

Copeland, C. "EXPERIMENT_SECTION Table Changes." TRDF-131. August 17, 1992.

Copeland, C. "EXPERIMENT_SECTION Table Changes." TRDF-130. August 17, 1992.

Copeland, C. "IMS QA/QC Check for STEEL_LAP_LENGTH and Cross-Profile Data Status." IMS Message Number TRDF-68. June 3, 1991.

Copeland, C. "INIT_B Check Revision and Other QA/QC Concerns." IMS Message Number TRDF-98. November 26, 1991.

Copeland, C. and W.O. Hadley. "INIT_B Check Correction and Revision and INV_E Check Clarification." IMS Message Number TRDF-63. May 16, 1991.

Copeland, C. "Recommended Procedures for Dealing with Inventory Data QA Checks." IMS Message Number TRDF-67. May 29, 1991.

Copeland, C. "Review of Data Checking Reports and IMS Procedures." IMS Message Number TRDF-52. April 11, 1991.

Copeland, C. "Traffic Software Version 3.1(b)." TRDF-120. May 5, 1992.

Copeland, C. "Traffic Table Modifications and Historical Traffic QA/QC Checks." TRDF-119 (Revised). June 12, 1992.

Copeland, C. and W.O. Hadley. "Use of Information from the COMMENTS Table." IMS Message TRDF-86. September 12, 1991.

German, J.L. "Basic Framework for Traffic Data and SHRP IMS Data." IMS Message TRDF-17. March 20, 1989.

Groeger, J.L. "Additional Test Data on Concrete Samples", IMS Message Number TRDF-117. May 5, 1992.

Groeger, J.L. "(a) Algorithm for Automating Completior of Gradation Data (b) Algorithm for Automating Completion of Atterberg Limits Data." IMS Message Number TRDF-109. February 17, 1992.

Groeger, J.L. "Algorithm for Updating Table TST_L06." IMS Message Number TRDF-80. July 31, 1991.

Groeger, J.L. "Algorithm for Populating L05A with Existing REF_LAYER IMS Data, Revised QA/QC Checks for TST_L05A and TST_L05B, Other Revised QA/QC Checks." TRDF-125a. May 29, 1992.

Groeger, J.L. "Documentation of: Decisions Reached Concerning the Materials Module of the IMS." IMS Message Number TRDF-69. June 10, 1991.

Groeger, J.L. "Material_C Checks for NIMS Data Release." IMS Message Number TRDF-75. June 25, 1991.

Groeger, J.L. "NA Region Laboratory Test Data." IMS Message Number TRDF-83. August 15, 1991.

Groeger, J.L. "Review and Refinements to the MATL_* and TST_* NIMS QA/QC." IMS Message Number TRDF-100. December 19, 1991.

Groeger, J.L. "Review of Maintenance Data for 3rd IMS Release for the North Atlantic Region." IMS Message Number TRDF-105. February 7, 1992.

Groeger, J.L. "Review of Maintenance Data for 3rd IMS Release for the North Central Region." IMS Message Number TRDF-106. February 7, 1992.

Groeger, J.L. "Review of Maintenance Data for 3rd IMS Release for the Southern Region." IMS Message Number TRDF-107. February 7, 1992.

Groeger, J.L. "Review of Maintenance Data for 3rd IMS Release for the Western Region." IMS Message Number TRDF-108. February 7, 1992.

Groeger, J.L. "Review of the MATL_E QA/QC Report for the Southern Region." IMS Message Number TRDF-118, Report 1. May 5, 1992

Groeger, J.L. "SHRP Section 19891125 - Data Entry of Layer "3" and "3A"." IMS Message Number TRDF-110. March 11, 1992.

Hadley, W.O. "Cross Reference of Data collections Guide Sheets with IMS Schema." IMS Message Number TRDF-78. June 28, 1991.

Hadley, W.O. "Enhanced and Augmented Data Dependency Checks Based on Initial IMS Level 1 Release Review." IMS Message Number TRDF-49. February 21, 1991.

Hadley, W.O. "IMS Intra Checks." IMS Message Number TRDF-62. May 15, 1991.

Hadley, W.O. "IMS Intra Checks Maintenance, IMS Message Number TRDF-55, April 26, 1991.

Hadley, W.O. "IMS Intra Checks REHABILITATION." IMS Message Number TRDF-57. April 29, 1991.

Hadley, W.O. "IMS Intra Checks SKID." IMS Message Number TRDF-56. April 26, 1991.

Hadley, W.O. "IMS Level 1 QA/QC Checks for Distress (Manual)." IMS Message Number TRDF-111 (Revised). May 29, 1992.

Hadley, W.O. "IMS Level 1 QA/QC Checks for Distress (PADIAS)." IMS Message Number TRDF-114. March 19, 1992.

Hadley, W.O. "IMS Level 2-F Check - Intermodal." IMS Message Number TRDF-134. September 29, 1992.

Hadley, W.O. "IMS Level 2: G Check - Experiment and Cell Verification." IMS Message Number TRDF-88. September 23, 1991.

Hadley, W.O. "Intra Checks for FWD." IMS Message Number TRDF-72. June 6, 1991.

Hadley, W.O. "Intra Checks - Materials Testing Data Module." IMS Message Number TRDF-65. May 22, 1991.

Hadley, W.O. "Intra-Module Checks - RUT." IMS Message Number TRDF-73. June 6, 1991.

Hadley, W.O. "Inventory Data Checks." IMS Message Number TRDF-61. May 15, 1991.

Hadley, W.O. "PCS-Law Comment on QA Checks for Manual Distress." IMS Message Number TRDF-129. August 14, 1992.

Hadley, W.O. "Range Checks for Deflection (FWD) Data." IMS Message Number TRDF-77 (Revised). June 25, 1991.

Hadley, W.O. "Results of the Review of the SHRP Sections which did not Achieve 'E' or 'Section Release' Status during the Second IMS Level 1 Release." IMS Message Number TRDF-91. September 30, 1991.

Hadley, W.O. "Revisions to Range Checks for Deflection (FWD) Data." IMS Message Number TRDF-96. November 20, 1991.

Hadley, W.O. "Second IMS Level Release, Data Dependency Tables." IMS Message Number TRDF-81. September 18, 1991.

Hadley, W.O. "Second IMS Level Release, Data Dependence Tables, Part 2." IMS Message Number TRDF-82. September 18, 1991.

Hadley, W.O. "Second IMS Data Release QA/QC Summary Report Corrections on Data Dependency Tables." IMS Message Number TRDF-87 (Revised). September 19, 1992.

Hadley, W.O. "Section Release (Level 1) Definitions." IMS Message Number TRDF-41. November 26, 1990.

Hadley, W.O. "SN and D Calculation Program - SAIC-73 and AU-167." IMS Message Number TRDF-76 (Revised). June 25, 1991.

Hadley, W.O. "Subsurface Layer Designation: Impact on Base Layer Assignment." IMS Message Number TRDF-92. October 4, 1991.

Hadley, W.O. and C. Copeland. "Data Dependence Checks for Material Data Module." IMS Message Number TRDF-51. April 8, 1991.

Hadley, W.O. and C. Copeland. "Enhanced Range, Critical Element and Intra Module Checks for Inventory Data - Basic on Initial IMS Level 1 Release Review." IMS Message Number TRDF-48. February 21, 1991.

Hadley, W.O. and C. Copeland. "Third Data Release QA/QC Summary Report - WRCO." IMS Message Number TRDF-104. February 3, 1992.

Hadley, W.O. and C. Copeland. "Third Data Release QA/QC Summary Report - SRCO." IMS Message Number TRDF-103. February 3, 1992.

Hadley, W.O. and C. Copeland. "Third Data Release QA/QC Summary Report - NCRCO." IMS Message Number TRDF-102. February 3, 1992.

Hadley, W.O. and C. Copeland. "Third Data Release QA/QC Summary Report - NARCO." IMS Message Number TRDF-101. February 3, 1992.

Hadley, W.O., C. Copeland, and M. Myers. "Friction and Deflection Intra-Module Checks." IMS Message Number TRDF-42. December 12, 1990.

Hadley, W.O. and C. Copeland. "Initial Inventory Status Report on NIMS Database - Based on January 1991 Level I Release, Region 1." TRDF-43. January 31, 1991.

Hadley, W.O. and C. Copeland. "Initial Inventory Status Report on NIMS Database - Based on January 1991 Level I Release, Region 2." IMS Message Number TRDF-44. January 31, 1991.

Hadley, W.O. and C. Copeland. "Initial Inventory Status Report on NIMS Database - Based on January 1991 Level I Release, Region 3." IMS Message Number TRDF-45. January 31, 1991.

Hadley, W.O. and C. Copeland. "Initial Inventory Status Report on NIMS Database - Based on January 1991 Level I Release, Region 4." IMS Message Number TRDF-46. January 31, 1991.

Hadley, W.O. and C. Copeland. "Intra Checks for Rut." IMS Message Number TRDF-70. June 5, 1991.

Hadley, W.O. and C. Copeland. "Inventory IMS Checks." IMS Message Number TRDF-50. April 8, 1991.

Hadley, W.O. and C. Copeland, "Recommended Code Value Additions to Cell Section Link Table (NIMS)." IMS Message Number TRDF-47. February 21, 1991.

Hadley, W.O. and C. Copeland. "Your Fax of August 11, 1992 Concerning Climatic Data QA/QC." IMS Message Number TRDF-128. August 14, 1992.

Hadley, W.O. and J.L. Groeger. "IMS Intra Checks on AASHTO_SOIL_CLASS." IMS Message Number TRDF-60. May 16, 1991.

Hadley, W.O and J.L. Groeger. "Proposed Revisions to the Resilient Modulus IMS Table and Revised Level C-E QA/QC Checks for the Mr Program." IMS Message Number TRDF-135. September 30, 1992.

Hadley, W.O. and M. Myers. "Revisions to Level 1 - Section Release QA/QC Checks for the Profile Module." November 20, 1991 and "Level 1 - Section Release QA/QC Checks for the Profile Module." IMS Message Number TRDF-95. October 25, 1991.

Hadley, W.O., C. Copeland, R. High, and H. Roper. "LTPP Data Availability Policy Recommendations." IMS Message Number TRDF-40 (Revised). October 25, 1990.

Hadley, W.O., C. Copeland, and M. Myers. "Revisions and Additions to Message number TRDF-42 Friction and Deflection Intra-Module Checks." IMS Message Number TRDF-71. June 6, 1991.

Hadley, W.O., J.L. Groeger, and M. Myers, "Additional Intrachecks - Materials Testing Data Module." IMS Message Number TRDF-66. May 23, 1991.

Hammet, N. "Backup Procedures for IMS Machine." IMS Message Number TRDF-22. June 2, 1989.

Hammet, N. "Distress Data sheets 1-9." IMS Message Number TRDF-18. March 28, 1989.

Hammet, N. "Draft AQ Plan and Data Quality Indicator (DQI) Flag." IMS Message Number TRDF-25. July 10, 1989.

Hammet, N. "IMS Error Recovery." IMS Message Number TRDF-31. October 18, 1989.

Hammet, N. "IMS Pre-release Meeting, Middle of July." IMS Message Number TRDF-23. June 29, 1989.

Hammet, N. "IMS Processing of Distress Data." IMS Message Number TRDF-29, September 7, 1989.

Hammet, N. "IMS Traffic Data." IMS Message Number TRDF-28. August 29, 1989.

Hammet, N. "LTPP IMS Development - SAIC P-016 Quarterly Report: Comments." IMS Message Number TRDF-33. October 24, 1989.

Hammet, N. "Materials Testing - Resolution of Layer No's." IMS Message Number TRDF-26. July 25, 1989.

Hammet, N. "Task 14 (IMS) Bi-Weekly Status." IMS Message Number TRDF-20, May 24, 1989.

Hedfi, A., W.O. Hadley, J.L. Groeger, S. Heinberg. "QA/QC Checks for SHRP Environmental Data." IMS Message number TRDF-121 (Revision). July 31, 1992.

High, R. "Comments on IMS Printer Reports and Data Access." IMS Message Number TRDF-34. November 5, 1989.

High, R. "Comments on Printed Reports of the Information Management System." IMS Message Number TRDF-38. June 26, 1990.

High, R. "Descriptive Codes for GPS Special Case Sections." IMS Message Number TRDF-16. March 17, 1989.

High, R. "History of Experiment and Cell Assignments for GPS Sections." IMS Message Number TRDF-37. June 21, 1990.

High, R. "Interface of IMS with Data Analysis." IMS Message Number TRDF-30. September 15, 1989.

High, R. "Interface of IMS with Data Analysis & Reporting." IMS Message Number TRDF-21. June 1989.

High, R. "Interface of IMS with Data Analysis & Reporting." IMS Message Number TRDF-21. June 1989.

High, R. "Revisions to the EXP_SECT.LIS Table." IMS Message Number TRDF-79. July 29, 1991

High, R. "SHRP LTPP Data Processing, Security and Availability Plan." IMS Message Number TRDF-35. December 6, 1989.

High, R. and W.O. Hadley. "IMS Level 2 Statistical Quality Control and Assurance Procedures." IMS Message Number TRDF-134a. September 11, 1992.

Moser, L. "Availability of Revised DCG Forms during October 1, 1988 - December 31, 1988." IMS Message Number TRDF-14. November 7, 1988.

Moser, L. "Comments on SAIC October 21/88 memo (SAIC #11) Recommending a 386 IBM PC Compatible with DOS for RIMS." IMS Message Number TRDF-12. October 25, 1988.

Moser, L. "Comments on SAIC #13, "Cut-off Dates for Final LTPP Data Specifications." IMS Message Number TRDF-13. October 25, 1988.

Moser, L. "Disk Space Estimates for Regional Data Collection Item." IMS Message Number TRDF-4. August 4, 1988.

Moser, L. "Feasibility of PC-DOS for RIMS." IMS Message Number TRDF-11. October 21, 1988.

Moser, L. "Hardware for Regions - Response to SAIC-14." IMS Message Number TRDF-15. November 8, 1988.

Moser, L. "Inventory Data Structure on CTT Implementation Plan." IMS Message Number TRDF-6. September 30, 1988.

Moser, L. "Monitoring Data-Material Testing Data and IMS Design." IMS Message Number TRDF-10. October 13, 1988.

Moser, L. "My Comments on the IMS Comprehensive Work Plan." IMS Message Number TRDF-3. August 19, 1988.

Moser, L. "NIMS Test Suite Sample Queries." IMS Message Number TRDF-7, October 6, 1988.

Moser, L. "Response to SAIC #9 - Inventory Design." IMS Message Number TRDF-8. October 7, 1988.

Moser, L. "Responses to Message #SAIC-9 Questions." IMS Message Number TRDF-5. September 22, 1988.

Moser, L. "Review of SAIC Revised Schedule and Work Plan Outline." IMS Message Number TRDF-2. July 5, 1988.

Moser, L. "SAIC Approach and Thinking on Software/Hardware Evaluation." IMS Message Number TRDF-1. July 5, 1988.

Pensock, Ed. "Incomplete IMS Sections - Task 6 and Misc. Other." IMS Message Number TRDF-36. February 20, 1990.

Uddin, W. "Materials Testing Information for IMS." IMS Message Number TRDF-19. March 30, 1989.

Long-Term Pavement Performance Advisory Committee

William J. MacCreery, *chairman*
W.J. MacCreery, Inc.

David Albright
New Mexico Department of Transportation

Richard Barksdale
Georgia Institute of Technology

James L. Brown
Pavement Consultant

Albert J. Bush, III
USAE Waterways Experiment Station

Robert L. Clevenger
Colorado Department of Highways

Ronald Collins
Georgia Department of Transportation

Guy Doré
Ministère des Transports du Québec

Charles E. Dougan
Connecticut Department of Transportation

McRaney Fulmer
South Carolina Department of Highways and Public Transportation

Marlin J. Knutson
American Concrete Pavement Association

Hans Jorgen Ertman Larsen
Danish Road Institute, Road Directorate

Kenneth H. McGhee
Consultant Civil Engineer

Raymond K. Moore
University of Kansas

Richard D. Morgan
National Asphalt Pavement Association

William R. Moyer
Pennsylvania Department of Transportation

David E. Newcomb
University of Minnesota

Charles A. Pryor
National Stone Association

Cesar A. V. Queiroz
The World Bank

Rolands L. Rizenbergs
Kentucky Transportation Cabinet

Gary K. Robinson
Arizona Department of Transportation

Frederic R. Ross
Wisconsin Department of Transportation

Ted M. Scott
American Trucking Association

Marshall R. Thompson
University of Illinois

Kenneth R. Wardlaw
Consultant

Marcus Williams
H.B. Zachry Company

Liaisons

John P. Hallin
Federal Highway Administration

Theodore R. Ferragut
Federal Highway Administration

Frank R. McCullagh
Transportation Research Board

Louis M. Papet
Federal Highway Administration