

Overview of MnROAD Reports

MnROAD Lessons Learned – December 2006

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1 Abstract

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 MnDOT. Though this brief does not account for all of the hundreds of MnDOT 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.

2 MnROAD Objectives in Research

In the 1980s, the Minnesota Department of Transportation (MnDOT) explored the idea of a Cold Regions Pavement Research Test Facility (CRPRTF), which led to a task force that consisted of MnDOT 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 Witzak, 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. Witzak, the University of Minnesota (UM), and MnDOT engineers, on research objectives for MnROAD. This early focus on research lead 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). MnROAD's progress with these objectives has discussed within a variety of reports and summarizes by the Minnesota Department of Transportation,

Newcomb et al., Worel and Eaton, and Worel et al. (5-9). Many of the points from these summaries will be repeated in the overview of various highlights and their accompanying reports in Section 3.

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:

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

These additional objectives are described in Sections 2.1-2.3.

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.

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.

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 MnDOT's GuideStar or the recent demonstrations of continuous compaction control.

3 MnROAD Experience as Detailed in Reports

In its first ten years, MnROAD has been involved in a number of projects of interest to pavement engineers in the state of Minnesota and throughout the country. Some of these

projects involve dedicated research, while others involve the construction and instrumentation of MnROAD's many test sections. The reports dealing with these projects are detailed in the following sub-sections, which attempt to categorize the reports by general topic. It should be noted that many of the reports are not easily typified by one category and may be mentioned in a number of categories.

3.1 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 to learn 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.

3.1.1 Instrumentation

MnROAD engineers involved in the construction and installation of sensors at the MnROAD site had the foresight to closely detail their experience in MnDOT reports, exemplified by reports such as Baker et al. (10). This report presented step-by-step installation procedures for 16 surface sensors installed at MnROAD to collect data on loading in the test sections. The report also describes testing procedures to verify the operation of the 16 surface sensors and check for any malfunctions, and the report 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 the various manufacturers, and 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 (11). 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 effective (11).

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 this later reporting was published through the MnDOT library. Furthermore, some of the material dealing with instrumentation in both the later

published and unpublished reports is frequently incidental to a larger topic within the report. The published reports include Wang and Baker and Burnham (12, 13).

3.1.2 *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 MnDOT 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 post-AASHO 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 the subgrade and/or base materials include Burnham and Johnson, Newcomb et al. (1994), Burnham, Newcomb et al. (1996), Dai and Zollars, and Dai and Van Deusen (14-19). 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. (20-26). 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, 11, 27, 28).

In addition to cataloging material properties, MnROAD engineers also made careful notes on the manner of testing used to determine material properties. Some of MnROAD's tests lead MnDOT to eventually 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.

3.1.3 *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 2002 MEPDG, and 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. An outstanding overview of the MnROAD database is Worel's "Guide to the MnROAD Database" (29).

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 (30). Later reports typically allude to procedural testing for non-automated data; however one example that details these procedures specifically is Burnham (31). 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 act as 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 (32-36). The most recent of these documents, by Lau and Strommen, illustrates the development of and existing calibration procedures for MnROAD's MEGADAC data acquisition system (37).

3.1.4 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 abused 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 (38-40). As only one of the reports is published through the MnDOT library, these documents suffer from a low visibility. However, were they more widely read, their value to the pavement community would become immediately evident both in the observations made and the procedure employed to make those observations.

3.2 Cold-Regions Research

By closely studying MnROAD's original research objectives, it is clear that MnROAD was originally designed as a so-called thickness, or structural, experiment. That is to say that MnDOT engineers set out to use the full-scale facility at their disposal to determine how thick a given pavement needed to be to perform adequately in a cold-region environment. However, MnROAD engineers quickly observed, with a little help from low-temperature cracking in their test sections, that the true question of a cold-regions pavement facility is eventually one of environment. Most early studies in cold-regions research focused on predictions of frost depths or material responses to freezing, such as the work of Bigl et al. (41, 42).

However, as the seasons accumulated on the test sections, later research focused on seasonal variations in pavement systems and low-temperature cracking. Both areas were immediately influential: in the state of Minnesota, legislation resulting from the seasonal variation research was estimated to have saved the state millions of dollars annually in maintenance and rehabilitation costs. Furthermore, MnROAD's experience in low-temperature cracking made it the sole facility in the world collecting extensive and well-documented data on this relatively understudied phenomenon.

3.2.1 Seasonal Variations in Pavements and Seasonal Load Limits

One of MnROAD's most publicized benefits to the state of Minnesota has been in the field of seasonal variations in pavements, and 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 (43).

This innovation in the approach to pavement and environment led to legislation concerning spring load restrictions for Minnesota's roadways (44, 45). The MnDOT 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 (46). Ovik et al. continues to raise interesting questions at MnDOT outside of seasonal variation: for instance, some limited data in the report suggests a comparison of MnDOT Base Classes 3, 4, 5, and 6 that many MnDOT officials feel could be the starting point of necessary research as aggregate shortages become more problematic in the state of Minnesota (43).

3.4 *MnPave and Local Road Design*

MnROAD's first contribution to a mechanistic-empirical design specific to MnDOT 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 (47-49). 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, MnDOT 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 (50, 51). Later MnDOT reports by Skok et al. builds upon the earlier work in LVR design by updating the design for Minnesota using MnPave (52, 53). These reports are the basis for a reliable, consistent design based upon local environmental data and pavement response data from MnROAD.

3.2.3 *Low-temperature 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 (54-57).

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, but 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 MnDOT that uses MnROAD data to attempt to model and account for the thermal cracking observed at MnROAD (59).

MnROAD's interest in preventing thermal cracking has led to experiments with new materials such as emulsified oil-gravel surfaces (see Section 3.8).

3.3 Drainage and Environmental Sensors

While engineers at MnROAD have collected a large amount of environmental data, they have also been able to construct full-scale experiments to evaluate the effects of certain variables on pavement systems. MnROAD's controlled live traffic allows researchers a safe test facility in which they can build and modify experiments. Some of these experiments in drainage took place during MnROAD's first ten years of operation and are detailed in reports.

In a paper prepared for the annual meeting of the Transportation Research Board, Ruth Roberson of MnDOT and Bjorn Birgisson of the University of Florida use the MnROAD facility and its data to study pavement drainage and use this study to design and construct two drainage configurations. While the authors initially intended to compare the two edge drains, they found that this comparison was made difficult by the fact that both schemes drained the systems in a limited capacity. For this reason, the authors recommend that the practice of retrofitting existing pavements with drainage schemes be reconsidered (60).

Another report by Olson and Roberson examined two similar concrete test sections with bituminous shoulders and edge drains. 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 preventative maintenance for pavements (61).

Other reports by Clyne et al. and Wang and Baker describe methods of collecting data on the saturation levels of pavement systems (62, 12). Ariza and Birgisson detail using various software models to determine the water flow through a pavement system, while Gupta et al. examines the materials in the base layers of the system and the abilities of the materials to retain water (63, 64).

3.5 Mechanistic-Empirical Design Verification

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 (65, 66). Other early work by Berg used MnROAD data to calibrate a frost depth prediction model (67).

Another significant project at MnROAD by Thomas Burnham and William Pirkl involved the application of data characterizing concrete test sections to the MnDOT 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 (68). 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; and
- evaluations of drainage models for pavement systems.

These reports include and are not limited to the work of Alvarez and Thompson, Ariza and Birgisson, Bao, Forst, Holewinski et al., Marasteanu et al., Mateos and Snyder, Wu et al., and Zhang et al. (69-75).

Though not a document produced during MnROAD's first ten years of operation, an NCHRP report to be published in late 2006 details the significant amount of MnROAD data and pavement expertise that has gone into the mechanistic-empirical design procedure under NCHRP Project 1-37A that is commonly known as the 2002 Mechanistic-Empirical Pavement Design Guide (MEPDG) (76). 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 (38-40). Furthermore, the thermal cracking model used by the MEPDG was calibrated using MnROAD thermal cracking. PCC performance and temperature data were used to re-calibrate the rigid models of the MEPDG and verify the Enhanced Integrated Climatic Model (EICM) predictions respectively.

3.6 Whitetopping

The process of overlaying asphalt pavements with thin concrete layers, known as whitetopping, is one that has been studied by MnDOT since 1993 and at MnROAD since 1997. Since that time, MnDOT 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 (77, 78). MnDOT 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 (27, 28, 79). 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 (80). In the course of just under four years, MnROAD engineers went from having little to no whitetopping experience to being a driving force behind the design and construction of whitetopping for asphalt pavements in the United States.

3.7 Aggregate Roadways

MnDOT and LRRB commissioned a report on MnROAD's aggregate road test sections shortly before the removal of those sections from MnROAD's low-volume loop test sections. This report by Lukanen determines a strong relationship between washboarding and the number of truck passes, which is that 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. Lukanen 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. Lukanen concludes by noting that aggregate gradations are not reliable predictors of performance in an aggregate road (81).

A second report on the aggregate sections, by Johnson and Baker, concludes MnROAD's experience with its aggregate test sections by discussing the sections in close detail, from construction to load response to distress observations and so on. Johnson and Baker make a few interesting observations on the rate of freezing and thawing under aggregate roads. The report states that 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 (82). Johnson and Baker's report was the "last word" 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.

3.8 Oil Gravel

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 hot mix asphalt (HMA) mix, 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 (83). 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 (39). This section was replaced, but two of the original three oil-gravel sections remain at MnROAD. These sections have performed very well, and unlike their HMA counterparts, have resisted thermal cracking entirely (84, 85). MnROAD's experience in oil-gravel roads combined with the remainder of MnDOT's experience with oil gravel throughout the state has helped to educate municipal and city engineers about oil gravel, a new pavement technology for road rehabilitation that would have gone unexplored had it not been for MnROAD's partnership with FINRA.

3.9 Exploration of New Technologies

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 (86, 87). 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 by MnDOT across 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 (14). Given the large amount of use the DCP devices 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 (15, 17). MnROAD's efforts with DCP have influenced MnDOT and its assessment of subgrades and pavement systems in the field and have been documented by Burnham (88), and in a report Siekmeier et al. go to great lengths to compare the DCP against other tests to assess soil compaction (89).

MnROAD has been instrumental in the adoption of GPR by MnDOT. 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 (90). 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 the first use of GPR at MnROAD, MnDOT has expanded both its GPR equipment and user expertise thanks to MnROAD. More importantly, MnDOT has expanded the number of fields in which GPR is a useful non-destructive method of assessing a given situation (91).

3.10 SafeTruck

The establishment in 1991 of the Minnesota Guidestar program, a cooperative initiative between MnDOT, 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 MnDOT 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 (92).

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 (93-95). The sum of this early work is recounted in a MnDOT report titled “SafeTruck – Sensing and Control to Enhance Vehicle Safety” (96).

Later work under the Guidestar aegis 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 (97). 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 (98). 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 (99-102). In 2004, UM researchers published the MnDOT 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 (103). Recent work has used MnROAD as a test site for an on-board system to estimate the tire-road friction coefficients in real-time using DGPS (104).

3.11 Continuous Compaction Control

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 (105).

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 MnDOT is also lending its MnROAD-derived experience to an FHWA-led IC Pooled Fund study (106). 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.

3.12 Environmental Biology

A number of experiments have been conducted at MnROAD that deal with issues in environmental biology. MnROAD is an especially attractive test site for experiments that

require an awareness of environmental conditions. 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 field-monitoring program that monitors the ability of roadside plants and a check dam in removing pollutants from storm water that ran off a pavement (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 a transportation-related experiment made much more accessible by the existence of MnROAD in terms of 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.

Finally, the use of MnROAD as a test site has allowed for an understanding of erosion control that has been incorporated into MnDOT's "Erosion Control Handbook for Local Roads" (109). This is another less visible example of MnROAD influencing pavements in Minnesota at the local level.

3.13 Top-down Cracking

A recent subject of intense study in pavements, top-down cracking has not been ignored by researchers at the University of Minnesota. In cooperation with MnROAD, and using MnROAD data, these researchers have investigated top-down cracks and the surface stresses that may cause these cracks. Reports by Holewinski et al., Soon et al., and Wang et al. describe these efforts to better understand top-down cracking using new theories and tools (110, 111, 104).

3.14 Miscellaneous Reporting

Another non-pavement experiment conducted at MnROAD was the installation of larger culverts, made of corrugated polyethylene, under 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 (112). 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.

MnROAD has also been used as site for equipment certification, as exemplified by documents by Janisch and Thomas (86, 87). Reports such as Burnham and Johnson

and Petersen also exhibit the use of MnROAD as a demonstration and/or test site for pavement-related equipment (14, 105).

4 Contributions of MnROAD Reports to Pavements

MnROAD reporting has provided the pavement community with a continual stream of well-documented research. Furthermore, this reporting has also encouraged other researchers and practitioners in pavements to take advantage of MnROAD's extensive library of pavement response and environmental data.

In both its reporting and database, MnROAD is among the forefront of pavement research facilities in the world. MnROAD is the premier facility for cold-regions research, and the extremes of Minnesota's seasonal variation position MnROAD as a site that provides a wealth of conditions for any pavement experiment. The extent of MnROAD's database and MnROAD's experience in test track know-how, construction techniques, material properties, and pavement research have ensured that MnROAD products will be a starting point in pavement research for decades to follow.

5 Recommendations

The main lesson from MnROAD's first ten years in terms of reporting is that in order for practitioners and researchers in pavements to be aware of work involving MnROAD, someone in the process of creating and publishing a given report or brief must make that work visible and easily accessible. The question is how to make these reports most visible and accessible. In reviewing the many reports for the Lessons Learned project, the research team felt that the MnDOT library provides MnDOT and MnROAD engineers with an adequate outlet for their publishing needs. The MnDOT library subjects the reports to editorial review, attaches important keywords to the reports, and then catalogues the reports so that they are easily discovered and obtained by interested parties from around the world.

The number of unpublished reports or reports that have been abandoned to a URL on the MnROAD website is just as large, if not larger, as the number of MnROAD reports published through the MnDOT library. While publishing MnROAD-related reports through the MnDOT library may create additional work for MnDOT engineers, it seems that the library is the best means for MnROAD to create a catalogue of reports. In doing this, MnROAD takes a step toward making its reports much easier for other researchers and practitioners to find, review, use, and cite in other work. As it stands, many of the unpublished MnROAD reports are difficult to cite because the rigor of other publishing libraries (such as the Transportation Research Record) do not allow authors to cite unpublished reports or papers.

This recommendation should not be considered in a negative light, however. The fact that MnDOT engineers have taken the time to follow-up on their analysis and produce reports, regardless of the visibility of those reports, is evidence of the considerable pavement knowledge to come out of MnROAD in its first ten years of operation.

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