



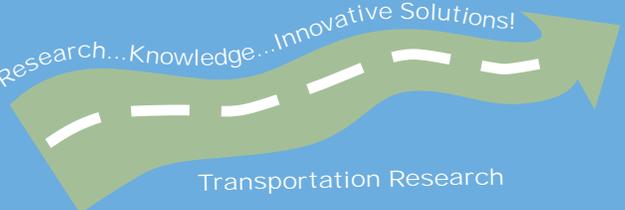
RESEARCH

2007-06

MnROAD Lessons Learned



Take the  steps... Research... Knowledge... Innovative Solutions!



Transportation Research

Technical Report Documentation Page

1. Report No. MN/RC-2007-06	2.	3. Recipients Accession No.	
4. Title and Subtitle MnROAD Lessons Learned		5. Report Date January 2007	
		6.	
7. Author(s) Derek Tompkins & Lev Khazanovich		8. Performing Organization Report No.	
9. Performing Organization Name and Address Dept. of Civil Engineering University of Minnesota 500 Pillsbury Drive SE Minneapolis, MN 55455		10. Project/Task/Work Unit No.	
		11. Contract (C) or Grant (G) No. (c) 81655 (wo) 175	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes http://www.lrrb.org/PDF/200706.pdf			
16. Abstract (Limit: 200 words) The Minnesota Department of Transportation (MnDOT) began construction on the Minnesota Road Research Project (MnROAD) in 1991 and opened the full-scale pavement research facility to live traffic in 1994. Since the time of its construction, MnROAD, the first major test track since the AASHO Road Test of the 1950s and 1960s, has learned a number of lessons on behalf of the greater pavement community. As part of completing the first phase of MnROAD (its first ten years of operation), researchers at the University of Minnesota reviewed the many products of MnROAD's first phase. The Lessons Learned project involved over fifty interviews, three hundred published and unpublished reports, papers, and briefs, and an online survey of pavement professionals. This report presents an overview of MnROAD products of interest at the local, state, and national levels. Furthermore, the report provides extensive references for these products in hopes of increasing awareness of MnROAD's under-publicized contributions to pavement engineering.			
17. Document Analysis/Descriptors pavement database, cold regions, accelerated pavement testing, full-scale experiments, test track expertise, pavement design, pavement modeling		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 63	22. Price

MnROAD Lessons Learned

Final Report

Prepared by:

Derek Tompkins
Pavement Research Institute
University of Minnesota

Lev Khazanovich
Department of Civil Engineering
University of Minnesota

January 2007

Published by:

Minnesota Department of Transportation
Research Services Section
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the Minnesota Department of Transportation and/or the Center for Transportation Studies. This report does not contain a standard or specified technique.

The authors and the Minnesota Department of Transportation and/or Center for Transportation Studies do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to this report.

Acknowledgements

The UM research team would like to thank all subjects for their candor and willingness to participate in interviews and surveys. Furthermore, the work in the technical briefs and final report is particularly indebted to Tom Burnham, Tim Clyne, Shongtao Dai, Bernard Izevbekhai, Maureen Jensen, Dave Johnson, Marc Loken, John Pantelis, John Siekmeier, and Ben Worel of the Mn/DOT Office of Materials for their reviews of early drafts and/or provision of materials for research.

Table of Contents

Chapter 1. Introduction.....	1
1.1. MnROAD Lessons Learned Project.....	2
1.2. Additional MnROAD Objectives in Research.....	3
1.2.1. Test Track Expertise.....	3
1.2.2. Pavement Rehabilitation and Maintenance.....	3
1.2.3. Non-pavement Topics.....	4
Chapter 2. Overview of MnROAD Products.....	5
2.1. Database.....	5
2.2. Test Track Expertise.....	8
2.2.1. Instrumentation.....	8
2.2.2. MnROAD Construction and Materials.....	8
2.2.3. Data Acquisition and Verification.....	8
2.2.4. Forensic Trenching.....	9
2.3. Research.....	10
Chapter 3. Highlights of MnROAD Phase 1.....	11
3.1. Seasonal Variation in Pavements, Spring Load Limits, and Winter Overloads...	11
3.2. MnPAVE.....	11
3.3. Verification of and Contributions to Mechanistic-Empirical Design Methods and Pavement Models.....	12
3.4. MnROAD and the Mechanistic-Empirical Pavement Design Guide.....	12
3.5. Thermal Cracking.....	13
3.6. Whitetopping.....	13
3.7. SafeTruck.....	13
3.8. Adoption of New Products.....	14
3.9. Edge-joint Sealing.....	15
3.10. Non-pavement Research.....	15
3.11. Aggregate Road Research.....	16
3.12. Oil Gravel Road Research.....	17
3.13. Low-volume Road Design.....	17
Chapter 4. Assessment of MnROAD Phase 1.....	18
4.1. Perspectives from Surveys and Interviews.....	18
4.2. Intangible Benefits.....	18
4.2.1. Pioneer of Second-generation Test Tracks.....	18
4.2.2. Education in Pavement Engineer.....	19
4.3. MnROAD Partnerships.....	20
4.3.1. Local Road Research Board.....	20
4.3.2. Out-of-state Agencies.....	20
4.3.3. Industry.....	21
Chapter 5. Conclusions about MnROAD Phase 1.....	22
5.1. Suggestions for Database.....	22

5.2. Suggestions for Data Analysis.....	23
5.3. Suggestions for Reporting and Research.....	24
5.4. Other Recommendations.....	25
References.....	26
Appendix A. Survey/Interview Subjects for the Lessons Learned Project	
Appendix B. Survey and Interview Questionnaire	
Appendix C. Summary of Survey/Interview Responses	
Appendix D. Suggestions for Future Research	
Appendix E. Lessons Learned Technical Briefs	
E.1. Overview of MnROAD Reports	
E.2. Guide to the MnROAD Database	
E.3. Educational Benefits of MnROAD	
E.4. MnROAD and the Adoption of New Products in Pavements	
E.5. Low Temperature Cracking Performance at MnROAD	
E.6. Mechanistic-Empirical Design and MnROAD	
E.7. MnROAD Mainline IRI Data and Lane Ride Quality	
E.8. Drainage and Pavement Performance	
E.9. MnROAD Observations on Low Volume Roads	
E.10. MnROAD Lessons Learned: Thin and Ultra-thin Concrete Overlays	
E.11. Non-pavement Research at MnROAD	
E.12. Climate Research at MnROAD	
List of Tables	
Table 1.1. Data collected at MnROAD.....	7

Executive Summary

In 1991 Minnesota Department of Transportation (Mn/DOT) officials broke ground near Albertville, Minnesota, for the construction of the Minnesota Road Research Project (MnROAD), a full-scale pavement test facility consisting of a 3.5-mile interstate roadway and a 2.5-mile low-volume roadway. To monitor pavement response and environmental conditions in each test cell, Mn/DOT installed over 4500 sensors in the pavement test cells to monitor pavement response and environmental data during the construction of these cells.

The effort Mn/DOT invested into the planning and construction of MnROAD was considerable given the fact that MnROAD was the first full-scale pavement test track since the American Association of State Highway Officials (AASHO) Road Test of the early 1960s. For this reason, a great deal of MnROAD's construction and instrumentation were closely monitored, recorded, and preserved by Mn/DOT engineers. This experience placed MnROAD at the forefront of the second generation of test tracks (those that follow the AASHO Road Test), even before MnROAD had opened to traffic in August 1994. Since that time MnROAD has been the site of a number of significant experiments in pavement engineering and other pavement-related fields.

The MnROAD Lessons Learned project was commissioned in 2005 by Mn/DOT and undertaken by the UM research team. The project involved a significant literature review component in which nearly 300 documents related to MnROAD were reviewed by the UM research team. These documents included:

- Reports, conference proceedings, and papers that involve MnROAD research or data in a substantial manner,
- Technical briefs that detail ongoing MnROAD experiments,
- Unpublished reports from Mn/DOT on MnROAD research or data,
- Published and internal reports on MnROAD's planning stages, and
- Procedural guides for MnROAD testing and operations.

As a part of early information gathering, the Lessons Learned project also consisted of interviews and surveys of professionals in pavement engineering. The results of these interviews and surveys are discussed in Chapter 4 of the report.

After the literature review and interviews, the UM research team determined that, in addition to the original fourteen research objectives established for MnROAD in its design stages, MnROAD's first decade of operation also involved a great deal of effort in three particular areas:

1. Characterizing the MnROAD project (test track expertise)
2. Pavement rehabilitation and maintenance
3. Non-pavement research.

These new objectives are discussed within Chapter 2 of this final report to provide an idea of the work not anticipated by MnROAD's original fourteen objectives.

One of the earliest efforts of the Lessons Learned project was the adoption of the term "products" instead of "research" to refer to the work done at the MnROAD facility. Chapter 2 of the final report describes MnROAD products as falling into one of three categories, which are: database; test track expertise; and research. These products are described in Chapters 2 and 3 of the final report using extensive references.

Given the volume and extent of research completed in MnROAD's first ten years, this final report discusses that research in terms of highlights of MnROAD research. Chapter 3 addresses the highlighted research topics, which are:

1. Seasonal Variation in Pavements, Spring Load Limits, and Winter Overloads
2. MnPAVE
3. Verification of and Contributions to Mechanistic-Empirical Design Methods and Pavement Models
4. MnROAD and the Mechanistic-Empirical Pavement Design Guide
5. Thermal Cracking
6. Whitetopping
7. SafeTruck
8. Adoption of New Products
9. Edge-joint Sealing
10. Non-pavement Research
11. Aggregate Road Research
12. Oil Gravel Road Research
13. Low-volume Road Design

Though each section of Chapter 3 cites the work of a number of reports, these highlights do not begin to exhaust the number of references available for the Lessons Learned project. The desire in discussing so-called highlights is to address the more substantial reports in discussing both MnROAD's well-known products and its lesser-known work as well. In addition to the body of the report addressing certain highlights, the UM research team and Mn/DOT personnel produced twelve technical briefs that describe underreported products to emerge from MnROAD's first decade of operation. The abstracts for each of the twelve briefs are presented in Appendix E.

The final report concludes by evaluating MnROAD's influence on pavements in Minnesota and throughout the nation. While room for improvement exists, most noticeably, in MnROAD's database and data analysis efforts, MnROAD made a number of valuable contributions to pavement engineering that justified MnROAD altogether. Finally, the UM research team concludes the final report by noting the need for MnROAD to select a focus for itself and pursue and market this focus aggressively in order for MnROAD to increase its visibility at the national level.

Chapter 1

Introduction

In the 1980s, the Minnesota Department of Transportation (Mn/DOT) explored the idea of a Cold Regions Pavement Research Test Facility (CRPRTF), which led to a task force that consisted of Mn/DOT engineers and officials, Federal Highway Administration (FHWA) and Strategic Highway Research Program (SHRP) administrators, representatives of industry, and consultants from universities. In May 1987, the task force settled upon proposed interstate and low-volume test section plans for what would be called the Minnesota Road Research Project (MnROAD) (1). The plans were then unveiled in a number of reports by Dr. Matthew Witczak, a consultant to the CRPRTF Task Force (2,3).

Concurrent with the development of test section plans was the focus of the task force, with the specific assistance of Dr. Witczak, the University of Minnesota (UM), and Mn/DOT engineers, on research objectives for MnROAD. This early focus on research led to the determination of the following fourteen objectives for MnROAD:

1. Evaluate empirical design methods;
2. Evaluate mechanistic design methods;
3. Develop mechanistic models;
4. Verify/improve frost prediction methods;
5. Investigate axle loads and pavement performance under spring thaw;
6. Develop vehicle load damage factors;
7. Investigate vehicle gearing/tire systems and pavement performance;
8. Investigate asphalt mixes and related pavement distresses/performance;
9. Investigate base/subbase properties and flexible pavement performance;
10. Investigate base/subbase properties and rigid pavement performance;
11. Investigate subgrade type and pavement performance;
12. Improve roadway instrumentation;
13. Examine “special design variables” in rigid pavements; and
14. Investigate level of reliability and associated variation in pavement performance (4).

Having both construction and research plans, various government and Mn/DOT officials broke ground near Albertville, Minnesota, in 1991 for the construction of a 3.5-mile interstate roadway and a 2.5-mile low-volume roadway, each roadway consisting of test sections and over 4500 sensors monitoring pavement response and environmental data.

The interstate roadway, or the mainline, is subjected to live traffic redirected from westbound traffic on US Interstate 94, while the low-volume road is subjected to a controlled 5-axle loading of 80 kip in one lane and 102 kip in the other. The MnROAD facility opened to traffic in August 1994, and as of December 31, 2003, the mainline flexible test sections received roughly 5 million Equivalent Single Axle Loads (ESALs) and the mainline rigid sections received approximately 7.8 million ESALs. Specifics of MnROAD’s traffic and its test sections through its first ten years can be found in summary reports such as Newcomb et al., the Minnesota Department of Transportation’s biennial MnROAD reports, and Worel (5-8).

The test sections at MnROAD were initially constructed as an overall structural experiment. However, these sections were not designed with the same intent. While the hot-mix asphalt (HMA) sections were designed to determine the structural performance of the entire pavement system, the structural component of the concrete (PCC) sections in question was

doweling and joint spacing. For this reason, these early 5 and 10 year sections performed differently. The performance of these sections provided a number of lessons, the foremost of which was for MnROAD's benefit: these sections—the HMA in particular—showed that the structural experiment would not go as planned. Instead, MnROAD's focus would become an environmental experiment. These points will be discussed later in the report.

1.1 MnROAD Lessons Learned Project

The MnROAD Lessons Learned project was commissioned in 2005 by Mn/DOT and undertaken by the UM research team. The aim of the project was to review MnROAD's first ten years of operation as Mn/DOT planned the Phase II reconstruction of the MnROAD facility. The project involved a significant literature review components in which nearly 300 documents related to MnROAD were reviewed by the UM research team. These documents included:

- Reports, conference proceedings, and papers that involve MnROAD research or data in a substantial manner,
- Technical briefs that detail ongoing MnROAD experiments,
- Unpublished reports from Mn/DOT on MnROAD research or data,
- Published and internal reports on MnROAD's planning stages, and
- Procedural guides for MnROAD testing and operations.

These documents as a whole are an impressive library of pavement research and test track knowledge. Most of the documents were made available to the UM research team through the cooperation of the Mn/DOT Office of Materials, and these documents included many internal documents that Mn/DOT never officially published.

As a part of early information gathering, the Lessons Learned project also consisted of interviews and surveys of professionals in pavement engineering. The UM research team conducted 36 interviews with Mn/DOT employees and persons in pavement research who were closely involved with MnROAD at some time in its first ten years. These interviews were based on a Mn/DOT-approved questionnaire, but subjects were encouraged to work beyond the questionnaire and discuss and critique MnROAD with as much candor as they desired. The online survey of researchers and practitioners in pavements was concluded in August 2006. The survey concerned the survey subjects' awareness of MnROAD and their use of MnROAD products in their work. The online survey filled out by survey subjects is provided in the appendices to the report. Although only 24 of 200 pavement professionals contacted responded to the survey, these responses were very valuable to ongoing Lessons Learned activities. Some of the more instructive responses were used as testimonials in presentations. The Lessons Learned team contacted particularly helpful respondents for additional insight on existing research and potential research.

The UM research team paid careful attention to any suggestions that surveys or interview subjects had for new research with existing data or potential research and experiments for the second phase of MnROAD. This investigation resulted in many suggestions, all of which are included in Section 4 of this report.

The Lessons Learned project included the production of a number of technical briefs and a final report. The UM research team was responsible for the technical briefs and the final report. Each of the UM-composed technical briefs highlighted underpublicized work at MnROAD, and the technical advisory panel for the Lessons Learned project developed the topics for the UM briefs and a MnROAD contact for each topic. These topics were:

1. IRI and Lane Ride Quality

2. Drainage
3. Low Volume Roads
4. Educational Benefits
5. Non-pavement Research
6. New products
7. Overview of MnROAD Reports
8. Instrumentation
9. Climatic Studies
10. Mechanistic-Empirical Design

In addition to the UM topics, the technical advisory panel assigned a number of topics to MnROAD engineers in hopes of stimulating additional technical briefs to complement those of the UM research team. In response to this initiative, MnROAD engineers produced a technical brief in three topics: the MnROAD database, thermal cracking in hot-mix asphalt (HMA) pavements, and whitetopping. These briefs will be mentioned again in sections to follow, and the titles and abstracts of all of the technical briefs produced for the Lessons Learned project are included in Appendix E.

1.2 Additional MnROAD Objectives in Research

Another product of the Lessons Learned project was a reaction to Mn/DOT's desire to better understand its research and reporting in terms of its original fourteen objectives. After the review of hundreds of published and unpublished MnROAD-related reports, papers, and briefs, the MnROAD Lessons Learned project determined that, in addition to the fourteen research objectives presented above, MnROAD's first decade of operation also involved a great deal of effort in three particular areas:

4. Characterizing the MnROAD project (test track expertise)
5. Pavement rehabilitation and maintenance
6. Non-pavement research.

These new objectives, which will be discussed throughout this report, are summarized below to provide an idea of the work not covered by MnROAD's original fourteen objectives in Newcomb et al. (4).

1.2.1 Test Track Expertise

One point not considered by the original objectives was the volume of original work MnROAD engineers would do in establishing the MnROAD test track itself. Much of the construction and instrumentation on MnROAD became as much a concern for MnROAD engineers as the research conducted using MnROAD, and as a result a many early reports specify instrumentation or materials, typify subgrade soils, or detail testing procedures. As MnROAD was the first test track since the AASHO Road Test of the 1960s, many of the current-day test tracks rely heavily on MnROAD's pioneering efforts in instrumentation, construction, data collection, and testing procedure.

1.2.2 Pavement Rehabilitation and Maintenance

While it may seem odd that MnROAD did not include rehabilitation and maintenance in its original research objectives, those objectives were, as mentioned above, focused on new construction and verifying existing design models. However, after the test sections at MnROAD experienced a few Minnesota winters and the effects of low-temperature thermal cracking, it

became immediately clear to MnROAD that a great deal of MnROAD's research would be in rehabilitation and maintenance, the responses of a pavement system to cold-regions conditions, and investigations into low-temperature cracking.

1.2.3 Non-pavement Topics

The final additional objective of MnROAD research is the use of the MnROAD facility for non-pavement research. While a few non-pavement experiments conducted at MnROAD could have been conducted elsewhere, a large majority existed only because the unique properties of MnROAD provided a laboratory not otherwise available. As MnROAD matured, more researchers outside of pavements became aware of MnROAD's abilities as a site for non-pavement experiments and used MnROAD for topics such as Mn/DOT's Intelligent Transportation System (ITS) program or the recent demonstrations of continuous compaction control.

Chapter 2

Overview of MnROAD Products

One of the earliest efforts of the Lessons Learned project was the adoption of the term “products” instead of “research” to refer to the work done at the MnROAD facility. Members of the technical advisory panel for the project rightfully pointed out that MnROAD’s benefits to pavements go beyond research, which typically is valued in terms of papers or reports published. MnROAD was also very active in its first ten years in supporting other researchers with MnROAD data and other test tracks by sharing their experiences. Hence, MnROAD products are considered to be data, research, and test track knowledge, and the following sub-sections detail these products.

2.1 Database

The MnROAD database is one of the main products of MnROAD’s first decade of operation. It contains valuable information for in-depth pavement research studies for cold climates. To help familiarize the reader with the MnROAD database, its size and impact will be compared with the premier database in the United States for pavement performance data, the Long-Term Pavement Performance (LTPP) database (9, 10). While both databases relate to pavement performance, they have some important differences.

The LTPP database is extremely large and contains data from many sections throughout the county, and since making its database more readily available, the LTPP database has become the primary source of field data for pavement researchers. Pavement sections in the LTPP database are found throughout North America, and these sections vary in a number of ways, such as climate, construction practice, material, etc. Furthermore, many of the sections were constructed long before inclusion in the LTPP database was a goal for a given pavement, and as a result the record keeping for the test sections (traffic assessments, construction records, etc.) may be limited.

The majority of LTPP sections are not instrumented, and as a result they are normally monitored no more than once per year on a basis that is not necessarily regular. As a result of the testing interval “scatter,” missing records, and the age of these sections, the LTPP data, while voluminous and widely used, can be difficult if a researcher desires specific, focused information for a given pavement or set of pavements. For instance, while the LTPP was a great source for the national calibration of the Mechanistic-Empirical Pavement Design Guide (MEPDG), it did not provide in-depth information required for local calibration of the mechanistic-empirical design procedures or validation of specific models in the MEDPG.

On the other hand, while the MnROAD database does not have the sheer volume of test sections and data of the LTPP database, in many other aspects it offers an interested researcher many benefits not available through LTPP. The construction of all MnROAD cells is closely monitored, and data to characterize the pavement system across a number of variables is readily available. Furthermore, a wide spectrum of dynamic response data characterizing very narrow intervals in time is available for each section, and the same spectrum is available for data from regular monitoring of the sections. Where MnROAD lacks the global amount of data as found with LTPP’s many test sections, it makes up for this by offering a wealth of construction, performance, material properties, and response data on any of MnROAD’s test sections. For this reason, MnROAD’s in-depth data has already been incorporated into the MEPDG, and

MnROAD's store of data is used by professionals in pavements and pavement research throughout the world.

As a result of an evaluation of various data collected at MnROAD and the storage of this data, the research team suggested the development of the *Guide to the MnROAD Database*, a reference document developed by Ben Worel, Operations Engineer at MnROAD (11). This brief describes the types of data being collected at MnROAD and the sensors or tests used to acquire each type of data. Furthermore, the brief lists these data types in a data table and details a few types of data and the methods of data collection for those examples.

As detailed in Worel, the MnROAD database contains records on over 300 types of data values that include load response sensor data, traffic monitoring, field monitoring, materials testing, environmental/climatic information, and general test cell information. Some of the values collected for each type of data value span as many as ten full years (and counting) and give the most complete data history of the phenomenon being monitored available from any test track facility. In addition to monitoring and maintaining the thousands of sensors used to collect response and environmental data, the *Guide* summarizes each of the 17 monitoring tests conducted by MnROAD, including Ground Penetrating Radar tests, pavement cores, and laboratory testing. MnROAD is without equal among test tracks and pavement databases in both the volume and breadth of data maintained.

The aim of Worel is then to give a brief "big picture" appreciation for the wide variety of data being collected at MnROAD, and it will be an excellent starting point for researchers who look to MnROAD for possible data. One of the problems that preceded the introduction of Worel to the MnROAD website was that a relative novice to MnROAD could have difficulty in determining if MnROAD had usable data and requesting that data in as efficient a manner as possible. Table 1 provides a brief summary of the many types of data regularly collected at MnROAD.

Table 1. Data collected at MnROAD (11)

<i>Subject Area</i>	<i>Data Type</i>	<i>Examples of Data Collected at MnROAD</i>
Cell Info	Cell Data	Design, Construction, Maintenance, Cell Layer/Lift Thickness, Cell Events, Elevations, GIS Data
Field Monitoring	Rutting	Straight Edge, Automated Laser Profile System (ALPS), Paper Traces, Pathways, PaveTech, Dipstick
	Ride	Pathways, PaveTech, Frost Pins, Faulting, Forensics, Friction
	Cracking	Distress Surveys, Crack Mapping, Cupping
	Strength	Dynamic Cone Penetrometer (DCP), Falling Weight Deflectometer (FWD)
Sensor Data	Pavement	Biaxial Strain Gage (BS), Concrete Embedment Strain Gage (CD, CE), Linear Variable Differential Transducer (DT), Horizontal Clip Gage (HC), Longitudinal Embedment Strain Gage (LE), Transverse Embedment Strain Gage (TE), Piezo-Accelerometer (PA), Dynamic Soil Pressure Cell (PG, PK), Steel Strain Gage (SS), Tiltmeter (TM), Vibrating Wire Strain Gage (VW)
	Subsurface	Subsurface Thermocouple (TC), Moisture Block (WM), Dynamic Pore Water Pressure Cell (DW), Thermistor (XD, XL, XT, XS), Open Stand Pipe (OS), Static Lateral Pressure Cell (PL), Static Soil Pressure Cell (PT), Resistivity Probe (RP), Static Pore Water Pressure Cell (SW), Tipping Bucket (TB), Time Domain Reflectometer (TD)
	Traffic	Mainline and LVR installations of Hydraulic Load cells, Kistler sensors
Lab Testing	Bituminous	Bituminous Dynamic Shear Rheometer, Bending Beam Rheometer, Direct Tension, Repeated Creep, Zero Shear Viscosity, Dynamic Modulus, Indirect Tension Test, Fracture Toughness, Mix Designs, Gradations
	Concrete	Concrete Air Voids, Compression, Coefficient of Thermal Expansion, Poisson's Ratio, Mix Designs
	Unbound	Resilient Modulus, Proctor Curves, Field Density, Gradations, Unsaturated Material Properties

2.2 Test Track Expertise

The challenge of forging a new path through the thirty years of changes to come about since the AASHO Road Test meant that MnROAD had many lessons for test tracks and pavements to come. MnROAD test track expertise was utilized in other major pavement test track facilities, such as WesTrack, the National Center for Asphalt Technology (NCAT), and the SHRP test road in Ohio. Officials from these and many other facilities have toured MnROAD and consulted with MnROAD engineers about the MnROAD facility itself. The willingness of MnROAD to offer information openly to all interested parties, be the subject test track expertise, data, or research, is the most significant benefit of its first ten years of operation. Some of the reports in MnROAD's many areas of expertise are detailed in Sections 3.1.1-3.1.5.

2.2.1 Instrumentation

MnROAD engineers involved in the construction and installation of sensors at the MnROAD site had the foresight to closely detail their experience in Mn/DOT reports, exemplified by reports such as Baker et al. (12). This report presented step-by-step installation procedures for 16 surface sensors installed at MnROAD to collect data on the test sections. The report also describes testing procedures to verify the operation of the 16 surface sensors and check for any malfunctions. The report also discusses the survivability of the sensors and possible sources of sensor failure.

Due to the large amount of sensors installed at MnROAD (over 4500), MnROAD gained considerable insight into the actual sensor life spans and durability to compare with the claims of manufacturers. Later work at MnROAD dealt with the problem of sensor failure, which MnROAD experienced on a large scale. One of the more prominent studies into this problem was conducted by MnROAD engineers and detailed by Burnham (13). This paper came about due to the failure of the original sensors embedded in MnROAD's concrete test sections. To replace these sensors, MnROAD engineers had to determine the orientation of the original sensors. In doing so, MnROAD engineers discovered that the in-situ position of the sensors differed greatly from the position intended for them in the original design. Once a feasibility study was concluded for retrofitting the failed sensors, MnROAD engineers installed new sensors into holes in the test sections from full-depth coring. These new sensors were then subjected to loading and monitored to determine if retrofitted sensors provided reliable data on loading. In this case, the engineers involved felt that the data collected by these new sensors was at least as accurate as the data collected by the original sensors and thus would be effective (13).

Reporting on MnROAD's instrumentation for both the dynamic response data collection and for the environmental sensors continued well through its first ten years, though only a few of these later reports were formally published. Some of these reports deal with instrumentation as an incidental topic to a larger issue within the paper or report, while others deal with instrumentation or an evaluation of a possible field instrument directly. The later reports that were formally published include Wang, Baker and Burnham, and Clyne et al. (14-16).

2.2.2 MnROAD Construction and Materials

At the time of its construction and shortly thereafter, MnROAD engineers conducted extensive testing and assessments of the components of each pavement system in each test section. Properties and observations on everything, from the subgrade to the aggregate in the various layers of the system to the weather conditions on a given construction day, were dutifully noted in a number of Mn/DOT reports. These reports, which exist not only for the early sections but

for most every section constructed since the beginning of MnROAD, are a library of road test expertise, and they continue to serve researchers today as a resource of material properties and characteristics in MnROAD's test sections.

Reports that characterize properties of the subgrade and/or base materials include Burnham and Johnson, Newcomb et al. (1994), Burnham, Newcomb et al. (1996), Berg et al., Bigl et al., Dai and Van Deusen, Dai and Zollars, and Gupta et al. (17-25). Reports that characterize the properties of the surface course include Stroup-Gardiner and Newcomb, Huhtala et al., Saarentko, Reinke, Adams et al., and Clyne et al. (26-32). The aforementioned planning reports by Witczak and DAMA, Inc. along with later reports by Burnham, Vandenbossche and Rettner, and Vandenbossche all act as good examples of reports that categorize the planning and construction of test sections (1-3, 13, 33, 34).

In addition to cataloging material properties, MnROAD engineers also made careful notes on the manner of testing used to determine material properties. For example, some of MnROAD's tests lead Mn/DOT to use the dynamic cone penetrometer (DCP) for use in the field, which is discussed in Section 3.8. Almost all of the reports detailed in the previous paragraph provide outstanding procedural sections in which the authors discuss the benefits and shortcomings of the tests applied.

2.2.3 Data Acquisition and Verification

The database at MnROAD is one of the main products of MnROAD's first decade of operation. MnROAD offers a wealth of construction, performance, material properties, and response data on any of MnROAD's 30-40 test sections. For this reason, MnROAD's in-depth data has already been incorporated into the MEPDG. MnROAD's array of constitutive data has been used in research by the Finnish National Road Administration (FINRA) in laboratory tests on asphalt mixes, by the US Army Corps of Engineers Cold Regions Research and Engineering Lab (CRREL) in testing of frozen soils and modeling of frost depths in subgrades, and by state departments of transportation and universities around the nation in a wide variety of research.

The processes of acquiring and verifying data were carefully studied and monitored in MnROAD's first decade of operation. One of the earliest reports to do so, by Cochran et al., describes the techniques used for the manual, non-automated observational data collected at MnROAD (35). Later reports typically allude to procedural testing for non-automated data; however one example that details these procedures specifically is Burnham (36). While many of the documents dealing with the automated acquisition of data from sensors are now unrelated to MnROAD's existing data acquisition and calibration procedures, they are a history left behind to evidence the considerable work that went into collecting dynamic response and environmental data at MnROAD. Those reports by Dogru et al., Dai and Van Duesen, Van Duesen, Lau and Alouini, Koubaa and Stolarski provide an excellent overview of MnROAD's experience in data acquisition and verification (37-41). The most recent of these documents, by Lau and Strommen, illustrates the development of and existing calibration procedures for MnROAD's data acquisition system (42). For more information on MnROAD's experience in data acquisition, consult the aforementioned technical brief on the MnROAD database by Worel (11).

2.2.4 Forensic Trenching

One of the advantages of the MnROAD facility is that it may divert live traffic to conduct extended investigations of test sections in a safe working environment. Outside of the removal of old test sections and the reconstruction of new test sections, no endeavor used this advantage

more than the forensic trenching done by MnROAD engineers. The forensic trenching done at MnROAD, described in reports by Isackson et al. and Mulvaney and Worel, contains many interesting insights on rutting and the structural importance of the base and subbase layers (43-45). As will be mentioned in the following sections, MnROAD's work in trenching has distinguished its rutting data from that of other test tracks, and according to researchers working on NCHRP 1-40D, MnROAD's trenching data has been instrumental in calibrating the predictive abilities of the MEPDG in predicting the rutting in the lifts of an asphalt pavement system.

2.3 Research

MnROAD has been the site of a number of experiments in pavement-related issues and has been the main source of data for hundreds of research projects in pavements. These projects have involved professionals in pavements from the world over. As the extent of research is quite comprehensive, and a more in-depth discussion of some of this research and reporting is contained in Section 3. Furthermore, MnROAD partners in research will be alluded to throughout Section 3 and discussed directly in Section 4.

Chapter 3

Highlights of MnROAD Phase 1

The following topics are a selection of issues in pavements that were addressed by MnROAD research and data in its first ten years of operation. Though each section cites the work of a number of reports, these highlights do not begin to exhaust the number of references available for the Lessons Learned project. The hope here is to touch on the more substantial reports in discussing both MnROAD's well-known products and its lesser-known work as well.

3.1 Seasonal Variation in Pavements, Spring Load Limits, and Winter Overloads

One of MnROAD's most publicized benefits to the state of Minnesota has been in the field of seasonal variations in pavements. This topic was covered in a number of thorough reports in 1999-2000. Using data from MnROAD, Ovik et al. conducted a close analysis of the moduli in various layers of a flexible pavement system. In doing so, the researchers divided the calendar year into five distinct seasons for the purposes of predicting the stiffnesses of layers in a mechanistic-empirical design method specific to Minnesota. This so-called fifth season falls during the early spring-thaw period, when an excess of moisture is present and the granular base has a minimal resilient modulus (46).

This innovation in the approach to pavement and environment led to legislation concerning spring load restrictions for Minnesota's roadways (47, 48). The Mn/DOT Office of Materials and Road Research continued to apply Ovik's understanding of seasonal variation in flexible pavement systems to new winter load limits for Minnesota's roadways (49). Ovik et al. continues to raise interesting questions at Mn/DOT outside of seasonal variation: for instance, some limited data in the report suggests a comparison of Mn/DOT Base Classes 3, 4, 5, and 6 that many Mn/DOT officials feel could be the starting point of necessary research as aggregate shortages become more problematic in the state of Minnesota (46).

3.2 MnPAVE

MnROAD's first contribution to a mechanistic-empirical design specific to Mn/DOT was with the thickness design program ROADENT developed by UM. Using the WESLEA model for layered elastic analysis as its basis, university researchers used low-volume road (LVR) data from MnROAD to verify and calibrate ROADENT, a thickness design program for flexible pavements (50-52). The calculated strains from the program were compared to the actual strains as captured by the many embedded sensors in the test sections. ROADENT was continuously calibrated in this way so that performance predictions by ROADENT would reflect the performance observed at MnROAD's full-scale LVR test sections. Later research recommended that the Soil Factor and R-Value design procedures for low-volume roads be reconsidered, as ROADENT required a thicker design than the other two for an equivalent roadway. This conclusion was significant for local agencies, most of whom used either the Soil Factor or R-Value design in planning their roadways, and the foundation of this conclusion was, of course, years worth of MnROAD LVR data.

In response to their own work in seasonal variations in pavements, Mn/DOT and UM researchers later developed MnPAVE, a mechanistic-empirical design software program with its basis in ROADENT but with many layers of additional sophistication. MnPAVE was developed using MnROAD performance data and, to a lesser extent, data from Minnesota highway sections

(53, 54). Later Mn/DOT reports by Skok et al. builds upon the earlier work in LVR design by updating flexible pavement design for Minnesota using MnPAVE (55, 56). These reports are the basis for a reliable, consistent design based upon local environmental data and pavement response data from MnROAD.

3.3 Verification of and Contributions to Mechanistic-Empirical Design Methods and Pavement Models

Much of the early work at MnROAD consisted of characterizing the pavement systems in each of the test sections. An early partnership between MnROAD and CRREL involved the use of MnROAD data characterizing its test sections to predict the performance of these test sections according to the CRREL mechanistic-empirical model for cold regions pavements (57, 58). Other early work by Berg used MnROAD data to calibrate a frost depth prediction model (59).

A significant project at MnROAD by Thomas Burnham and William Pirkl involved the application of data characterizing concrete test sections to the Mn/DOT rigid pavement design guidelines, the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO-93), and the 1984 Portland Cement Association Thickness Design for Concrete Highway and Street Pavements (PCA-84). Burnham and Pirkl found that the predicted serviceable life of each test section was highly variable as the researcher moved between design methods and levels of reliability (60). The gross inaccuracies of these models and the discrepancies between their predictions as exposed by Burnham and Pirkl's study was the first major use of full-scale test track data to evaluate existing pavement design methods, and this particular study illustrated that the design methods of the early 1990s were inadequate.

A number of researchers at universities have taken advantage of MnROAD data to conduct wide-ranging activities in:

- calibrations of finite element structural models;
- validations of mechanistic-empirical design parameters and methods;
- the development of models to predict low-temperature cracking performance of asphalt pavements;
- evaluations of drainage models for pavement systems; and
- investigations of tire-induced stresses and surface-initiated cracks.

These reports include and are not limited to the work of Alvarez and Thompson, Ariza and Birgisson, Bao, Forst, Holewinski et al., Mateos and Snyder, Soon et al., Wu et al., and Zhang et al. (61-70).

3.4 MnROAD and MEPDG

As documented in NCHRP 1-40D (report to be published in late 2006), MnROAD contributed a significant amount of MnROAD data and pavement expertise to the mechanistic-empirical design procedure under NCHRP Project 1-37A that is commonly known as the Mechanistic-Empirical Pavement Design Guide (MEPDG) (71). To calibrate the MEPDG's ability to predict rutting in the lifts of an asphalt pavement, the MEPDG team used forensic trenching data from trench studies done on MnROAD test sections and described in the aforementioned reports by Isackson et al. and Mulvaney and Worel (43-45). Furthermore, the thermal cracking model used by the MEPDG was calibrated using MnROAD thermal cracking. PCC performance and temperature data were also used to re-calibrate the rigid models of the MEPDG and verify the Enhanced Integrated Climatic Model (EICM) predictions respectively.

3.5 Thermal Cracking

As soon as MnROAD engineers had watched Minnesota winters wreak havoc on the binders in the hot-mix asphalt (HMA) test sections, these engineers understood the importance of MnROAD as a cold-regions facility and immediately began making close observation of low-temperature, or thermal, cracking in the HMA test sections. Test section assessment reports by Palmquist, Worel et al., Palmquist et al., and Zerfas describe in detail the damage done by the Minnesota's climatic extremes (72-76).

Two example reports of authors using MnROAD material and thermal cracking data to evaluate or develop thermal cracking models. Waldhoff et al. described the use of MnROAD data to verify the predictions of the Superpave Indirect Tensile Test (77). More importantly, using MnROAD's as-built and material properties, Waldhoff compared the predictions of the Superpave thermal cracking model (TCMODEL) with observed cracking at MnROAD to suggest revisions for TCMODEL. Near the conclusion of MnROAD's first ten years of research, Marasteanu et al. conducted the first major research for Mn/DOT that uses MnROAD data to attempt to model and account for the thermal cracking observed at MnROAD (78).

MnROAD's interest in preventing thermal cracking has led to a partnership with the Finnish National Road Administration (FINRA) and experiments into new materials such as emulsified oil-gravel surfaces, which have proved to be more resistance to thermal cracking than typical HMAs. MnROAD's experience in oil gravel is detailed in Section 3.12. More detailed information on MnROAD experience in low temperature cracking is contained in the Mn/DOT technical brief by Clyne (79).

3.6 Whitetopping

The process of overlaying asphalt pavements with thin concrete layers, known as whitetopping, is one that has been studied by Mn/DOT since 1993 and at MnROAD since 1997. Since that time, Mn/DOT engineers at the Office of Materials and Road Research have produced a variety of reports and presented many papers on the design and construction of whitetopping. These reports detail MnROAD's experience with a variety of full-scale thin and ultra-thin whitetopping designs in both high- and low-volume trafficked MnROAD test sections over a three and a half year period (80, 81). Mn/DOT researchers have also been involved in a number of whitetopping experiments on highways and low-volume roads around Minnesota that borrow their design, construction, and repair techniques from MnROAD test section experience (33, 34, 82). MnROAD has also been in the enviable position of being able to use its wide array of load response sensors to monitor the performance of these thin concrete slabs in real-time (83).

In the course of the four years between 1993 and 1997, MnROAD engineers went from having little to no whitetopping experience to being a national leader in the design and construction of whitetopped pavements. After MnROAD's first ten years, MnROAD engineers are excited about the possibility of creating a design method for thin and ultra-thin concrete overlays based on MnROAD's extensive experience. For more detail on MnROAD's experience in whitetopping, please consult the Mn/DOT technical brief by Burnham (84).

3.7 SafeTruck

The establishment in 1991 of the Minnesota Guidestar program, a cooperative initiative between Mn/DOT, the Federal Highway Administration, UM, and other members, ensured that work in intelligent transportation systems (ITS) would become a key area of interest for engineers in transportation-related fields in Minnesota throughout the 1990s. Some of the more noticeable

non-pavement issues investigated at MnROAD have been assistive or autonomous vehicle guidance systems and the technologies associated with those systems. These issues arose out of Mn/DOT and MnROAD's combined need for driver-assist technologies to ensure the safety of the operator of the truck that provides the load repetitions on the low-volume road at MnROAD (85).

In addition to the impetus for this project coming from a specific MnROAD need, MnROAD's ability to control traffic flow to maintain a safe testing environment made it an ideal test site for the work done in this project. The earliest research in this work (between 1994 and 1997) involved investigating different radar sensing systems and global positioning systems (GPS) guidance systems to create a semi-tractor capable of preventing crashes and controlling the vehicle if the driver were to become incapacitated. In this time, UM researchers modified a Navistar 9400 truck tractor (called SafeTruck) to meet their specifications. In addition to SafeTruck, during this time period UM researchers also developed and tested a heads-up display (HUD) prototype that provides a driver with lane boundaries in conditions of poor visibility. SafeTruck was first successfully demonstrated for the public in April 1997 at the MnROAD facility (86-88). The sum of this early work is recounted in a Mn/DOT report by Alexander et al. titled "SafeTruck – Sensing and Control to Enhance Vehicle Safety" (89).

Later work in Guidestar used MnROAD as a testing facility to refine the GPS in sensing the position of the vehicle and the controls of the truck in responding to the GPS feedback—these modifications comprised the Differential Global Positioning System, or DGPS (90). Other work modified the so-called Virtual Bumper, a series of radar and laser sensors that detect potential collisions. In the event of a possible collision, this system then assists the operator in avoiding those collisions through automated feedback to the vehicle control, which can modify the vehicle's trajectory (91). The sum of SafeTruck, the HUD, and the Virtual Bumper was labeled the driver assistive system (DAS), and later additions and modifications to these systems were described in a number of reports (92-95). In 2004, UM researchers published the Mn/DOT Report "System Performance and Human Factors Evaluation of the Driver Assistive System (DAS)," an excellent bookend to the work done in ITS that used MnROAD as its main test site during MnROAD's first ten years of operation (96). The most recent work in MnROAD's first ten years used MnROAD as a test site for an on-board system to estimate the tire-road coefficients in real-time using DGPS (97).

3.8 Adoption of New Products

In addition to serving as a site for research, MnROAD has also served the state of Minnesota as a testing ground for new pavement technologies. In some cases, this has involved the use of MnROAD engineers in certifying practitioners in the use of equipment (98, 99). Two notable techniques in pavement assessments, the dynamic cone penetrometer (DCP) and ground penetrating radar (GPR) have been first explored at MnROAD before seeing greater use in the state of Minnesota.

MnROAD personnel have applied the DCP to test sections since the initial stages of MnROAD beginning in June 1991. During the construction phase, MnROAD engineers conducted over 700 DCP tests at the MnROAD facility and retained all of this test data in the MnROAD database (17). Given the large amount of DCP testing at MnROAD have tolerated, in reports by MnROAD engineers suggested and made a series of physical modifications to the device itself and proposed the development of an automated DCP (ADCP) based on MnROAD's experience with the DCP (18, 20). MnROAD's extensive use of DCP aided Mn/DOT's

implementation of DCP to assess pavement systems in the field, as noted by Burnham (100). Siekmeier et al. also detail a comparison of DCP with other tests to assess soil compaction (101).

MnROAD has been instrumental in the adoption of GPR by Mn/DOT. In the earliest work using GPR at MnROAD by Maser in 1994, GPR was used to evaluate the thicknesses of the test sections and compare these values against known design thicknesses (102). This early test acted as a pilot quality control for MnROAD (to confirm that sections were constructed to design) and simultaneously as a way for the researcher to compare the GPR's assessment against actual thicknesses (determined through coring). A later report by Loken states that since GPR assessments began at MnROAD, Mn/DOT has expanded both its GPR equipment and user expertise. The MnROAD research group continues to provide production GPR testing services to Mn/DOT's and local road authorities. In addition, Mn/DOT has expanded the number of fields in which GPR is a useful non-destructive method of assessing a given situation (103).

A recent pavement technology in the United States is a quality control process known as continuous compaction control or intelligent compaction (IC). Through demonstrations at MnROAD and the involvement of MnROAD engineers in a statewide IC Task Force, many factors related to the use of IC in unbound material compaction have been uncovered through MnROAD. During the on-site demonstrations, MnROAD engineers confirmed the steps involved in the IC process and the tools used to complete each step. The compactor was found to be easy to operate and capable of measuring the stiffness and adjusting the compactive force. Engineers also confirmed the data transfer from compactor to server. Overall, MnROAD engineers found that intelligent compactors do an excellent job of ensuring uniformity in compaction and acquiring the soil modulus for the next generation of mechanistic-empirical pavement design (104). IC has been used on selected projects in Minnesota since the demonstrations at MnROAD, and IC is planned to be implemented for MnROAD's Phase II reconstruction.

MnROAD experience has been involved during work plan development for IC in NCHRP 21-09, a federally funded project to determine the reliability of IC equipment and develop construction specifications for projects involving IC, and Mn/DOT is also lending its MnROAD-derived experience to an FHWA-led IC Pooled Fund study (105). Thanks to MnROAD experience and initiatives, Minnesota has a docket of projects and demonstrations scheduled that involve IC, and this experience will likely play a large role in the development of IC in the United States.

3.9 Edge-joint Sealing

Olson and Roberson examined two similar concrete test sections with bituminous shoulders and edge drains (106). One of the two sections had its longitudinal edge joint (the joint between the shoulder and the pavement) sealed, while the other did not. The authors collected data to support the claim that the total volume of water entering the pavement system for a rain event was reduced by as much as 85% through the use of an edge seal. For this reason, the authors held that the edge-joint seal should become standard practice in construction preventative maintenance for pavements. While the edge-joint seal has yet to gain acceptance in Minnesota as a specified practice, many Mn/DOT districts have noted the success of edge-joint seals, but Mn/DOT has not yet established a specification using these results.

3.10 Non-pavement Research

MnROAD is an especially attractive test site for experiments that require an awareness of environmental conditions, such as those required by an environmental biologist. The constant monitoring of temperature and moisture provide data for the biologist to use as a reference in validating field data. Furthermore, the close monitoring of the site itself and the controlled traffic prevent the experimental setup from becoming disturbed or damaged.

Biesboer and Elfering detail a program that monitors the ability of roadside plants and a check dam to remove pollutants from pavement runoff (107). The authors monitored the site from June 2000 to June 2002, and found that the vegetation and check dam reduced pollution in the water tested by as much as 54 percent. This study in road runoff is an example of an experiment that would otherwise be difficult to conduct without MnROAD, as MnROAD's controlled conditions simplified setting up the experiment, monitoring the conditions to which the experiment is exposed, and protecting the experiment from being disturbed.

Gale and Biesboer discuss the use of MnROAD as a facility to conduct an experiment in methods to establish vegetation on the near in-slopes of roadsides (108). The study examines the use of three different soil treatments: two different erosion control materials and the amendment of the soil with organic materials. Along the roadside, the researchers installed a wide variety of plants. The use of MnROAD as a testing facility helped protect and control the experiment, and for this reason the soil treatments went undisturbed and performed as expected. However, the authors found that the use of these treatments did not improve the establishment of the plants within two meters of the road.

Another non-pavement experiment conducted at MnROAD was the installation of larger corrugated polyethylene culverts in test sections in the low-volume loop. Simpson, Gumpert, & Heger, Inc. detail the installation of the culverts and the various modeling and loading tests investigated to track the performance of the culverts over 3.5 years (109). The authors found that the culverts performed well and showed no signs of increased deflections over that time. Furthermore, the authors were able to provide recommended minimum depth covers for the culverts based on their experience at MnROAD.

3.11 Aggregate Road Research

Mn/DOT and LRRB commissioned a study on MnROAD's aggregate road test sections shortly before the removal of those sections, later published in Lukanen (110). This work resulted in a number of interesting conclusions and recommendations, the foremost of which is on the nature of full-scale testing itself. The study describes the true measure of the aggregate sections' performance as their ability to allow the loading truck to pass unimpeded. When the truck could no longer maintain its 30 mph speed on any single section, all aggregate sections (in addition to the section causing the problem) would be bladed to avoid safety concerns for the operator of the truck. Hence, rutting and washboarding were naturally the most closely studied modes of deterioration. The severity and frequency of these phenomena limited the observations due to the fact that when one section approached "failure" in terms of the safety concerns for the truck operator, all sections and ongoing observations were subsequently reset.

Despite this limitation, the study found a strong relationship between washboarding and the number of truck passes. Due to this relationship, more washboarding occurred in the 80 kip lane than in the 102 kip lane. Forensic cross-sections of the sections revealed that the rutting experienced occurred in the aggregate and not the subgrade. It was also found that the use of the chip seal reduced the likelihood of washboarding, though a comparison between the sections

suggested nothing conclusive as regards chip sealing and rutting. The study also noted that aggregate gradations are not reliable predictors of performance in an aggregate road (110).

Another report by Johnson and Baker on MnROAD's experience with its aggregate test sections discusses the sections in every detail, from construction to load response to distress observations (111). This report makes a few interesting observations on the rate of freezing and thawing under aggregate roads. The freeze/thaw under aggregate roads was much different than the freezing and thawing under HMA sections at MnROAD: the subgrade under aggregate sections froze approximately 4 to 5 days sooner than the subgrade below the HMA. Furthermore, the subgrade under the aggregate sections took between 11 and 35 days longer to thaw than the subgrade under the HMA (111). This second report was the final report on MnROAD's aggregate test sections and is an excellent review of one of the few full-scale, fully instrumented aggregate roads in the United States.

3.12 Oil gravel Road Research

MnROAD has been involved with a number of experimental techniques and materials, and its experience with emulsified oil gravel is certainly unique to test tracks. This experience came about through a long-lasting partnership with the Finnish National Road Administration (FINRA). The oil gravel, which consists of a softer binder than a typical HMA, typically exhibits a long life and low amount of cracking in Finland. Given its experience with low temperature cracking, MnROAD officials implemented oil-gravel on three sections in the low-volume loop (112). One of the sections showed distresses shortly after construction, but a forensic trench study of the section suggested that the distress was due to the strength of the base material and not a fault of the oil-gravel surface (44). This section was replaced, but two of the original three oil-gravel sections remain at MnROAD. These sections have resisted thermal cracking entirely (113, 114). MnROAD's experience in oil-gravel roads combined with the remainder of Mn/DOT's experience with oil gravel throughout the state has helped to educate municipal and city engineers. Furthermore, the cost savings of oil gravel roadways are a potential benefit to local governments. Had it not been for MnROAD's partnership with FINRA, this new pavement technology for road rehabilitation would have gone unexplored.

3.13 Low-volume Road Design

Low-volume road (LVR) data from MnROAD were used by UM researchers to verify and calibrate ROADENT, a thickness design program based on WESLEA and developed by UM (50-52). The calculated strains from the program were compared to the actual strains as captured by the many embedded sensors in the test sections. ROADENT was continuously calibrated in this way so that performance predictions by ROADENT would reflect the performance observed at MnROAD's full-scale LVR test sections.

The report recommended that the Soil Factor and R-Value design procedures for low-volume roads be reconsidered, as ROADENT requires a thicker design than the other two for an equivalent roadway. This conclusion was significant for local agencies, most of whom used either the Soil Factor or R-Value design in planning their roadways, and the foundation of this conclusion was, of course, years worth of MnROAD LVR data. A later Mn/DOT report by Skok et al. builds upon the earlier work in LVR design by updating the design for Minnesota using MnPAVE (56). This work has benefited low-volume roadways at the city and country level by providing a reliable, consistent design based upon local environmental data and pavement response data to loading in that particular environment.

Chapter 4

Assessment of MnROAD Phase 1

Another important aspect of the Lessons Learned project is to use the research, interviews, and surveys conducted to assess MnROAD in terms of its objectives and its influence on pavements. This particular section will deal with three areas: the perception of out-of-state professionals in pavements of MnROAD, the intangible benefits of MnROAD on the larger pavement community, and the relationships MnROAD fostered in its first ten years. As for its products, both Sections 2 and 3 are a general testament to the breadth of experience at MnROAD in a variety of topics and success of MnROAD in discovering new areas of research. Any further assessment of MnROAD's products are contained in Section 5. It should also be noted that the UM research team culled together, from its interviews and surveys, evaluations of the following three topics. These assessments are provided to assist MnROAD in its second phase of operation.

4.1 Perspectives from Surveys and Interviews

The interviews and online surveys yielded many useful responses. While Mn/DOT perspectives on MnROAD were critical to the success of the Lessons Learned project, the assessment of MnROAD by out-of-state practitioners and researchers in pavement engineering was equally important to the project. The subjects for surveys and interviews were a cross-section of out-of-state pavement professionals: some were employees of other departments of transportation, some were industry consultants or representatives, and others were university researchers. A list of these subjects is presented in Appendix A. The survey and interview questionnaires used as a guideline for responses are included in Appendix B. Responses to multiple choice questions for both the surveys and interviews have been tallied and are reported in Appendix C.

4.2 Intangible Benefits

Intangible benefits are those that cannot be illustrated by pointing to a database, reports, extensive facilities, or experienced staff. One of the desires of Mn/DOT for the Lessons Learned project was to assess the benefits of MnROAD that are difficult to quantify in terms of dollars or published reports.

4.2.1 Pioneer of second-generation test tracks

Since its opening, MnROAD has been toured by officials from other major pavement test track facilities, such as WesTrack, the National Center for Asphalt Technology (NCAT), and the SHRP test road in Ohio. Furthermore, these officials have consulted with and asked many questions of MnROAD engineers, and in doing so, they built upon MnROAD expertise in developing their own test tracks. MnROAD was (and continues to be) very open with these other test tracks, and in making itself available in this manner, it has benefited pavement engineering tremendously.

What many professionals in pavements ignore is that MnROAD followed the AASHO Road Test of the late 1950s by three decades. As a result, unlike the MnROAD lessons learned as an example for test tracks of the 1990s and beyond, the lessons learned in at the AASHO Road Test in Illinois were not available to MnROAD's planners and contractors. MnROAD was

left to discover these lessons on its own and, in doing so, took on the burden of learning lessons for the sake of a number of research facilities to follow.

4.2.2 Education in pavement engineering

Many universities from around the nation have been involved with MnROAD. Many of MnROAD's relationships with these universities involve working closely to provide data and pavement expertise on research projects. MnROAD has been particularly active with universities in the Midwest, such as Minnesota State University, the University of Iowa, the University of Illinois, Iowa State University, North Dakota State University, and the University of Wisconsin. While these relationships are valuable both for their contributions to pavements and their educational value to students, MnROAD's most noticeable benefit to education in pavements in its first ten years was in the relationship between MnROAD and the University of Minnesota (UM).

MnROAD's relationship with UM extends beyond its relationship with UM students, researchers, and professors. This relationship has affected the structure of the university itself. One of the main benefactors of MnROAD's influence in education is the Center for Transportation Studies (CTS), an administrative resource created at UM in 1986 to generate funds for, bring publicity to, and indirectly guide UM research in transportation economy, traffic safety and flow, transportation infrastructure (including pavements), and transportation planning. CTS experienced a significant growth spurt in the early 1990s that extended through MnROAD's first ten years of operation, and this growth spurt and the existence of MnROAD is clearly no coincidence.

Prior to 1989, the Department of Civil Engineering at UM had no professors in pavement engineering and very few students engaged in pavement activities. By 1993, the civil engineering department had two dedicated pavement positions, and by 2004, the civil engineering department had graduated over 35 graduate-level students who worked in MnROAD-related pavement issues alone (does not account for graduate students involved in non-MnROAD-related pavement topics). It is difficult to imagine that these pavement positions and these students would have existed were it not for the close involvement of MnROAD engineers with CTS and UM and the involvement of UM students with MnROAD.

In 2004, a task force commissioned to expand the governance of and increasing research opportunities at MnROAD, led to the creation of the Transportation Engineering and Road Research Alliance (TERRA). TERRA is a pooled-fund consortium of industry representatives, Mn/DOT officials, UM representatives, local and out-of-state governments, and research institutions. The introduction of TERRA not only provided additional research funds to MnROAD, TERRA also brings a variety of industrial and institutional research interests much closer to MnROAD's attention. As it has done for UM, MnROAD is acting as a database and test facility for an expanded group of pavement engineers—namely, the members of TERRA. However, this activity does not exclude UM researchers: in many cases, UM professors and students benefit from their experience with MnROAD and expertise in cold-regions pavements by being given the opportunity to conduct the research needs proposed by TERRA members. TERRA also presents MnROAD with the opportunity to pass along valuable pavement and test track expertise to some of TERRA's members, such as the government of Norway and Iowa State University, and act as an educational resource for even more of the pavement community.

While these many institutional and organizational changes are significant, there are other less complicated processes by which MnROAD is advancing its educational influence in

pavement engineering. The most noticeable of these processes is the introduction into the pavement community of former Mn/DOT employees who have worked closely with MnROAD data or the MnROAD facility. The advancement of these previous Mn/DOT employees in industry, government, and academic positions demonstrates the large amount of pavement expertise that can be had at MnROAD and the benefit of obtaining this experience. The involvement of these employees in high-visibility projects serves as a reminder of MnROAD's influence throughout the pavement community. Noted a survey respondent, "The major impact [of MnROAD] I have noticed is the number of young engineers from Mn/DOT and the University who have learn about pavements while working on projects at the MnROAD and are now making an impact on the pavement community by now training others, conducting research, and serving on NCHRP/pooled fund/FHWA committees, etc."

4.3 MnROAD Partnerships

One of the foremost goals of the MnROAD project was to establish and nurture relationships between MnROAD and other agencies in government, industry, and education, and through these relationships discover areas of pavement research that have interest and whose pursuit will lead to needed, usable products. The following sections detail some of these relationships

4.3.1 LRRB

The importance of the Minnesota Local Road Research Board (LRRB) in the research operations at MnROAD, especially those operations on the low-volume loop, cannot be overstated. In 1959, state legislators created LRRB to conduct research in pavements using municipal and county state aid funds. The board consists of ten members: four county engineers, two city engineers, three Mn/DOT officials, and one representative from the University of Minnesota. Since MnROAD's opening, LRRB has been a valuable partner to MnROAD, both as a consistent source of funding and as a basis for project initiatives. Given this level of participation, LRRB obviously was involved in a great number of notable research projects in MnROAD's first ten years of operation. Almost all of MnROAD's low-volume loop sections involved/currently involve funds from LRRB and/or derive their origins from LRRB research initiatives, and much of the mainline research benefits from local agencies. MnROAD's relationship with LRRB was one of its most successful in its first ten years of operation.

4.3.2 Out-of-state agencies

In its first ten years, MnROAD was involved with a number of agencies, including:

- Federal Highway Administration (FHWA)
- Transportation Research Board (TRB)
- Strategic Highway Research Program (SHRP)
- U.S. Army Cold Regions Research and Engineering Laboratory (CRREL)
- Finnish National Road Administration (FINRA)
- Manitoba Ministry of Transportation

There are obviously many universities, departments of transportation, and engineering consulting firms not included on this list. MnROAD has worked with practitioners and researchers in a significant way on the local, state, national, and international levels.

Overall, MnROAD's partnerships with these agencies introduced a broader perspective to MnROAD's operations and goals in research. These partnerships generated interest in and contributed a great deal of expertise to projects that would have otherwise not existed without the

partners. Furthermore, the partnerships helped promote MnROAD outside of Minnesota and generate new contacts for new partnerships. That being said, one of the drawbacks of these partnerships is the inability to convince partners to bear the majority of the relationship's financial burden. In almost every partnership, Mn/DOT was the main financial sponsor of the cooperation.

To improve the relationships and make them more beneficial to MnROAD and Mn/DOT, MnROAD must keep in mind that while it is important to attract researchers from other states and countries, it is also important to establish dual or federal sponsorships. Furthermore, new projects with local applications should make certain that local researchers are involved in the projects to maximize outcome for Minnesota and to provide continuity from one project to the next. A good example of this is pooled fund project TPF-5(80) headed by Prof. Mihai Marasteanu of UM. This study, titled "Investigation of Low Temperature Cracking in Asphalt Pavements," takes place with the support of a large consortium of interested parties including the University of Illinois, Iowa State University, the University of Wisconsin, and more than ten state departments of transportation.

4.3.3 Industry

Representatives of industry have played an important role in MnROAD from the early planning stages onward. These representatives include contractors and material providers. In the first ten years of MnROAD, industry representatives have been present on panels and advisory committees for a number of MnROAD construction and research projects. In this capacity, industry representatives have contributed valuable technical advice to MnROAD, its engineers, and associated researchers and practitioners in MnROAD-related projects. These advisory efforts are also present in TERRA, which includes representatives of industry as part of its membership.

While MnROAD established valuable contacts with industry representatives, one general concern of these relationships is that MnROAD has not been able to develop these relationships beyond advice. One obstacle to furthering these relationships is that while MnROAD's needs and interests for operations and research are quite public, the industry's needs, particularly in research, are difficult for MnROAD to discern. The hope is that were industry to better formulate its needs, MnROAD could develop or initiate research that is guided, in part, by these needs. The idea then would be that MnROAD would be in a better position to ask for the industry representative to either contribute financially to that research or actively promote MnROAD's interests and needs at a national level. As it stands, while MnROAD's relationship with industry involves an exchange of ideas, there is a reluctance to provide MnROAD with any significant contribution in terms of either finance or promotion.

Part of the solution to receiving financial support from industry remains on MnROAD's side of the transaction. MnROAD must better understand the product that an industry representative expects of a given project, and MnROAD must be willing and able to provide that product in a reasonable time frame. MnROAD must also continue to push for contributions beyond advice in hopes that newer, more substantial relationships for both sides will come to be.

Chapter 5

Conclusions about MnROAD Phase 1

It is the opinion of the UM research team that the success of the first ten years of the Minnesota Road Research Project will become apparent to anyone who takes a moment to review the data, research, and test track expertise that resulted from these ten years of operation. The critics of MnROAD often point to unanalyzed data or underused test sections as if these problems negate all of MnROAD's valuable work. However, based on the influence of MnROAD in the larger pavement community, not to mention the state of Minnesota, this is not so.

On a state and local level, the pavement knowledge generated by MnROAD has improved roadways to a noticeable extent. MnROAD engineers have provided a local design method (MnPAVE) that is built upon MnROAD data. This design is therefore very well suited to pavements in Minnesota. MnROAD's most notable contribution to local and state roads has been in studies on the seasonal variation of pavement systems. The legislation resulting from this work led to changes in Minnesota's allowable loading for given seasons on its roadways, and many believe this topic alone "paid for MnROAD" in that it saved rehabilitation and maintenance budgets tens, perhaps hundreds, of millions of dollars.

On the national level, MnROAD has influenced pavement engineering in a manner as significant as its contributions on the local level, though these contributions are subtle and less visible to those outside of pavements. The earliest of these contributions was the evaluation of thickness design on concrete pavements. This evaluation found that these design methods were inadequate. MnROAD's experience with pavement responses to environment also brought the phenomenon of low-temperature (thermal) cracking in asphalt pavements to prominence. MnROAD remains the main repository in the world on thermal cracking data and expertise. MnROAD's work in design verification and thermal cracking alone made MnROAD a resource that could not be ignored by serious professionals in pavement engineering in the United States.

The opportunity for MnROAD, as it anticipates its second phase of operation, is to use the Lessons Learned project as other test tracks have used MnROAD expertise: MnROAD's second phase planners can learn from the lessons of MnROAD's first phase. The first of the three following sub-sections detail issues from MnROAD's first phase in its database, data analysis, and research and reporting. Appendix Section 5.3 also provides insight on possible directions for research using either data from MnROAD's first phase or new experiments that could be implemented in MnROAD's second phase. The final sub-section brings together a few suggestions from interviews and surveys and briefs to reiterate key lessons from MnROAD's first ten years of operation.

5.1 Suggestions for Database

In the interviews and surveys, while many subjects felt the state and operation of the MnROAD database was adequate, many were quick to offer their own suggestions on how to adjust the database to make it friendlier to both MnROAD engineers who must maintain and release data to the public and researchers who want to use the data. These suggestions can be distilled into one statement: MnROAD requires a more coherent policy for its database operations. More specifically, this policy must account for the following:

1. Responsible data entry (data collected must be entered into the database and not abandoned on CDs or personal computers)

2. Initial data quality check (data must be “cleaned” immediately to make the data more usable)
3. Adequate database description (use website resources to describe data to an extent that MnROAD engineers are not required to handle every data request personally)
4. Improved data access (data should be periodically released and time-stamped via a compact disc or FTP server)

It is hoped that these four points will improve the amount of MnROAD data available, the quality of that data, and the ease of accessing that data for the end-user.

Releases through CDs or FTP servers will help both ends of the data request transaction: MnROAD personnel will no longer devote as much energy to requests and users will have a definite idea of where to get their data. The releases will make citation of MnROAD data much easier and thereby improve the visibility of MnROAD. As it stands, many users of MnROAD data are unsure how to cite the use of this data in their reference sections, as MnROAD does not provide its users with guidelines (unlike other large databases such as LTPP). The UM research team also suggests that MnROAD consider releasing its data in Microsoft Access format, as opposed to the current Oracle format.

5.2 Suggestions for Data Analysis

The main criticism of MnROAD’s first ten years is that, due to a lack of data analysis, MnROAD missed many opportunities to make a more significant impact at the state, local, and national levels. This comment was repeated by nearly every interview subject, many of whom otherwise viewed MnROAD with very different perspectives. Had MnROAD placed the same emphasis on data analysis that it did on data collection, the outcome of MnROAD’s first ten years would be much different.

However, the generation of unanalyzed data is not unique to MnROAD, and so the blame cannot rest entirely on MnROAD engineers. It is only reasonable that a research facility on the scale of MnROAD, a facility that is forging its own way and learning lessons for itself and those to follow, would generate the amount of unused data that it did. Severe limitations in its funding since 1999 often forced MnROAD managers to make tough choices between data collection and data analysis. In addition, with the frequent turnover of new employees or reductions in staff, many research projects (and related data sets) were abandoned entirely, and due to the nature of research, employees were reluctant to take up the research of those before them.

The Lessons Learned project will hopefully place MnROAD in a position to make data analysis a priority in its Phase II. It is important to begin comprehensive data analysis as soon as possible. This sense of “comprehensive research” implies three tasks. The first task is a review of the database and data quality checks, the second is initial data mining to help establish research directions, and final task is comprehensive data analysis in one of the selected strategic directions.

To emphasize the importance of data analysis to the second phase of MnROAD, it is necessary to develop a data analysis roadmap for all the data to be collected on the existing sections and the reconstructed sections. Each measured quantity should be predicted or estimated prior to the initiation of the data collection program. Initial data analysis should follow data collection. If the measured values do not correspond to the predicted values, this should trigger checking of the quality of the collected data and, if necessary, re-measurements. If the measured data are found to be reliable, but significantly different from the predicted values, this indicates a need for research effort explaining this phenomenon. While these steps were

followed to a certain degree in MnROAD's first phase, that experience taught MnROAD the importance of entering and verifying its data immediately. In the absence of responsible data collection and data quality checks, problems such as the need for work in validation years after the data has been collected as evidenced in Koubaa and Stolarski (39).

Finally, a long-term data analysis program should be established. As a minimum, it should include sponsoring one joint project between Mn/DOT and UM in data analysis every year. This will provide continuity in the data analysis efforts, so that data sets are not lost due to the release and addition of new employees at MnROAD, and this cooperative effort with help bolster the educational benefits of MnROAD.

5.3 Suggestions for Reporting and Research

The main difficulty for MnROAD research is one of visibility. Those reports or papers relating to MnROAD that are published through a journal, conference proceedings, or department of transportation library do not suffer these problems. However, far too much MnROAD research is buried in forgotten slides from workshop presentations or unpublished papers abandoned to obscure URLs. The next phase of MnROAD would benefit from making an effort to see that MnROAD-related work is published in a manner that makes it easier for those using MnROAD research to cite this work.

One benefit of publishing would be that these reports would be catalogued somewhere and more easily found by researchers. Many of the unpublished MnROAD-related reports (those appearing only on the MnROAD website) often list on their technical report documentation pages a registration number with the National Technical Information Service (NTIS). However, a search of NTIS reveals many papers published through the Mn/DOT Library were not registered with NTIS. Hence, these unpublished MnROAD reports cannot be found through Mn/DOT and NTIS, two large search engines that would otherwise direct many interested engineers to the work.

The simple fact is that online "publication" of MnROAD-related documents by posting material to a URL or presenting information only in one slide at a conference or workshop is not sufficient. Though some MnROAD engineers do not have the time in their workday needed to fit the guidelines to publish through the Mn/DOT library, it is currently the only method of presenting MnROAD work to the public in a secure, catalogued, centralized, easily referenced location. Otherwise, simply posting reports/briefs/papers to a personal website or the MnROAD website (the current medium for a number of reports) relegates this work to the whimsy of countless file servers, unreliable URLs, and other obstacles. These practices of burying reports only reduce the visibility of MnROAD and its products.

One method of promoting the use of MnROAD research and increasing the visibility of this work would be for MnROAD to encourage the use of MnROAD data in pavement classes at the University of Minnesota. This would also strengthen MnROAD's relationship with the UM. MnROAD could also, with the assistance of the Center for Transportation Studies, sponsor a national or state student paper competition that promotes research using MnROAD data. Either of these ideas are fairly simple and will help to keep MnROAD data alive in pavement research beyond the life of a MnROAD test section.

A number of opportunities for future research have been catalogued by the UM research team through the surveys, interviews, and discussions of MnROAD research. These suggestions are grouped in general topic areas and are discussed in Appendix D.

5.4 Other Recommendations

The main difficulties for MnROAD's first phase were those of data analysis and data mining. As MnROAD had declining numbers of staff over its first ten years and yet increasing volumes data, data analysis and mining became impossible due to a backlog of responsibilities for MnROAD engineers. The main priority for MnROAD's second phase should be data analysis and mining.

Other problems with MnROAD in its first phase were those associated with visibility and ease of use. Many professionals in pavements have confessed to knowing of MnROAD and wanting to use its data or research, but not knowing how to access those MnROAD products despite repeated attempts. Many products of the Lessons Learned project will facilitate the ease of use—particularly Worel's *Guide to the MnROAD Database*. MnROAD must still make further overtures to potential users of MnROAD products. These include the points discussed in previous sections, some of which include the regular publishing, stamping, and release of data and an effort to make sure that research projects result in a catalogued, peer-reviewed paper or report through a journal, conference proceeding, department of transportation library, etc.

MnROAD's first ten years also saw many of MnROAD's partnerships with various agencies suffer from an imbalance, especially in terms of financing. One method of continuing the spirit of partnership from MnROAD's first phase but bolstering these partnerships with substantial contributions would be for MnROAD to more actively seek out pooled fund studies. These pooled funds would provide support for research using the MnROAD facility or MnROAD data where this support has previously come mostly from Mn/DOT.

Another suggestion as MnROAD looks toward its second phase is that MnROAD should formulate several research tracks and concentrate MnROAD data collection and analysis efforts on these research tracks. One possible categorization of important research in MnROAD's second phase might be:

1. Cold-regions research
 - a. Thermal cracking
 - b. Environmental degradation of pavements
2. Structural modeling/model verification
3. Climatic model verification
4. Low volume roads (design, construction, materials, performance, etc.)
5. Pavement rehabilitation and maintenance

Whatever the categories may be, the purpose of these categories is to develop key areas of research and make a commitment to these areas in data collection and data analysis.

A final recommendation that has been repeated by many of those involved with MnROAD is that MnROAD must establish itself as the premier cold-regions research facility in the nation, if not the entire world, if this is in fact the focus that MnROAD determines for itself. While MnROAD most likely occupies the role, MnROAD must do a better job of publicizing this fact and crafting its research goals to this role. Doing so will help focus MnROAD in its second phase in terms of possible test sections and research proposals. The key to MnROAD's future, in the opinion of the UM research team, is that MnROAD must choose an identity/focus for itself and effectively market this focus if it is to achieve increased recognition at a national level.

References

1. Witczak, M.W. and R. O. Wolters. *Background and Conceptual Plan: Mn/DOT Cold Regions Pavement Research Test Facility (CRPRTF)*. Commercially Unpublished Report to the Cold Regions Pavement Research Test Facility Task Force. Minnesota Department of Transportation, 1989.
2. DAMA, Inc.. *Pavement Test Section Plan: Low Volume Road Site – Access Road. Mn/DOT I-94 Cold Regions Pavement Research Test Facility (CRPRTF)*. Commercially Unpublished Report to the Minnesota Department of Transportation CRPRTF Task Force. DAMA, Inc., Silver Spring, MD, 1988.
3. DAMA, Inc.. *Pavement Test Section Plan: I-94 Main Experiment – 5 and 10 Year Design. Mn/DOT I-94 Cold Regions Pavement Research Test Facility (CRPRTF)*. Commercially Unpublished Report to the Minnesota Department of Transportation CRPRTF Task Force. DAMA, Inc., Silver Spring, MD, 1988.
4. Newcomb, D. E., D. M. Johnson, H. B. Baker, and S. M. Lund. *Minnesota Road Research Project: Work Plan for Research Objectives*. Report MN-RC-1990-03. Minnesota Department of Transportation, 1990.
5. Minnesota Department of Transportation. *Transportation Research 1997-98 Biennial Report*. Serial Report by the Office of Research Services. Minnesota Department of Transportation, 1998.
6. Minnesota Department of Transportation. *Transportation Research 1999-2000 Biennial Report*. Serial Report by the Office of Research Services. Minnesota Department of Transportation, 2000.
7. Newcomb, D. E., G. Engstrom, D. A. Van Deusen, J. A. Siekmeier, and D. H. Timm. *Minnesota Road Research Project: A Five-Year Review of Accomplishments. Proc., 9th International Conference on Accelerated Pavement Testing*, Reno, Nevada, 1999.
8. Worel, B. and L. Eaton. *MnROAD Phase-1 Summary and Phase-2 Future Vision*. Presented at 2nd International Conference on Accelerated Pavement Testing, Minneapolis, Minnesota, 2004.
9. *Introduction to LTPP Data*. FHWA, Office on Infrastructure Research and Development, 1999.
10. *LTPP Data User's Reference Manual*, Report No. FHWA-RD-97-001, Federal Highway Administration, Pavement Performance Division, 1997.
11. Worel, B. *Guide to the MnROAD Database*. Supplementary Unpublished Report for Lessons Learned Project, Contract No. 81655. Minnesota Department of Transportation, 2006.
12. Baker, H. B., M. R. Buth, D. A. Van Deusen. *Minnesota Road Research Project Load Response Instrumentation Installation and Testing Procedures*. Report MN-RC-1994-01. Minnesota Department of Transportation, 1994.
13. Burnham, T. R. *Construction Report for MnROAD PCC Test Cells 32, 52, and 53*. Report MN-RC-2002-04. Minnesota Department of Transportation, 2002.
14. Burnham, T. R. *Concrete Embedment Strain Sensors at the MnROAD Project: As-Built Orientation and Retrofit*. Presented at 1st International Conference on Accelerated Pavement Testing, Reno, Nevada, 1999.

15. Wang, D. and J. Baker. *MnROAD TDR Evaluation and Data Analysis*. Report MN-RC-2004-15. Minnesota Department of Transportation, 2004.
16. Clyne, T. R., V. R. Voller, and B. Birgisson. *Evaluation of a Field Permeameter to Measure Saturated Hydraulic Conductivity of Base/Subgrade Materials*. Report MN-RC-2001-19. Minnesota Department of Transportation, 2001.
17. Burnham, T. and D. Johnson. *In Situ Foundation Characterization Using the Dynamic Cone Penetrometer*. Report MN-RC-1993-05. Minnesota Department of Transportation, 1993.
18. Newcomb, D. E., Van Duesen, D. A. and T. R. Burnham. *Characterization of Subgrade Soils and Granular Base Materials at the Minnesota Road Research Project*. Report MN-RC-1994-19. Minnesota Department of Transportation, 1994.
19. Burnham, T. R. *Minnesota Road Research Project Subgrade and Base Material Sampling and Testing Guide*. Report MN-RC-1995-03. Minnesota Department of Transportation, 1995.
20. Newcomb, D. E., Chadbourn, B. A., Van Duesen, D. A. and T. R. Burnham. *Initial Characterization of Subgrade Soils and Granular Base Materials at the Minnesota Road Research Project*. Report MN-RC-1996-19. Minnesota Department of Transportation, 1996.
21. Berg, R. L., S. R. Bigl, J. Stark, and G. Durell. *Resilient Modulus Testing of Materials from MnROAD, Phase 1*. Report MN-RC-1996-21. Minnesota Department of Transportation, 1996.
22. Bigl, S. R. and R. L. Berg. *Testing of Materials from the Minnesota Cold Regions Pavement Research Test Facility*. Report MN-RC-1996-24. Minnesota Department of Transportation, 1996.
23. Dai, S. and D. Van Deusen. Field Study of In Situ Subgrade Soil Response under Flexible Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1639*, TRB, National Research Council, Washington, D.C., 1998, pp. 23-35.
24. Dai, S. and J. Zollars. Resilient Modulus of Minnesota Road Research Project Subgrade Soil. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1786*, TRB, National Research Council, Washington, D.C., 2002, pp. 20-28.
25. Gupta, S., Singh, A., and A. Ranaivoson. *Moisture Retention Characteristics of Base and Sub-base Materials*. Report MN-RC-2005-06. Minnesota Department of Transportation, 2004.
26. Stroup-Gardiner, M. and D. E. Newcomb. *Investigation of Hot Mix Asphalt Mixtures at MnROAD*. Report MN-RC-1997-06. Minnesota Department of Transportation, 1997.
27. Huhtala, M., H. Spoofo, L. Saarinen, and P. Halonen. *Asphalt Mixture Laboratory Tests*. Report MN-RC-1997-20. Minnesota Department of Transportation, 1997.
28. Huhtala, M., H. Spoofo, L. Saarinen, and P. Halonen. *Minnesota Road Research Project (MnROAD) - Asphalt Mixture Laboratory Tests*. Report nr. 395. Technical Research Centre of Finland, 1997.
29. Saarenketo, T. *Tube Suction Test – Results of Round Robin Tests on Unbound Aggregates*. Finra Report 19/2000. Finnish National Road Administration, 2000.

30. Reinke, G. *Torsional Fatigue and High Temperature Stiffness Modulus of Cells 3, 4, 17 & 18 of MnROAD's 1992/1993 Paving Work*. Mn/DOT Call # TE250.R445. Minnesota Department of Transportation, 2001.
31. Adams, J., R. Mulvaney, B. Reprovich, and B. Worel. *Investigation of Construction-Related Asphalt Concrete Pavement Temperature Differentials*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2001.
32. Clyne, T. R., X. Li, M. O. Marasteanu, and E. L. Skok. *Dynamic and Resilient Modulus of Mn/DOT Asphalt Mixtures*. Report MN-RC-2003-09. Minnesota Department of Transportation, 2003.
33. Vandenbossche, J. M. and D. L. Rettner. *The Construction of US-169 and I-94 Experimental Thin and Ultra-Thin Whitetopping Sections in Minnesota*. Report MN-RC-2001-07. Minnesota Department of Transportation, 2001.
34. Vandenbossche, J. *The Construction and Performance of Ultra-Thin Whitetopping Intersections on US-169*. Report MN-RC-2004-19. Minnesota Department of Transportation, 2004.
35. Cochran, G., D. Palmquist, J. Siekmeier, G. Johnson, T. Burnham, C. Schrader, and R. Roberson. *MnROAD Testing Protocols - Volume I*. Report MN-RC-1997-22. Minnesota Department of Transportation, 1997.
36. Burnham, T.R. *PCC Joint Faulting Measurements at the MnROAD Project*. Commercially Unpublished Report for the Office of Materials and Road Research. Minnesota Department of Transportation, 2003.
37. Dogru, S., V. Rajan, K. Rieck, J. R. Slagle, B. S. Tjan, and Y. Wang. *DFQL: A Graphical Data Flow Query Language for Retrieval, Analysis, and Visualization of a Scientific Database*. Report MN-RC-1996-02. Minnesota Department of Transportation, 1996.
38. Dai, S. and D. Van Deusen. *Digital Signal Processing for MnROAD Offline Data*. Report MN-RC-1996-09. Minnesota Department of Transportation, 1996.
39. Van Deusen, D. *Selection of Flexible Backcalculation Software for the Minnesota Road Research Project*. Report MN-RC-1996-29. Minnesota Department of Transportation, 1996.
40. Lau, W. C. and M. S. Alouini. *Development of Automated Procedures for Dynamic MegaDAC Calibration and Data Recovery*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2002.
41. Koubaa, A. and H. Stolarski. *Assistance in the Validation of the MnROAD Database*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2003.
42. Lau, W. C. and R. Strommen. *Dynamic Megadac Calibration Procedure and Development Manual*. Commercially Unpublished Procedural Manual for the Office of Materials and Road Research. Minnesota Department of Transportation, 2002.
43. Isackson, C., S. Dai, and D. Boerner. *Minnesota Road Research Project Forensic Investigation 199701*. Report MN-RC-1999-33. Minnesota Department of Transportation, 1999.
44. Mulvaney, R. and B. Worel. *MnROAD Cell 26 Forensic Investigation*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2001.

45. Mulvaney, R. and B. Worel. *MnROAD Mainline Rutting Forensic Investigation*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2002.
46. Ovik, J. M., B. Birgisson, and D. E. Newcomb. *Characterizing Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure*. Report MN-RC-2000-35. Minnesota Department of Transportation, 2000.
47. Ovik, J. M., D. A. Van Deusen, and J. A. Siekmeier. *Improved Spring Load Restriction Guidelines Using Mechanistic Analysis*. Report MN-RC-2000-18. Minnesota Department of Transportation, 2000.
48. Minnesota Department of Transportation. *2000 Spring Load Restrictions Task Force Legislative Report*. Commercially Unpublished Report. Minnesota Department of Transportation, 2001.
49. Ovik, J. M. and J. A. Siekmeier. *Investigation of the Impact of Increased Winter Load Limits*. Report MN-RC-2004-25. Minnesota Department of Transportation, 2004.
50. Chadbourn, B.A., D. E. Newcomb and D. H. Timm, "Measured and Theoretical Comparisons of Traffic Loads and Pavement Response Distributions," *Proc. 8th Intl. Conf. on Asphalt Pavements*, University of Washington, Seattle, 1997.
51. Timm, D. H., B. Birgisson, and D. E. Newcomb. *Mechanistic-Empirical Flexible Pavement Thickness Design: The Minnesota Method*. Report MN-RC-1999-10. Minnesota Department of Transportation, 1999.
52. Timm, D. H., B. Birgisson, D. E. Newcomb, and T. V. Galambos. *Incorporation of Reliability into the Minnesota Mechanistic-Empirical Pavement Design Method*. Report MN-RC-1999-35. Minnesota Department of Transportation, 1999.
53. Chadbourn, B., S. Dai, P. Davich, J. Siekmeier, and D. Van Deusen. *Mn/DOT Flexible Pavement Design - MnPAVE Beta Version 5.1*. Commercially Unpublished Report for the Office of Materials and Road Research. Minnesota Department of Transportation, 2002.
54. Chadbourn, B. MnPAVE Homepage. Minnesota Department of Transportation, Office of Materials and Road Research, Maplewood, Minnesota.
<http://www.mrr.dot.state.mn.us/research/MnPAVE/MnPAVE.asp>. Accessed 31 May 2006.
55. Skok, E. L., D. E. Newcomb, and D. H. Timm. *Minnesota Low Volume Road Design 1998*. Report MN-RC-1999-34. Minnesota Department of Transportation, 1999.
56. Skok, E. L., D. H. Timm, M. L. Brown, and T. R. Clyne. *Best Practices for the Design and Construction of Low-Volume Roads*. Report MN-RC-2002-17REV. Minnesota Department of Transportation, 2002.
57. Bigl, S. R and R. L. Berg. *Modeling of MnROAD Test Sections with the CRREL Mechanistic Pavement Design Procedure*. Report MN-RC-1996-22. Minnesota Department of Transportation, 1996.
58. Bigl, S. R and R. L. Berg. *Material Testing and Initial Pavement Design Modeling: Minnesota Road Research Project*. Report MN-RC-1996-23. Minnesota Department of Transportation, 1996.
59. Berg, R. L. *Calculating Maximum Frost Depths at MnROAD: Winters 1993-94, 1994-95, and 1995-96*. Report MN-RC-1997-21. Minnesota Department of Transportation, 1997.

60. Burnham, T. R. and W. M. Pirkl. *Application of Empirical and Mechanistic-Empirical Pavement Design Procedures to MnROAD Concrete Pavement Test Sections*. Report MN-RC-1997-14. Minnesota Department of Transportation, 1997.
61. Alvarez, C. and M. R. Thompson. *Mechanistic-Empirical Evaluation of the MnROAD Mainline Flexible Pavement Sections*. Report FHWA-IL-UI-263. Illinois Department of Transportation, 1998.
62. Ariza, P. and B. Birgisson. *Evaluation of Water Flow through Pavement Systems*. Report MN-RC-2002-30. Minnesota Department of Transportation, 2002.
63. Bao, W. *Calibration of Flexible Pavement Structural Model Using MnROAD Field Data*. M.S. Thesis. University of Minnesota, Minneapolis, 2000.
64. Forst, J. *Calibration of Rigid Pavement Structural Model Using MnROAD Field Data*. M.S. Thesis. University of Minnesota, Minneapolis, 1998.
65. Holewinski, J. M., S. C. Soon, A. Drescher, and H. Stolarski. *Investigation of Factors Related to Surface-Initiated Cracks in Flexible Pavements*. Report MN-RC-2003-07. Minnesota Department of Transportation, 2003.
66. Mateos, A. M. *Load Equivalency Factors from the Structural Response of Flexible Pavements*. M.S. Thesis. University of Minnesota, Minneapolis, 2000.
67. Mateos, A. and M. B. Snyder. Validation of Flexible Pavement Structural Response Models with Data from the Minnesota Road Research Project. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1806*, TRB, National Research Council, Washington, D.C., 2002, pp. 19–29.
68. Soon, S. C., A. Drescher, and H. K. Stolarski. Tire-Induced Surface Stresses in Flexible Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1896*, TRB, National Research Council, Washington, D.C., 2004, pp. 170-176.
69. Wu, H., J. Mahoney, G. Turkiyyah, L. M. Pierce, J. Uhlmeyer, and R. Mulvaney. *Non-Uniform Tire Pressure Effects on Surface Initiated Cracks with EverFlex: A Three-Dimensional FEA Tool for Flexible Pavements*. Presented at 9th International Conference on Asphalt Pavements, International Society for Asphalt Pavements, Copenhagen, 2002.
70. Zhang, Z., H. K. Stolarski, and D. E. Newcomb. *Development and Simulation Software for Modelling Pavement Response at MnROAD*. Report MN-RC-1994-31. Minnesota Department of Transportation, 1994.
71. Darter, M. *NCHRP Project 1-40D(02), Technical Assistance to NCHRP and NCHRP Project 1-40A: Versions 0.9 and 1.0 of the M-E Pavement Design Software*. Project in Process, TRB, National Research Council, Washington, D. C., 2006.
[http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+1-40D\(02\)](http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+1-40D(02)). Accessed 31 May 2006.
72. Palmquist, D. *MnROAD Pavement Condition – 1994-1998*. Report MN-RC-1999-11. Minnesota Department of Transportation, 1999.
73. Worel, B., T. Andersen, and R. Mulvaney. *1999 MnROAD SuperPave Tracking, Low Volume Road Cells 33-35*. Commercially Unpublished Final Report for State Project 8816-40. Minnesota Department of Transportation, 2003.
74. Palmquist, D., B. Worel, and W. Zervas. *2002 MnROAD Hot-Mix Asphalt Mainline Test Cell Condition Report*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2002.

75. Zerfas, W. *2002 Superpave Report*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2003.
76. Zerfas, W. *2003 Superpave Report*. Commercially Unpublished Report to the Office of Materials and Road Research. Minnesota Department of Transportation, 2004.
77. Waldhoff, A., W. G. Buttlar, and J. Kim. Investigation of Thermal Cracking at MnROAD Using the Superpave IDT. *Proc. 45th Annual Conference of the CTAA*. Canadian Technical Asphalt Association (CTAA), Winnipeg, Manitoba, 2000, pp. 229-258.
78. Marasteanu, M. O., X. Li, T. R. Clyne, V. R. Voller, D. H. Timm, and D. E. Newcomb. *Low Temperature Cracking of Asphalt Concrete Pavements*. Report MN-RC-2004-23. Minnesota Department of Transportation, 2004.
79. Clyne, T. R., B. J. Worel, and M. O. Marasteanu. *Low Temperature Cracking Performance at MnROAD*. Supplementary Unpublished Report for Lessons Learned Project, Contract No. 81655. Minnesota Department of Transportation, 2006.
80. Vandenbossche, J. and A. J. Fagerness. Performance, Analysis, and Repair of Ultra-Thin and Thin Whitetopping at Minnesota Road Research Facility. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1809*, TRB, National Research Council, Washington, D.C., 2002, pp. 191–198.
81. Vandenbossche, J. M. and D. L. Rettner. *One-Year Performance Summary of Whitetopping Test Sections at the MnROAD Test Facility*. Presented at the 1st International Conference on Accelerated Pavement Testing, Reno, Nevada, 1999.
82. Burnham, T. and D. Rettner. Whitetopping and Hot-Mix Asphalt Overlay Treatments for Flexible Pavement: Minnesota Case History. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1823*, TRB, National Research Council, Washington, D.C., 2003, pp. 3-10.
83. Vandenbossche, J. M. *The Measured Response of Ultra-Thin and Thin Whitetopping to Environmental Loads*. Presented at 7th International Conference on Concrete Pavements, Orlando, Florida, 2001.
84. Burnham, T. *MnROAD Lessons Learned: Thin and Ultra-Thin Concrete Overlays*. Supplementary Unpublished Report for Lessons Learned Project, Contract No. 81655. Minnesota Department of Transportation, 2006
85. Shankwitz, C. and M. Donath. *MIMIC Sensor Technology for Highway Vehicle Applications: Potential and Challenges for the Future*. Report MN-RC-1995-10. Minnesota Department of Transportation, 1995.
86. Shankwitz, C. and M. Donath. *Collision Avoidance: Smart Trucks on Rural Roads*. Report MN-RC-1995-11. Minnesota Department of Transportation, 1995.
87. Shankwitz, C. and M. Donath. *Autonomous Vehicle Guidance Evaluation*. Report MN-RC-1995-12. Minnesota Department of Transportation, 1995.
88. Alexander, L., M. Donath, M. Hennessey, V. Morellas, and C. Shankwitz. *A Lateral Dynamic Model of a Tractor-Trailer Experimental Validation*. Report MN-RC-1997-18. Minnesota Department of Transportation, 1997.
89. Alexander, L., S. Bajikar, H. Lim, V. Morellas, T. Morris, and M. Donath. *SafeTruck – Sensing and Control to Enhance Vehicle Safety*. Report MN-RC-1998-29. Minnesota Department of Transportation, 1998.
90. Alexander, L. and M. Donath. *Differential GPS Based Control of a Heavy Vehicle*. Report MN-RC-2000-05. Minnesota Department of Transportation, 2000.

91. Gorjestani, A., M. Donath, and L. Alexander. *Radar Based Longitudinal Virtual Bumper Collision Avoidance System Implemented on a Truck*. Report MN-RC-2000-07. Minnesota Department of Transportation, 2000.
92. Rajamani, R., A. Shrivastava, C. Zhu, and L. Alexander. *Fault Diagnostics for Intelligent Vehicle Applications*. Report MN-RC-2001-20. Minnesota Department of Transportation, 2001.
93. Donath, M., C. Shankwitz, and H. Lim. *A GPS-Based Heads Up Display for Driving Under Low Visibility Conditions*. Report MN-RC-2003-03. Minnesota Department of Transportation, 2003.
94. Gorjestani, A., L. Alexander, B. Newstrom, P. Cheng, M. Sergi, C. Shankwitz, and M. Donath. *Driver Assistive Systems for Snowplows*. Report MN-RC-2003-13. Minnesota Department of Transportation, 2003.
95. Rakuskas, M., N. Ward, C. Shankwitz, and M. Donath. *System Performance and Human Factors Evaluation of the Driver Assistive System (DAS)*. Report MN-RC-2004-09. Minnesota Department of Transportation, 2004.
96. Rakuskas, M., N. Ward, C. Shankwitz, A. Gorejestani, and M. Donath. *System Performance and Human Factors Evaluation of the Driver Assistive System (DAS): Supplemental Track Test Evaluation*. Report MN-RC-2004-12. Minnesota Department of Transportation, 2004.
97. Wang, J., L. Alexander, and R. Rajamani. *GPS Based Real-Time Tire-Road Friction Coefficient Identification*. Report MN-RC-2005-04. Minnesota Department of Transportation, 2004.
98. Janisch, D. W. and C. M. Turgeon. *Sawing and Sealing Joints in Bituminous Pavements to Control Cracking*. Report MN-RC-1996-27. Minnesota Department of Transportation, 1996.
99. Thomas, J. *Mn/DOT Pavement Smoothness Measuring Device Certification Program*. Commercially Unpublished Report. Minnesota Department of Transportation, 2005.
100. Burnham, T. R. *Application of Dynamic Cone Penetrometer to Minnesota Department of Transportation Pavement Assessment Procedures*. Report MN-RC-1997-19. Minnesota Department of Transportation, 1997.
101. Siekmeier, J. A., D. Young, and D. Beberg. Comparison of the Dynamic Cone Penetrometer with Other Tests During Subgrade and Granular Base Characterization in Minnesota. *Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume, ASTM STP 1375*, S. D. Tayabji and E. O. Lukanen, Eds., American Society for Testing and Materials, West Conshohocken, PA, 1998.
102. Maser, K. *Ground Penetrating Radar Survey of Pavement Thickness on MnROAD Sections*. Report MN-RC-1995-06. Minnesota Department of Transportation, 1995.
103. Loken, M. *Current State of the Art and Practice of Using GPR for Minnesota Roadway Applications*. Commercially Unpublished Final Report for Investigation Number 771. Minnesota Local Road Research Board, 2005.
104. Petersen, D. L. *Continuous Compaction Control MnROAD Demonstration*. Report MN-RC-2005-07. Minnesota Department of Transportation, 2005.
105. Siekmeier, J., L. Petersen, C. Nelson, and R. Peterson. Intelligent Soil Compaction: Technology, Results, and a Roadmap toward Widespread Use. In *TRB 85th Annual Meeting Compendium of Papers*. CD-ROM. Report 06-2914. Transportation Research Board, Washington, D.C., 2006.

106. Olson, R. and R. Roberson. *Edge-Joint Sealing as a Preventative Maintenance Practice*. Report MN-RC-2003-26. Minnesota Department of Transportation, 2003.
107. Biesboer, D. and J. Elfering. *Improving the Design of Roadside Ditches to Decrease Transportation-Related Surface Water Pollution*. Report MN-RC-2004-11. Minnesota Department of Transportation, 2004.
108. Gale, S. and D. Biesboer. *The Effect of Novel Soil Amendments on Roadside Establishment of Cover Crop and Native Prairie Plant Species*. Report MN-RC-2004-41. Minnesota Department of Transportation, 2004.
109. Simpson, Gumpertz, & Heger, Inc. *Performance of Thermoplastic Pipe under Highway Vehicle Loading*. Report MN-RC-2000-22. Minnesota Department of Transportation, 2000.
110. Lukanen, E. O. *An Evaluation of Aggregate and Chip Seal Surfaced Roads at MnROAD*. Report MN-RC-1998-24. Minnesota Department of Transportation, 1997.
111. Johnson, G. D. and D. Baker. *Evaluation of Aggregate Sections at MnROAD*. Report MN-RC-2000-29. Minnesota Department of Transportation, 2000.
112. Wood, T. J. *Low Volume Road Construction with Oil-Gravel*. Commercially Unpublished Report to Office of Materials and Road Research. Minnesota Department of Transportation, 1999.
113. Johnson, G. Minnesota's Experience with Thin Bituminous Treatments for Low-Volume Roads. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1819*, TRB, National Research Council, Washington, D.C., 2003, pp. 333–337.
114. Clyne, T. R., E. N. Johnson, and T. J. Wood. *Performance of Oil Gravel Test Sections in Minnesota*. Commercially Unpublished Report to Office of Materials and Road Research. Minnesota Department of Transportation, 2005

Appendix A

Survey/Interview Subjects for Lessons Learned Project

Name	Title	Affiliation
Beckemeyer, Curt	Vice President	Applied Research Associates, Inc.
Burnham, Tom	Research Project Engineer	Mn/DOT
Button, Joe	Senior Research Fellow	Texas Transportation Institute
Chadbourn, Bruce	Research Project Engineer	Mn/DOT
Clyne, Tim	Forensic Engineer	Mn/DOT
Cochran, George	Retired	Mn/DOT
Corley-Lay, Judith	State Pavement Management Engineer	NCDOT
Dai, Shongtao	Research Operations Engineer	Mn/DOT
Daleiden, Jerome	Operations Manager	Fugro Consultants LP
Darter, Michael	Principal Engineer	Applied Research Associates, Inc.
Dempsey, Barry	Professor Emeritus	University of Illinois
Engstrom, Glenn	Chief Geotechnical Engineer	Mn/DOT
Garg, Navneet	Senior Research Engineer - Technical Lead	SRA International, Inc.
Garrity, John	Bituminous Engineer	Mn/DOT
Geib, Gerald	Pavement Design Engineer	Mn/DOT
Green, Roger L.	Pavement Research Engineer	Ohio Department of Transportation
Grogg, Max	Programs Delivery Engineer	FHWA
Harvey, John	Associate Professor	UC PRC
Izevbekhai, Bernard	Research Operations Engineer	Mn/DOT
Johns, Bob	Director	CTS, UM
Johnson, Dave	Manager (MnROAD)	Mn/DOT
Johnson, Ed	Research Project Engineer	Mn/DOT
Johnson, Greg	Research Project Engineer	Mn/DOT
Kearney, Edward	Director of Engineering	Wirtgen America Inc.
Kim, Richard	Professor	NC State University
Larson, Roger	Senior Engineer	Applied Pavement Technology
Lippert, David	Acting Engineer of Materials and Phys Res	IL DOT
Loken, Marc	Senior Research Engineer	Mn/DOT
Lukanen, Erland	Director	PRI, UM
Mack, James	Senior Engineer	Quality Engineering Solutions
Mallela ,Jag	Group Leader, Research and Technology Transfer	Applied Research Associates, Inc.

Name	Title	Affiliation
Morian, Dennis	Director, Civil Engineering	Quality Engineering Solutions
Mulvaney, Ron	Assistant Concrete Engineer	Mn/DOT
Newcomb, David	Vice President, Research and Technology	National Asphalt Pavement Association
Olson, Roger	Research Operations Engineer	Mn/DOT
Palmquist, Dave	Soils Engineer	Mn/DOT
Rao, Chetana	Engineer	Applied Research Associates
Rettner, Dave	Principal Engineer	American Engineering Testing
Roberson, Ruth	Research Scientist	Mn/DOT
Roesler, Jeff	Assistant Professor	University of Illinois
Salomon, Delmar	President	Pavement Preservation Systems, LLC
Schwartz, Doug	Concrete Engineer	Mn/DOT
Siekmeier, John	Senior Research Engineer	Mn/DOT
Skok, Gene	Retired	University of Minnesota
Snyder, Mark	Consultant	Independent
Strommen, Bob	Site Senior Electronics Technician (MnROAD)	Mn/DOT
Tayabji, Shiraz	Regional Manager	CTL Group
Thomas, Jill	Associate Director	MAPA
Turgeon, Curt	Research Operations Engineer	Mn/DOT
Uhlmeyer, Jeff	Pavement Design Engineer	WSDOT
Van Deusen, Dave	Pavement Design Engineer	Mn/DOT
Vandenbossche, Julie	Professor	UPitt
Von Quintus, Harold	Principal Engineer	Applied Research Associates, Inc.
Wainaina, Njoroje	State Geotechnical Engineer	North Carolina DOT
Wegman, Daniel	Account Manager	Flint Hills Resources
Wood, Tom	Construction Project Manager	Mn/DOT
Worel, Ben	Operations Engineer	Mn/DOT
Zerfas, William	Assistant Pavement Design Engineer	Mn/DOT
Zollars, John	Research Specialist	Mn/DOT

Appendix B

Survey and Interview Questionnaire

FINAL SURVEY FOR ONLINE PUBLICATION

General Information

1. What is your name and affiliation?

Name, Work title

Use of MnROAD

2. Have you worked on or been closely associated with any projects involving MnROAD resources (data, reports, facilities, staff expertise, etc.)?

<yes/no>

2Y. If “yes” to #2, please list each project and its associated results below.

<text field that numbers each project entered>

2N. If “no” to #2, please continue the survey but skip #3, #4, #5, #7, #8.

3. For each project/result described in #2Y, please attach one of the three choices below to describe the importance of MnROAD resources to each project.

<Each of the above enumerated projects from #2Y is associated with one of the multiple choices below>

- A. Essential – MnROAD was the only source for the data needed to accomplish critical tasks
- B. Helpful – the use of MnROAD data enriched the data pool and aided the research
- C. Of no use to the project – the MnROAD data did not contribute to the results for a variety of reasons

4. Outside of your own work, were MnROAD results/data used in any master’s/PhD theses you know of? If so, please list the authors of these theses below, including the publishing university and, if possible, the title/topic of the thesis.

Yes/No, <text>

Implementation of MnROAD

5a. Have any of the results from your work using MnROAD resources been implemented (changed specifications, modified design practices, so on)? If so, what was the impact of each implementation?

<text>

5b. Aside from implementation, in what other ways did your results contribute to the pavement community at large?

<text>

6. How has MnROAD improved both research in pavement engineering and pavements in the field? Please provide a few examples to illustrate the overall improvements brought about through MnROAD.

<text> or Choices?

Referencing of MnROAD

7. How were the results you obtained using MnROAD resources made available to others?
- A. Research reports
 - B. Refereed Papers
 - C. Conference proceedings
 - D. PhD/Master's thesis
 - E. Other (fill-in blank)
8. How did you generally reference the use of MnROAD in reports, papers, etc?
- A. In text
 - B. Footnote/endnote
 - C. Bibliography/References
 - D. Acknowledgements
 - E. Other (fill-in blank)

MnROAD Suggestions

9. What research or analysis not explored by MnROAD could be performed with existing MnROAD data?
- <text>
10. What additional data could have been collected at MnROAD, and what research might have resulted from doing so?
- <text>
11. What additional experiments would you like to see conducted at MnROAD?
- <text>
12. What needs to be done to make the MnROAD data more accessible and usable?
- A. Have not accessed MnROAD data
 - B. The MnROAD data needs no additional accessibility
 - C. Better information on what's available
 - D. Internet access
 - E. More computed parameters
 - F. Other (fill-in blank)
13. What recommendations can you make to improve the MnROAD website as a resource? To answer, choose up to 4 of the following:
- A. The MnROAD website does not need any significant changes
 - B. Search option for MnROAD-related reports
 - C. Data dictionary that gives structure of data, frequency of collection, data types, etc. at MnROAD
 - D. Add abstract to describe reports available at MnROAD website
 - E. Organize/title documents (4 pagers, reports, etc) so they are easier to browse and recognize

F. Other (with fill-in blank)

14. What should be done to increase the influence of MnROAD? To answer, choose as many of the following as you see fit:

- A. More personal interaction of MnROAD researchers with out-of-state organizations
- B. Make data more accessible
- C. Improve website
- D. Standardize referencing of MnROAD reports and data usage
- E. Increased involvement with materials and/or engineering organizations (e.g. ASCE, NSSGA)
- F. Improve data quality
- G. Create and carry out a marketing and technology transfer plan of existing results and opportunities
- H. Other (with fill-in blank)

FINAL INTERVIEW QUESTIONNAIRE

This questionnaire precedes an interview that is part of the research for a project titled “MnROAD Lessons Learned.” The Lessons Learned project aims to formally review MnROAD’s accomplishments, contributions to research, and influence on the pavement community in general.

As the interview will follow this questionnaire very closely, please read the questionnaire ahead of time. Doing so may give you the chance to sort out forgotten dates, names, titles, projects, etc. Feel free to write down any responses you may have and bring those responses to the interview. These written responses will give the research team extra information that the time allotted for the interview could not provide.

General Information

1. What is your name and affiliation?

Name, Work Title

2. When and in what capacity did you first become involved with MnROAD?

Dates, Former Work Title(s)

Work at MnROAD (Use and Implementation of MnROAD)

3. What project(s) did you conduct using MnROAD resources (data, reports, facilities, staff expertise, etc)?

<text>

4. With whom did you work on your MnROAD projects?

<text>

5. What results from your MnROAD work (limited to 3 examples) do you consider the most important?

<text>

6a. How were these results implemented?

<text>

6b. Outside of implementation, in what other ways did your results contribute to the pavement community at large?

<text>

Referencing MnROAD

7. How were your MnROAD-related activities reported?

- A. Published reports
- B. Unofficial reports
- C. Journal/conference papers
- D. Conference presentations
- E. PhD/Master's thesis
- F. Other (fill-in blank)

8a. Did any of your work at MnROAD go unreported? If so, please summarize your unreported work using MnROAD.

Yes/No, <text>

8b. If any of your work using MnROAD went unreported, what complications prevented the publishing of your work?

- A. Not enough resources to properly document findings
- B. Avoidance of documenting negative results
- C. Need to work on other projects
- D. Problems with compliance with strict formatting
- E. Other (please write out)

9. Did you encounter any instances where your work at MnROAD is alluded to in other studies but not formally referenced?

Yes/No

10. How do you reference the use of MnROAD-related results in reports?

- A. In text
- B. Footnote/endnote
- C. Bibliography/References
- D. Acknowledgements
- E. Other (please write out)

MnROAD Suggestions

11. How has MnROAD influenced research in pavement engineering and pavements in the field? Please provide a few examples to illustrate your opinion.

<text> or Choices?

12. What research or analysis not explored by MnROAD could be performed with existing MnROAD data?

<text>

13. What additional data could have been collected at MnROAD, and what research might have resulted from doing so?

<text>

14. If you have used the MnROAD website, what recommendations can you make to improve it as a resource? To answer, choose up to 4 of the following:

- A. The MnROAD website does not need any significant changes
- B. Search option for MnROAD-related reports
- C. Data dictionary that gives structure of data, frequency of collection, data types, etc at MnROAD
- D. Add abstract to describe reports available at MnROAD website
- E. Organize documents (4 pagers, reports, etc) so they are easier to browse
- F. Other (please write out)

15. Which of the following do you feel are most important to increasing the influence of MnROAD? To answer, choose as many of the following as you see fit:

- A. More personal interaction of MnROAD researchers with out-of-state organizations
- B. Make data more accessible
- C. Improve website
- D. Standardize referencing of MnROAD reports and data usage
- E. Increased involvement with materials and/or engineering organizations (e.g. ASCE, NSSGA)
- F. Improve data quality
- G. Create and carry out a marketing and technology transfer plan of existing results and opportunities
- H. Other (please write out)

16. What additional experiments would you like to see conducted at MnROAD?

<text>

17. What researchers with national or international reputations have used MnROAD resources? Yielding what results?

<text>

Appendix C

Summary of Survey/Interview Responses

While this appendix tallies responses from the surveys and interviews, it is important to note that each survey and interview was conducted at the discretion of the respondent. In the particular case of the interviews, while the intent was to follow the questionnaire of Appendix B closely, it became apparent to the Lessons Learned research team after a few interviews that, given the amount of MnROAD information many interview subjects were eager to explore, the questionnaire was, at best, a loose guideline for the interviews. Hence, if the subject did not touch upon certain questions (including multiple choice questions), then those questions were unanswered in favor of a discussion of the other topics that the subject felt were appropriate.

It follows, then, that the following summary does not express a comprehensive view of the subjects interviewed or surveyed, and for this reason, the summary is presented simply to account for the completion of the survey/interview stage of the Lessons Learned project. Also note that “Did Not Respond” (DNR) tallies were counted for subjects who overlooked questions or discussed questions in a superficial manner (i.e. not choosing available multiple choice answers including an “Other” option, if present). Totals for each response are indicated in italics to the right of the response. Write-ins (for “Other” choices) on multiple questions that were submitted by more than one respondent are indicated as well.

FINAL SURVEY FOR ONLINE PUBLICATION

Use of MnROAD

2. Have you worked on or been closely associated with any projects involving MnROAD resources (data, reports, facilities, staff expertise, etc.)?

YES – 13

NO – 11

DNR - 0

4. Outside of your own work, were MnROAD results/data used in any master’s/PhD theses you know of? If so, please list the authors of these theses below, including the publishing university and, if possible, the title/topic of the thesis.

YES – 8

NO – 5

DNR – 11

Implementation of MnROAD

5a. Have any of the results from your work using MnROAD resources been implemented (changed specifications, modified design practices, so on)? If so, what was the impact of each implementation?

YES – 7

NO – 6

DNR – 11

Referencing of MnROAD

7. How were the results you obtained using MnROAD resources made available to others?
- A. Research reports *A – 12*
 - B. Refereed Papers *B – 5*
 - C. Conference proceedings *C – 9*
 - D. PhD/Master's thesis *D – 4*
 - E. Other (fill-in blank) *E – 3*
- DNR - 11*
8. How did you generally reference the use of MnROAD in reports, papers, etc?
- A. In text *A – 8*
 - B. Footnote/endnote *B – 2*
 - C. Bibliography/References *C – 6*
 - D. Acknowledgements *D – 4*
 - E. Other (fill-in blank) *E – 1*
- DNR - 12*

MnROAD Suggestions

12. What needs to be done to make the MnROAD data more accessible and usable?
- A. Have not accessed MnROAD data *A – 8*
 - B. The MnROAD data needs no additional accessibility *B – 1*
 - C. Better information on what's available *C – 12*
 - D. Internet access *D – 11*
 - E. More computed parameters *E – 3*
 - F. Other (fill-in blank) *F – 0*
- DNR - 0*
13. What recommendations can you make to improve the MnROAD website as a resource? To answer, choose up to 4 of the following:
- A. The MnROAD website does not need any significant changes *A – 2*
 - B. Search option for MnROAD-related reports *B – 13*
 - C. Data dictionary that gives structure of data, frequency of collection, data types, etc. at MnROAD *C – 9*
 - D. Add abstract to describe reports available at MnROAD website *D – 14*
 - E. Organize/title documents (4 pagers, reports, etc) so they are easier to browse and recognize *E – 10*
 - F. Other (with fill-in blank) *F – 6*
- DNR – 2*

14. What should be done to increase the influence of MnROAD? To answer, choose as many of the following as you see fit:

- A. More personal interaction of MnROAD researchers with out-of-state organizations *A – 14*
 - B. Make data more accessible *B – 12*
 - C. Improve website *C – 7*
 - D. Standardize referencing of MnROAD reports and data usage *D – 7*
 - E. Increased involvement with materials and/or engineering organizations (e.g. ASCE, NSSGA) *E – 8*
 - F. Improve data quality *F – 3*
 - G. Create and carry out a marketing and technology transfer plan of existing results and opportunities *G – 9*
 - H. Other (with fill-in blank) *H – 8*
- DNR – 0*

FINAL INTERVIEW QUESTIONNAIRE

Referencing MnROAD

7. How were your MnROAD-related activities reported?

- A. Published reports *A – 2*
 - B. Unofficial reports *B – 3*
 - C. Journal/conference papers *C – 1*
 - D. Conference presentations *D – 1*
 - E. PhD/Master's thesis *E – 1*
 - F. Other (fill-in blank) *F – 3*
- DNR - 30*

8a. Did any of your work at MnROAD go unreported?

- YES – 4*
- NO – 1*
- DNR – 30*

8b. If any of your work using MnROAD went unreported, what complications prevented the publishing of your work?

- A. Not enough resources to properly document findings *A – 0*
 - B. Avoidance of documenting negative results *B – 1*
 - C. Need to work on other projects *C – 2*
 - D. Problems with compliance with strict formatting *D – 0*
 - E. Other (please write out) *E – 1*
- DNR – 32*

9. Did you encounter any instances where your work at MnROAD is alluded to in other studies but not formally referenced?

- YES – 0*
- NO – 3*
- DNR – 32*

10. How do you reference the use of MnROAD-related results in reports?
- | | |
|-----------------------------|----------|
| A. In text | A – 1 |
| B. Footnote/endnote | B – 0 |
| C. Bibliography/References | C – 1 |
| D. Acknowledgements | D – 1 |
| E. Other (please write out) | E – 0 |
| | DNR – 34 |

MnROAD Suggestions

14. If you have used the MnROAD website, what recommendations can you make to improve it as a resource? To answer, choose up to 4 of the following:

- | | |
|---|---------|
| A. The MnROAD website does not need any significant changes | A – 1 |
| B. Search option for MnROAD-related reports | B – 9 |
| C. Data dictionary that gives structure of data, frequency of collection, data types, etc at MnROAD | C – 5 |
| D. Add abstract to describe reports available at MnROAD website | D – 3 |
| E. Organize documents (4 pagers, reports, etc) so they are easier to browse | E – 8 |
| F. Other (please write out) | F – 15 |
| | DNR – 7 |

Write-in responses:

Contract firm to revise/maintain MnROAD website – 4

Provide regular updates of MnROAD website – 6

15. Which of the following do you feel are most important to increasing the influence of MnROAD? To answer, choose as many of the following as you see fit:

- | | |
|--|---------|
| A. More personal interaction of MnROAD researchers with out-of-state organizations | A – 9 |
| B. Make data more accessible | B – 10 |
| C. Improve website | C – 4 |
| D. Standardize referencing of MnROAD reports and data usage | D – 3 |
| E. Increased involvement with materials and/or engineering organizations (e.g. ASCE, NSSGA) | E – 9 |
| F. Improve data quality | F – 6 |
| G. Create and carry out a marketing and technology transfer plan of existing results and opportunities | G – 14 |
| H. Other (please write out) | H – 16 |
| | DNR – 3 |

Write-in responses:

Analyze existing data – 5

Appendix D

Suggestions for Future Research

RESEARCH USING EXISTING DATA

Material Studies

1. HMA properties and performance
2. Oil Gravel – Why does it work? Why no thermal cracking?
3. Asphalt aging and construction appearance
4. RAP - ratios of RAP and performance in base/course

Environmental Effects

5. Thermal Cracking – environment and traffic, does traffic just exacerbate existing problems?
6. Thermocouple data – thermal modeling of pavements (10 yrs, every 15 min, thermocouple data throughout pavements)
7. Right lane/Left lane: ride and time/environment on each lane
8. Seasonal effects on IRI
9. Material changes, drainage, and thawing data that has not been analyzed and published

Concrete

10. Forensics on concrete
11. Warp/curl effects – database of warp/curl measurements have gone unused
12. Shrinkage effects (long-term)
13. Relationship between dowel bar size, joint spacing, load transfer

Pavement System Design and Analysis

14. Publish complete design procedure on UTW (after latest construction)
15. Lots of traffic data on weigh-in-motion and need to calibrate continuously - this needs to be followed up on
16. Update empirical design methods using MnROAD data
17. Calibration of strain in computer programs to MnROAD data
18. Ride observations on cell 19 (HMA)
19. LVR: base materials related to cracking/performance
20. Effectiveness of certain bases as relates to pavement performance

Involved Data Analysis

21. Detailed analysis on failure of cells and why
22. Overall attempt to look at design variables in various test sections and make a cross-comparison on the goodness of these variables
23. Strain distribution under loading
24. FWD data - full history of deflections
25. 80K vs. 102K lanes – has overloaded truck caused much more damage to LVR?

PROPOSED RESEARCH

New Experiments

1. Use of a Heavy Vehicle Simulator on MnROAD cells for “overloading” at end of cell life
 - a. Follow-up HVS with forensics
2. Early-on dynamic strain: no early verification
3. Early age strain/climate data in PCC

4. Artificially induced distresses and the rehabilitation of these distresses
5. Noise data
6. Aging of HMA - how has asphalt changed over time
7. Surface friction/Braking forces (wheel on a trailer)
8. Environment-only (unloaded) cell to get “environment-only” data
9. Construction data on cells to explain later distresses
10. Top-down cracking
 - a. Asphalt tensile strength as an initiator of top-down cracking

New Instruments or Pavement Assessment Techniques

11. A way to detect surface temperature at regular intervals (in-place IR camera)
12. Bridge structures - using GPR for bridge assessment
13. More accurate or more confident weigh-in-motion data
14. Use of multidepth deflectometers
15. Use of Georgia fault meter on pavements
16. Additional profile data (to characterize slab geometry w/ changing conditions)

Appendix E

Lessons Learned Technical Briefs

The sections of Appendix E each represent a title and corresponding abstract for the technical briefs produced for the Lessons Learned project. The briefs were authored by the UM research team (with the assistance of John Tweet of UM) and by Ben Worel, Tim Clyne, and Tom Burnham of the Mn/DOT Office of Materials. These briefs are standalone products of the project that detail lesser known or underrepresented MnROAD products. To obtain these briefs, refer to the MnROAD website (<http://mnroad.dot.state.mn.us/research/mnresearch.asp>) or the CTS publications index (<http://www.cts.umn.edu/publications/index.html>).

E.1 Overview of MnROAD Reports

From the start of construction on MnROAD in June 1990 to the conclusion of MnROAD's first ten years of operation in 2004, engineers at MnROAD were busy with a number of core activities: conducting research in pavements, collecting and analyzing data, and developing and maintaining the world's largest full-scale pavement test track. Many of these activities were recorded in a number of reports published by Mn/DOT. Though this brief does not account for all of the hundreds of Mn/DOT reports that mention MnROAD, it will review MnROAD's objectives in research and characterize the reports dealing with MnROAD's activities in its first ten years of operation.

E.2 Guide to the MnROAD Database

MnROAD, located near Albertville, Minnesota (40 miles northwest of Minneapolis-St. Paul) is one of the most sophisticated, independently operated pavement test facilities of its type in the world. MnROAD's Phase-I was completed in 1991-1993, which consists of two unique road segments located parallel to Interstate 94:

- A 3.5-mile mainline interstate roadway carrying "live" traffic averaging 28,500 vehicles per day with 12.4 % trucks.
- A 2.5-mile closed-loop low-volume roadway carrying a controlled 5-axle tractor-semi-trailer to simulate conditions of rural roads.

The MnROAD data is collected in a number of different methods and processes, which impacts the methods that are used to store the data (both calculated and raw). The purpose of this document is to describe what data has been collected and where it is stored for research use.

MnROAD Database consists of the following data sources, which will be covered in this report.

E.3 Educational Benefits of MnROAD

Since opening for operations in 1994, MnROAD has served the pavement community in many capacities. One frequently overlooked intangible benefit of MnROAD's first ten years of operations is the involvement of MnROAD in educating pavement engineers. The educational contributions of MnROAD are most noticeable in the close relationship between MnROAD and the University of Minnesota (UM). The UM/MnROAD partnership has assisted a large number of under- and post-graduate students in their classwork or research, and this partnership is directly responsible for the creation of two dedicated pavement professors in the Department of Civil Engineering at UM. Furthermore, MnROAD has been used throughout its lifespan as a staging facility for a variety of demonstrations and verification testing of a number of issues for all members of the pavement community. The number of MnROAD engineers who have moved on to other positions in pavement engineering and used their MnROAD experience to great success also suggests both the educational benefits and far-reaching influence of MnROAD in pavement

engineering. Finally, MnROAD's extensive database and long history of well-documented research ensures that MnROAD will continue to educate pavement engineers far into the future.

E.4 MnROAD and the Adoption of New Products in Pavements

Throughout its decade of operation, MnROAD has become a major resource in the pavement community for test track expertise, pavement data, and pavement research. However, one overlooked benefit of MnROAD's first phase of operation is the effort of MnROAD engineers to introduce, develop, and encourage the use of new technologies and techniques for pavement engineers. While the list of new products tested and/or developed at MnROAD is extensive, this brief will focus on three products and the influence of those products outside of MnROAD: the Dynamic Cone Penetrometer, used to estimate the strength of subgrades; Ground Penetrating Radar, used in pavements to assess, among other things, layer thicknesses and subsurface conditions; and Continuous Compaction Control, which involves continuously measuring soil compaction and adjusting the needed force to compact the soil. These three highlights emphasize the ability of MnROAD to:

1. serve as a test facility for pavement and pavement foundation experiments,
2. develop new technologies and procedures for pavement engineering,
3. contribute in a significant manner to pavement engineering both at a local and national level.

It is hoped that this brief exposes the reader not only to a few past accomplishments of MnROAD in new technologies but will give a better idea of the promise and ability of MnROAD in the development and adoption of these technologies.

E.5 Low Temperature Cracking Performance at MnROAD

The Minnesota Road Research Project (MnROAD) was constructed in 1990-1993 as a full-scale pavement testing facility. Several different cells were built with various materials, mix designs, and structural designs. Two different asphalt binders were used during the original construction: PG 58-28 and PG 64-22. The sections have all shown various degrees of low temperature cracking. In general the cells with stiffer binder (PG 64-22) experienced a higher number and greater severity of thermal cracks than those with the softer binder. The ride quality of the pavements has been adversely affected by the deterioration of the low temperature cracks.

In 1999 three cells were reconstructed on the Low Volume Road as a study specifically examining low temperature cracking. These sections were designed using the exact same Superpave mix design except for the asphalt binder type, which differed at the low temperature performance grade. The performance grades for Cells 33, 34, and 35 were PG 58-28, 58-34, and 58-40 respectively. After several years in service these sections have begun to show marked differences in performance. Cell 35 has shown the most cracking, even though it has the softest grade at -40. The cracks on Cell 35 do not look like typical thermal cracks, while Cell 33 exhibits the expected typical thermal cracks. Cell 34 had virtually no distress after six years.

E.6 Mechanistic-Empirical Design and MnROAD

In its first ten years of operation, MnROAD's data and road research contributed to many issues in pavement engineering. In particular, MnROAD made its greatest contribution in the field of mechanistic-empirical (ME) design. MnROAD's data has used to calibrate and verify a number of pavement design guides, including MnPave, an ME design program created by MnROAD engineers and adopted by Mn/DOT. Furthermore, the use of this data as inputs into existing

design methods has exposed some of the inadequacies of commonly used design methods. This brief details MnROAD's involvement in ME design and describes the capacity of MnROAD as a lasting influence on mechanistic-pavement design for years to come.

E.7 MnROAD Mainline IRI Data and Lane Ride Quality

Since 1994, MnROAD engineers have regularly conducted ride quality assessments on both the low-volume road (LVR) and mainline test cells and collected the data from these assessments in the MnROAD database. While other facilities and DOTs have observed the ride quality of their roads, none have done so to the extent of the information in the MnROAD database. The data history includes several measurements for each of the 11 years, multiple measurements for particular days, and assessments of the left and right lanes (as opposed to an average assessment across both lanes). One simple analysis that can be accomplished using an extensive history of International Roughness Index (IRI) data is a comparison of the ride quality of the driving and passing lanes in a given pavement. Though even more analysis could be done (seasonal changes in IRI, for example), the lane ride comparison was recently addressed by two graduate researchers at the University of Minnesota. This brief details that analysis for the mainline IRI data and discusses the development of Mn/DOT's IRI specifications and the use of MnROAD test sections to calibrate IRI test equipment.

E.8 Drainage and Pavement Performance

One of the more difficult aspects of a pavement system for the engineer to study is the system's response to moisture. Along with the dynamic (load response) sensors installed during the construction of MnROAD, engineers at MnROAD also installed a variety of sensors to monitor the environmental effects that the pavement systems experience. Furthermore, MnROAD engineers conduct a variety of environmental measurements to monitor the test pavements. After ten years of operation, MnROAD engineers have collected a long history of data for analysis. Furthermore, thanks to the reconstruction of some test cells, MnROAD engineers have been able to develop full-scale experiments to test various hypotheses about pavement drainage. This brief will detail some analysis and experiments using MnROAD data and/or the MnROAD facility.

E.9 MnROAD Observations on Low Volume Roads

In its first decade of operation, MnROAD used its 2.5-mile low-volume road (LVR) for extensive experiments and continuous data collection on a variety of test sections. These efforts have led to a number of benefits to Minnesota roadways and to the larger pavement community. This brief details the low-volume road at MnROAD and the work done using the low-volume road in LVR design, aggregate road studies, and the adoption of new LVR materials. As MnROAD looks forward to its second phase of operation, this brief will provide recommendations for the low volume road and continued benefits of the low-volume road.

E.10 MnROAD Lessons Learned: Thin and Ultra-thin Concrete Overlays

Thin and ultra-thin concrete overlays (also known as whitetoppings) are a pavement rehabilitation option that has been increasing in popularity in the U.S. over the past 15 years. One area of deficiency in the use of ultra-thin and thin concrete overlays is the lack of a rational design method. While several local (1,2) and industry (3,4) design methods have been formulated, few are based on mechanistic-empirical research born out of actual field performance. Fortunately, the Minnesota Road Research Project (MnROAD) has contributed

significantly to the understanding of the field performance of thin and ultra-thin concrete overlays.

In 1997, three thin (TWT) and three ultra-thin (UTW) concrete overlay test sections were constructed on the interstate portion of the MnROAD facility. The objective in locating these thin concrete surface layers on the interstate was to accelerate traffic related distresses. In 2004, after enduring over 6 million concrete equivalent single axles loads (CESALs), the UTW test sections needed to be replaced due to severe surface distresses. Later that year, four new thin concrete overlay test sections were constructed in their place. Table 1 summarizes the experimental designs studied at the MnROAD facility.

The following sections highlight the lessons learned from the testing and monitoring of the MnROAD concrete overlay test sections.

E.11 Non-pavement Research at MnROAD

Since opening for operations in 1994, MnROAD has produced a considerable amount of pavement response and environmental data on its many test sections, and the research and reports resulting from this data are evidence of MnROAD's lasting influence in pavement engineering. The MnROAD facility, however, is capable of experiments, demonstrations, and research outside of pavement engineering, and products from the first ten years of its operation support its use as a non-pavement research facility. The brief describes these non-pavement products, the ability and flexibility of MnROAD staff in adapting the facility to non-pavement research, and the potential of MnROAD to host non-pavement research.

E.12 Climate Research at MnROAD

From the beginning, MnROAD was imagined by its planners as a cold-regions research facility for pavements. In its first decade of operation, MnROAD was the site of numerous experiments whose main aim was to observe the effects of a Minnesota winter (or more than one winter) on the pavement system, from the materials in the surface course to the soils in subgrade. In holding to its goals as a cold-regions research facility, MnROAD engineers developed an extensive knowledge of pavement construction, design, and maintenance in cold-regions climates. In many areas, MnROAD engineers were pioneers in their particular cold-regions study: for instance, MnROAD engineers were some of the first in the United States to closely observe low-temperature cracking in pavements. Furthermore, MnROAD has gathered a significant amount of environmental data and data related to cold-regions phenomena such as low-temperature cracking. This brief details some of the MnROAD products dealing with MnROAD's experience in cold-regions pavements.