

## **Mechanistic-Empirical Design and MnROAD**

MnROAD Lessons Learned – December 2006

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### **1 Abstract**

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 MnDOT. 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.

### **2 Background**

In its fourteen original objectives for research, MnROAD had a significant focus upon both verifying and developing mechanistic-empirical (ME) models for pavements using MnROAD data. At the time of the creation of these objectives, the empirical data for existing design methods came from the AASHO Road Test of the late 1950s and early 1960s. Seeing as how a number of important variables had changed since the time of the AASHO Road Test (e.g. both frequency and maximum weight had increased), MnROAD recognized the opportunity to re-evaluate the standard design procedures, all of which were built upon the same AASHO Road Test data. This re-evaluation would of course begin with the material, environmental, traffic, and response data from MnROAD and then involve the analysis of MnROAD/MnDOT engineers or other out-of-state researchers.

As reflected by MnROAD's research objectives, pavement engineers and pavement design methods of the early 1990s were concerned almost exclusively with design thickness. Soon after opening to traffic, MnROAD began to observe that its test sections were experiencing more distress and damage from environmental effects than from traffic. In line with this observation, many MnROAD engineers were quick to point out during the Lessons Learned project that "MnROAD was a thickness experiment that turned into an environmental experiment." Hence, MnROAD engineers were quick to shift their focus on thickness to a new emphasis on environmental effects in the performance of a given pavement system. This shift succeeded, of course, excellent work dealing with the "thickness" question that will be detailed later in this brief, including an evaluation of concrete design methods and the development of a local mechanistic-empirical design method known as ROADENT.

After observing the effects of environment on MnROAD's test sections, cold regions studies became a priority for MnROAD. Much of this work centered around seasonal variations in pavements and accounting for these effects in the MnPave design method under development by MnROAD engineers. Other work involved closely observing and recording low-temperature cracking and working toward a model of this

phenomenon. Many times, the work in cold regions topics coincided with pavement design, and this brief will summarize the work in a few of these topics.

Overall, MnROAD continued to be a source for a number of more general topics in pavement design and modeling. Its main focus as a source has been the contribution of pavement data and expertise in one or more of the following:

1. climatic data;
2. traffic information;
3. construction and material information; and
4. pavement performance and response data

This brief will also detail MnROAD's contribution of the above critical data sets to general topics in mechanistic-empirical research, including NCHRP Project 1-37A, the Mechanistic-Empirical Pavement Design Guide (MEPDG), and pavement modeling.

### 3 MnROAD Research and Data in Mechanistic-Empirical Design

MnROAD experience in and contributions to research in pavement design and modeling were some of the foremost concerns of its first ten years. The following topics present some experiences that point to the value of MnROAD and MnROAD data in advancing the state-of-the-art in pavement design methods and models.

#### 3.1 Cold-regions Design and Modeling

An early partnership between MnROAD and the U.S. Army Cold Regions Research and Engineering Labs (CRREL) represented some of the first work to use MnROAD data to refine a mechanistic-empirical design method. In the case of the CRREL work, researchers at CRREL used MnROAD test section data to further develop their mechanistic pavement design procedure for seasonal frost areas. A main reason that the MnROAD facility was attractive to CRREL for its research can be found in sources such as Figure 1.

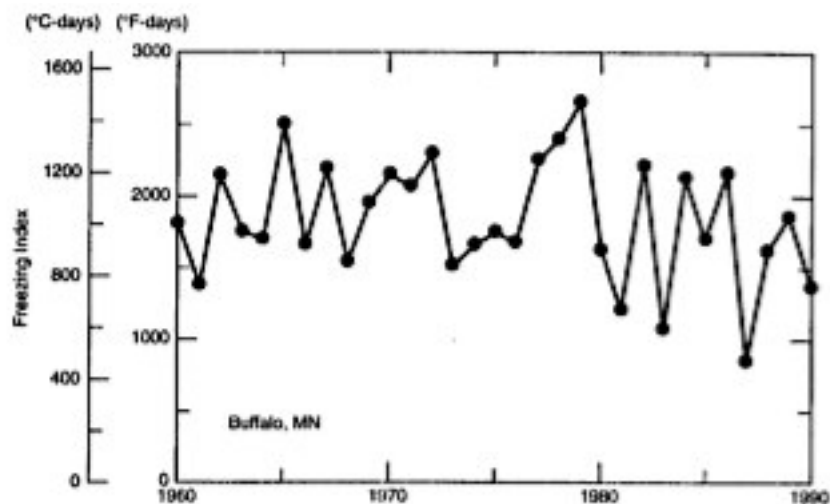


Figure 1. Seasonal freezing index with time at Buffalo, Minnesota (Bigl and Berg 1996).

The relatively high freezing indices repeated over the course of thirty years is evidence of the fact that MnROAD experiences the “cold” in cold-regions research, and for this reason CRREL partnered with MnROAD for a number of research topics in the first

years of MnROAD's first decade. This work was detailed in MnDOT Report 1996-22 by Bigl and Berg and MnDOT Report 1996-23 by Bigl and Berg.

The CRREL research began with extensive laboratory tests on materials from MnROAD test sections. (These tests are described in the Lessons Learned technical brief on Climate Studies at MnROAD.) The material studies conducted by CRREL contributed the necessary input parameters for CRREL to model test sections at MnROAD and predict performance. The first of CRREL's two MnDOT reports gives details about the nature of CRREL's mechanistic design procedure and its four components:

1. FROST, to predict the amount of frost heave, settlement, temperature, water content, pore water pressure, ice content, and density of the pavement structure and its components;
2. TRANSFORM, to divide the structure into layers and assign each layer a corresponding resilient modulus, Poisson's ratio, and density value;
3. NELAPAV, to calculate the stresses, strains, and deflections at a given location in the pavement using a nonlinear layered elastic model
4. CUMDAM, to calculate the damage experienced by the pavement system.

Fine points on these components are provided by CRREL in MnDOT Report 1996-22.

The modeling done by CRREL using MnROAD data had three phases that are closely detailed in the CRREL reports. CRREL's first simulation was to model temperatures from a year close to the mean freezing index and apply these conditions to eleven test sections at MnROAD. The second simulations were for adjustments in parameters and special environmental conditions (temperature extremes, etc.) over a season on a total of nine test sections. The third and final simulation was to model two test sections over 21 seasons. Overall, the models suggested that mechanistic design was very uncertain in predicting the performance of a pavement system. However, the research provided CRREL with an opportunity to refine their mechanistic procedure and prepare for MnROAD environmental and performance data to refine their models. Unfortunately, the comparison and use of this data was never put into practice by CRREL due to time constraints.

Later work by Berg in MnDOT Report 1997-21 calculated maximum frost penetration depths, using the modified Berggren equation, for the test sections at MnROAD over three winters. These calculated depths were then compared against the measured frost depths for the same period of time and discussed. Berg found that the calculations overestimated frost depths substantially. As the author suspected that some of this error might have been due to measurement error, Berg recommends that MnROAD reevaluate its measurement data from the test sections that were particularly divergent from the expected frost depths. Berg also found, however, that by adjusting certain inputs (thermal conductivity of materials and mean annual soil temperature), he was able to obtain calculations that better agreed with MnROAD measurements. Berg's study, as an appendix to the CRREL reports, concludes by providing MnROAD with more directions for research and environmental measurements.

### **3.2 Evaluating Concrete Design**

Another early project at MnROAD was described in MnROAD Report 1997-14 by Thomas Burnham and William Pirkl. This research project involved the application of

data characterizing MnROAD 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). This report sought to examine the parameter values used as inputs for the respective designs and determine the predicted service lives of these test sections using each of the three design methods and the parameter values.

The first step in this process was to determine the needed parameter values for each design method based upon MnROAD data at hand. These parameter values were then compared to the assumed values used to design the sections at the time of their construction. Burnham and Pirkl discovered a number of discrepancy between the assumed and as-built parameter values for each of the three design methods. While some of the discrepancies could be explained by construction or material difficulties, the authors felt that others spoke to the limitations and assumptions involved in certain influential parameters. The authors made recommendations for future research on other parameters that could not be addressed in the scope of this report (load transfer and drainage coefficients).

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. The 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 as noted by survey subjects in the Lessons Learned project, this particular study illustrated that the concrete design methods of the early 1990s were inadequate.

### **3.3 ROADENT**

In the planning stages of MnROAD, one of the primary research concerns, as mentioned above, was the creation of a Minnesota-specific mechanistic-empirical design method for pavements that was both built upon MnROAD data and developed locally by MnDOT and UM researchers. This objective was realized through an FHWA pooled fund study involving MnDOT whose product was the flexible design procedure known as the "Minnesota Method," which was incorporated into the flexible thickness design program called ROADENT. ROADENT was developed by David Timm, David Newcomb, and Bjorn Birgisson of UM and called upon the expertise of a number of MnROAD engineers.

The so-called heart of ROADENT—that is, its mechanistic pavement model—is the Waterways Experiment Station Layered Elastic Analysis (WESLEA) to for design and analysis in a flexible pavement system. WESLEA uses information for loading, layer thickness, layer modulus of elasticity, and layer Poisson's ratio for up to five layers to calculate critical strains in the system. Based upon an evaluation of existing layered elastic analysis programs using MnROAD response data, UM researchers felt that WESLEA would best serve the Minnesota method of flexible pavement design.

ROADENT handles inputs in a number of innovative ways. First is ability to use load spectra, in addition to ESALs, to describe traffic. Furthermore, in concert with work in seasonal variation in pavements that would later be published in MnDOT Report 2000-35 by Ovik et al., ROADENT accounts for the seasonal variability of the pavement

system by requiring the seasonal modulus value and season duration for that modulus for each layer. A seasonal temperature for that season is also incorporated to account for variability in the asphalt surface. To incorporate reliability analysis into ROADENT, layer moduli and thickness variability were established by UM researchers using data from MnROAD.

Researchers also calibrated the performance transfer functions used by the fatigue and rutting equations in predicting pavement distress and failure. These transfer functions were calibrated using MnROAD data. Finally, ROADENT calculates damage on a given pavement system using Miner's hypothesis. The flowchart for the mechanistic-empirical design of ROADENT is illustrated by Figure .

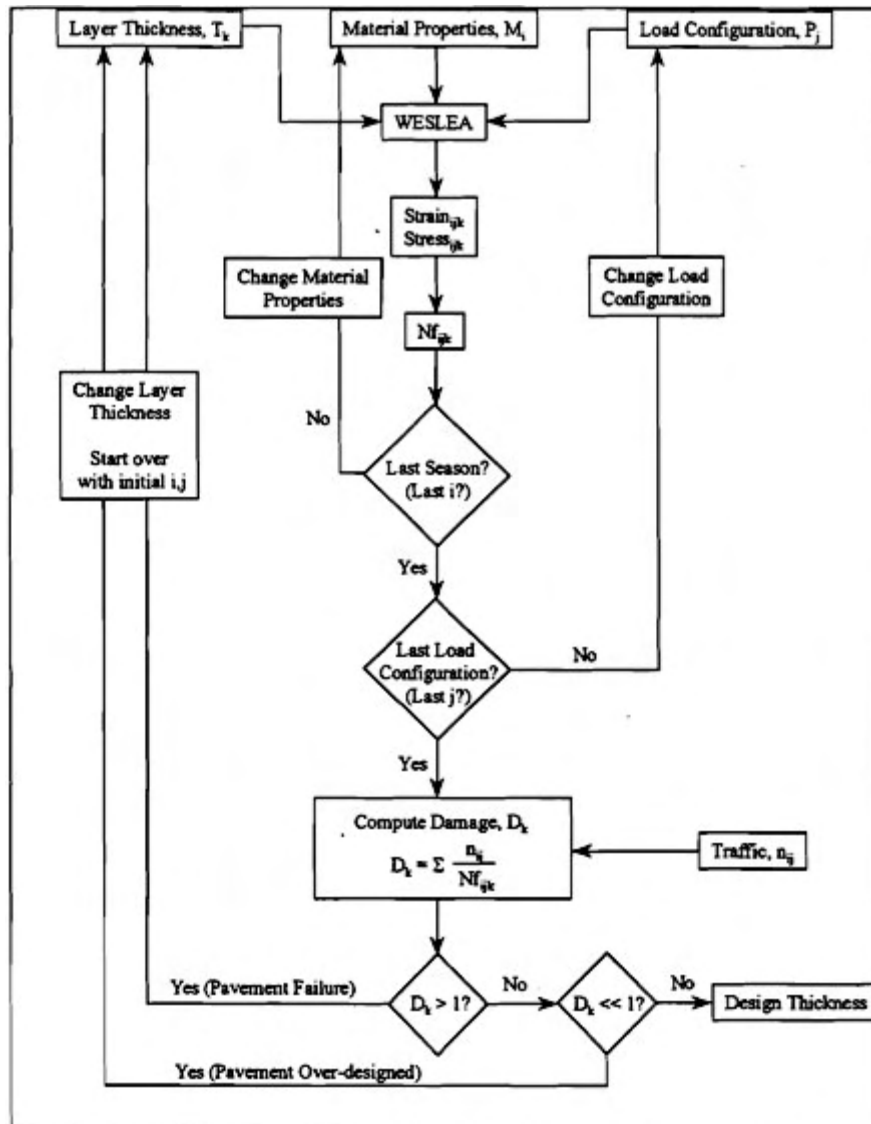


Figure 2. Minnesota flexible design flowchart (Timm et al. 1999)

While this design procedure was used locally, due to the large number of calculations involved in specifying ROADENT to the user's needs, MnDOT pursued an expansion

upon ROADENT in terms of the front-end experience. This expansion became what is now known as MnPave.

### 3.4 MnPave

The MnDOT flexible pavement design method, built upon ROADENT, was integrated into a software package called MnPave in 1999. MnPave is designed to make pavement design methods more accessible to practitioners in pavements. The MnPave software utilizes a graphical user interface that allows users to point and click to adjust various inputs in the design. As MnPave is built on ROADENT, many of the features of ROADENT are reproduced in MnPave.

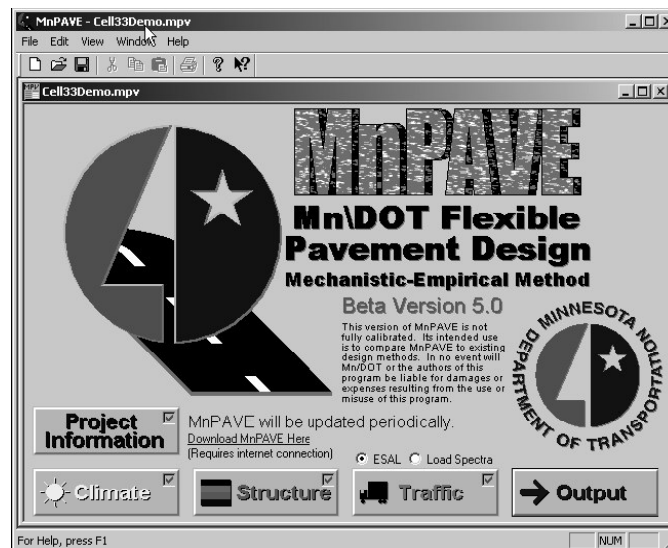


Figure 3. The start-up screen of MnDOT's MnPave Design software (Chadborn et al. 2002).

The MnPave package also places an emphasis on seasonal affects and the work done in MnDOT Report 2000-35 by Ovik et al. This work includes dividing the year into five seasons, two of which are “Early Spring” and “Late Spring.” These periods are defined by the level of moisture in the aggregate base and the degree of freezing in the subgrade: these factors contribute largely to layer stiffness. Furthermore, MnPave allows users to characterize the duration of their seasons. By placing the so-called fifth season front and center in the MnPave software, MnDOT is introducing to state and local pavement engineers the idea that thickness concerns must be considered alongside and understanding of climate and environment.

The MnPave software has been adopted across the state quite readily. Low-volume road construction practices for the state of Minnesota were revised in 2002 (in MnDOT Report 2002-17) to account for the existence of MnPave. Furthermore, MnPave is used in a number of pavement engineering classes at UM to educate students on pavements and introduce them to tools for pavement design. These and other steps taken to promote MnPave ensure that regional mechanistic-empirical design methods, especially those such as MnPave that account for seasonal variation, will be closely studied and familiar to the next generation of pavement engineers.

### 3.5 Mechanistic-Empirical Design Guide

As the creators of the MEPDG recommend that local agencies should verify and calibrate the MEPDG prior to implementation, MnDOT and UM used MnROAD data substantially in adapting the MEPDG for Minnesota environmental conditions. The data generally required in this process is that of: climate, traffic, construction/materials, pavement performance, and pavement response. It goes without saying that MnDOT called upon the resources of MnROAD to provide this data in considerable detail.

MnROAD climate data was useful in verification of the EICM temperature predictions for concrete pavements. Weigh-in-motion (WIM) data collected on the mainline test sections provided critical traffic data and allowed for a comparison of MnROAD's traffic versus the predicted traffic by the MEPDG's assumed traffic. As the MnROAD database has distinguished itself from other databases with the spectrum of information it provides on the construction and constituents of its test sections, there was no lack of material or construction data for the verification/calibration efforts. Finally, it was in pavement response/performance data where MnROAD was particularly useful.

Forensic trenching work done at MnROAD provided very distinctive information to the verification/calibration of MEPDG, so much so that the information recovered from the forensic studies of rutted test sections was incorporated into the general rutting models of the MEPDG. This information was discussed in reports by Isackson et al. and Mulvaney and Worel. These reports contributed to MEPDG's ability to predict rutting by accounting for the structural failure of pavement system in rutting and examining the rutting in various lifts of the pavement. This information was invaluable during calibration of the MEPDG and will be detailed in later documents to come out of the MEPDG project.

#### **4 MnROAD Contributions to Mechanistic-Empirical Design**

MnROAD's most important contribution to the pavement community is arguably its contributions to mechanistic-empirical design. MnROAD data has provided valuable input to a variety of mechanistic-empirical design methods and models. More importantly, MnROAD strain gauge data has been used to verify that layered elastic theory, an assumption upon which most flexible design methods and models are based, is a valid approximation of pavement response. This verification is taken for granted by so many researchers that it is virtually ignored. However, in confirming that the assumptions of layered elastic theory can be used as an approximation of pavement response and thus are a valid basis for mechanistic-empirical design, MnROAD indirectly bolstered all existing flexible design methods, including MnPave and MEPDG.

Also in line with this verification of layered elastic theory is MnROAD's work in evaluating existing pavement design methods for concrete (rigid) pavements. The work in MnDOT Report 1997-14 was non-anecdotal evidence of the fact that the mechanistic-empirical design methods of the early 1990s were not adequately predicting performance of pavements, which led to many costly under- and over-designed roadways. Many professionals in pavement engineering feel that this contribution alone justifies MnROAD's entire first ten years of existence—such is the need for non-anecdotal evidence on a full-scale basis about pavement design methods.

MnROAD has also been a valuable source of quality data to professionals working on pavement design. The most notable example of this is MnROAD's

relationship with MEPDG. Not only has MnROAD data been used by the MEPDG, a great deal of MnROAD expertise and observations have gone into the MEPDG as well. For instance, the MEPDG software currently assumes that traffic volume is uniform throughout the year. Analysis of MnROAD traffic data has shown that this assumption is not valid for the WIM on the mainline test sections. Furthermore, as noted above, MnROAD's forensic trench studies provided the MEDPG with new insights on rutting. In providing its data for studies in pavement design, MnROAD has most notably been of great assistance to those looking to verify the predictions of a given method or model. All of the above highlights feature some kind of verification, most notably that of MnPave, which is built upon MnROAD data and expertise.

## 5 Recommendations

MnROAD's contributions to pavement design methods and pavement modeling are one of MnROAD's strongest virtues in its first ten years. By making its data public and openly discussing MnROAD experiences with its test sections, MnROAD engineers made its data and pavement expertise a desired commodity for pavement engineers seeking to verify or calibrate their method or model with empirical data. For this reason, very few recommendations that have not been stated in other briefs are possible in regards of additional contributions of MnROAD to pavement design methods or pavement models. In following other Lessons Learned recommendations, such as those addressing MnROAD's database or its release of information, MnROAD will in turn make its contributions to pavement design and modeling even more influential. So long as MnROAD's focus remains, in part, upon providing detailed climatic data; traffic information; construction and material information; and pavement performance and response data, MnROAD data will influence pavement design methods and pavement models for decades to follow.

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