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Integrated Tools for Pavement Design and Management

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February 2014

Research Project
Final Report 2014RIC14

LRRB
LOCAL ROAD RESEARCH BOARD

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
2014RIC14		

4. Title and Subtitle

Integrated Tools for Pavement Design and Management

5. Report Date

February 2014

6.

7. Author(s)

W. James Wilde

8. Performing Organization Report No.

9. Performing Organization Name and Address

Center for Transportation Research and Implementation
Minnesota State University, Mankato
342 Trafton Science Center N.
Mankato, MN 56001

10. Project/Task/Work Unit No.

11. Contract (C) or Grant (G) No.

(C) 94288

12. Sponsoring Organization Name and Address

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, MN 55155

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

http://www.lrrb.org/pdf/2014RIC14.pdf

16. Abstract (Limit: 250 words)

This report provides a brief overview of recent research and current usage of various pavement-related topics in Minnesota, including:

Use of RAP in local pavement design,
Implementation of an updated vehicle classification scheme,
Pavement design charts for ten-ton designs,
Revision and update of the FWD Viewer Tool, and
Overlay design method for the FWD Viewer Tool.

The review of these topics includes recommendations for further study or for implementation. The two topics related to the FWD Viewer Tool were investigated further, including implementation which was included in this project. Implementation activities included development of spreadsheet tools and statewide training among local transportation engineers for their use.

17. Document Analysis/Descriptors

Recycled materials, Vehicle classification, Pavement design, Ten-ton, Falling weight deflectometers, Asphalt pavements, Overlays (Pavements)

18. Availability Statement

No restrictions. Document available from: National Technical Information Services, Alexandria, VA 22312

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	39	

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Acknowledgements

This project was funded by the Minnesota Local Road Research Board and the State Aid Division of the Minnesota Department of Transportation. The project team would like to thank the engineers and staff in the MnDOT State Aid Division for their assistance in this project, as well as the members of the technical advisory panel, who were instrumental in the development of the project and the associated tools. The expertise and experience of the panel members were invaluable throughout the project.

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Executive Summary

This report describes the evaluation of several topics of interest to the Minnesota Local Road Research Board (LRRB) and the State Aid Division of the Minnesota Department of Transportation (MnDOT). Initial reviews were conducted on the following topics.

- Use of RAP in Local Pavement Design
- Implementation of Vehicle Classification Update
- Ten-Ton Pavement Design Charts
- Update of FWD Viewer Tool
- Overlay Design Method for FWD Viewer Tool

For each topic in the list above, a review of current literature and other activities was conducted. Recommendations from the literature were compiled, and a full set of recommendations was developed.

The two topics related to the FWD Viewer Tool were selected for further investigation and implementation. The tool update was completed first, and subsequently was updated further through another project with the LRRB and the MnDOT State Aid Division, and is reported in the Implementation of TONN 2010 report, currently in the publication process. The overlay method for the FWD Viewer Tool was added to this project after the first version of the tool had been completed. As each version of the tool was completed, a set of training sessions were developed and delivered to the users of the viewer tool. The audience for these training sessions was primarily engineers at county highway agencies.

Chapter 1. Introduction

This report describes the results of efforts by Minnesota State University, Mankato (MSU) to evaluate several topics of interest to the Minnesota Department of Transportation (MnDOT) and the Minnesota Local Road Research Board (LRRB). In some cases, the results of the evaluations conducted for this project were recommended for implementation, and appropriate measures were taken to move forward. For other topics, implementation plans and actions were not requested. In those cases, recommendations were made and no further action has been taken by MSU.

Project Objectives

The primary objective of this project was to review existing methods, data and tools for pavement design, maintenance, and rehabilitation and to recommend implementation and/or training needs for each. Individual evaluations were conducted for several topics. From those evaluations, implementation plans and training recommendations were made. For one tool, the implementation plans and subsequent training program were carried out.

Content of the Report

The report addresses each method or topic in individual chapters. Each chapter is divided into sections for the initial evaluation, recommendations, suggested implementation plans, and the execution of the implementation plan, where requested. The following topics are included in the remaining chapters of this report.

- Use of RAP in Local Pavement Design
- Implementation of Vehicle Classification Update
- Ten-Ton Pavement Design Charts
- Update of FWD Viewer Tool
- Overlay Design Method for FWD Viewer Tool

Each topic is divided into sections, including the current status of the tool or method, the discussions and efforts made in conducting the evaluation(s) of the tool or method, and detailed recommendations for moving forward with further development or implementation of the tool or method.

The contract for this project was established such that new tools could be evaluated and recommendations could be implemented with simple amendments to the contract. For example, the Falling Weight Deflectometer (FWD) Viewer Tool was the first tool to be updated in this way. For each possible evaluation and implementation component, tasks were in evaluation and implementation subtasks.

Chapter 2. Use of RAP in Local Pavement Design

The Minnesota Department of Transportation has conducted several research and field studies on the proper use and expected performance of recycled asphalt pavement (RAP). A partial list of the past and current projects includes the following, which are evaluated in further detail in this chapter.

- Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality
- Resilient Modulus and Strength of Base Course with Recycled Bituminous Material
- Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and MnPAVE Pavement Design
- Recycled Pavements Using Foamed Asphalt in Minnesota
- Best Practices for RAP Use Based on Field Performance
- Recycled Asphalt Pavement: MnROAD Study of Fractionated RAP
- Design and Performance of Asphalt Mixtures Containing High Percentage Recycled Materials

Evaluation

The evaluation in this section consists of a review of previous and current research project funded by MnDOT and the LRRB. The detailed review of each project's objectives, conclusions, and recommendations is presented in the *Background Information* subsection below, including a summary of the major issues related to the use and performance of RAP. The recommendations section provides a short list of suggestions for future MnDOT and LRRB research and implementation related to the use of RAP in Minnesota.

Background Information

This section presents summaries of the objectives, conclusions, and recommendations of various research studies funded by MnDOT and the LRRB related to the performance of asphalt pavements constructed with RAP.

Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality [1]

Li, X., T.R. Clyne, and M.O. Marasteanu, *Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality*, LRRB Report No. 2005-02, July 2004.

The objective of this study was to investigate the effect of various types and percentages of RAP on asphalt binder and asphalt mixture properties for typical Minnesota asphalt mixtures. This is a first step in the more complex process of developing a rational design for asphalt

Ten mixtures were prepared and tested. Two RAP sources and two asphalt finders were used. Control mixes and additional mixes with 20% and 40% of each RAP source were used. Dynamic modulus, stiffness, and moisture susceptibility testing were used to determine the effect of various percentages of RAP on mixture properties.

The authors reported the following conclusions and recommendations.

Reported Conclusions

1. The complex modulus and the stiffness of asphalt mixtures increase with the addition of RAP. For example at 21ºC and 1 Hz, the addition of 20% RAP to the mixture with binder PG 58-28 resulted in a 23% increase in complex modulus, and adding 40% RAP resulted in a 62 % increase in complex modulus.
2. The experimental data indicated that the asphalt binder grade had a significant effect on the stiffness of the resulting asphalt mixture and asphalt binder. For example the complex modulus of the mixture incorporating the stiffer asphalt binder, PG 58-28, was 50% higher than the mixture containing the PG 58-34 at 4ºC and 10 Hz.
3. The RAP source significantly affects the asphalt mixture and the corresponding asphalt binder properties. Mixtures incorporating millings (defined as RAP from a single source) exhibited a higher complex modulus than those with RAP (recycled material combined from a number of sources and crushed at the HMA plant) under similar testing conditions.
4. The complex modulus increased as the test temperature decreased or as the loading frequency increased for the whole testing temperature and frequency range.
5. At 21ºC and 1.0 Hz, about 18% of millings may be used with a PG 58-34 asphalt binder to obtain a complex modulus equal to a mixture made entirely with PG 58-28 asphalt binder.
6. Mixtures containing RAP showed significant variability and the variability increased with the increase in RAP content. The mixture complex modulus test results had more variability at low temperatures than the rest of the temperature range.
7. The experimental data obtained for the binders and mixtures investigated in this study indicate that using 20% RAP in asphalt mixtures does not significantly affect the performance of the resulting mixtures. Amounts of RAP totaling 40% have a much larger effect on the performance of the mixtures, which indicates that the current allowable levels of RAP in MnDOT specifications are adequate.

Reported Recommendations

1. Extend the asphalt mixture testing to investigate the performance of RAP mixtures under repeated loading cycles, such as repeated creep and fatigue tests.
2. Perform moisture susceptibility tests at lower temperatures, such as 10ºC.
3. Extend the asphalt binder testing to include low temperature direct tension (and calculate MP1a critical temperature), repeated creep and strain sweeps at high and low temperatures. It is also recommended to increase the number of RAP sources for future research and to collect existing information about the materials being recycled if possible.

Resilient Modulus and Strength of Base Course with Recycled Bituminous Material [2]

Kim, W., and J.F. Labuz, *Resilient Modulus and Strength of Base Course with Recycled Bituminous Material*, LRRB Report No. 2007-05, January 2007.

The objective of this study was primarily to assist MnDOT in developing specifications for the use of RAP materials as a base course. Reclaimed materials were obtained from CR 3 in Wright County. Blends of base materials with various RAP contents were produced, including 0%, 25%, 50%, and 75% RAP content.

Reported Conclusions

1. In terms of stiffness and strength, base course containing 50% aggregate – 50% RAP performed similar to 100% aggregate with proper compaction. For the field sites studied, the reclaimed material was coarser as %RAP increased, and the in-situ blend was equivalent to the 50-50 mix.
2. To match densities measured in the field for bases containing aggregate with RAP, laboratory specimens were compacted using a gyratory process with compaction pressure of 600 kPa and 50 gyrations. Further research is needed to evaluate compaction effort and material behavior such as change in stiffness.
3. The specimens with 65% OPM were stiffer and stronger (cohesion increased assuming friction angle remained constant) than the specimens with 100% OPM at the same density, probably due to the increase in soil suction and compaction energy with decrease in moisture.
4. From triaxial tests with cyclic loading, specimens with RAP exhibited at least two times greater permanent deformation than the 100% aggregate material. Further research is needed to understand the mechanism of higher permanent deformation in RAP material.

Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and MnPAVE Pavement Design [3]

Westover, T.M., J.F. Labuz, and B.B. Guzina, *Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and MnPAVE Pavement Design*, MnDOT Report No. 2007-25, June 2007.

The motivation for this study was to improve the quality of pavement design by examining the relationship between laboratory measurements made on the base materials and field measurements conducted on in-place pavement sections. Objectives were to quantify stiffness of aggregate bases containing recycled asphalt and concrete pavements.

Fifteen pavement projects were selected from a group of 117 for inclusion in this study. This list of projects was further reduced to four, based on availability of FWD data, for correlation of this data with resilient modulus properties.

Reported Conclusions

1. Traditional “peak-based” analysis of FWD data can lead to significant errors in elastostatic backcalculation due to dynamic effects.
2. Base materials exhibit considerably increased stiffness in frozen months compares to thawed months.

Recycled Pavements Using Foamed Asphalt in Minnesota [4]

Eller, A., and R. Olson, *Recycled Pavements Using Foamed Asphalt in Minnesota*, LRRB Report No. 2009-09, February 2009.

The objectives of this project were to develop a specification and design guide, and document the projects constructed in Minnesota, to begin a record of pertinent data regarding the performance of foamed asphalt stabilized base.

Falling Weight Deflectometer testing was conducted on three test sites in Olmsted County and two sites in Fillmore County.

Reported Conclusions

1. Mix design may be most critical for FDR pavement operations with foamed asphalt because of inherent variations in base thickness. Overestimation of base thickness based on data from coring may cause the reclamation machine to unintentionally mix additional subgrade material in with the pavement materials.
2. Draft special provisions were developed for "Full Depth Reclamation with Foamed Asphalt" and "Cold In-Place Recycle with Foamed Asphalt, Full Recycling Train Mix Design".

Best Practices for RAP Use Based on Field Performance [5]

Johnson, E.N., and R. Olson, *Best Practices for RAP Use Based on Field Performance,* LRRB Report No. 2009-15, April 2009.

This project included a literature review and survey of current practice in the use of RAP. A set of five test sections were established based on the responses to the survey. In addition, a set of laboratory tests was developed. Tests conducted included dynamic modulus, bulk specific gravity, binder content, performance grade, and aggregate gradation. The testing was oriented toward the properties of wear courses using RAP.

The study recommended that agencies revise their policies to include RAP in the wear course for the following reasons.

1. Based on the laboratory test results and field observations, all of the mixtures performed acceptably in terms of rutting resistance.
2. Asphalt high temperature performance grades (PGs) indicate the contribution of rut resistance provided by the binder. This particular data set possessed similar high temperature PGs, and no strong relationship resulted between high temperature PG and percent RAP. However, RAP material can often have elevated high temperature PGs that could beneficially contribute stiffness during conditions when mixtures are prone to rutting.
3. Results from this study found only a moderate relationship between the percent of RAP in the mix and the onset of early thermal cracking.
4. The low-temperature grade of the binders and percentage of new binders used in this study were strongly related to early performance. This reinforces the concept that it is possible to address concerns about low-temperature performance during the mixture design phase, whether or not the design includes RAP.

MnROAD Study of RAP and Fractionated RAP [6]

Johnson, E.N., M. Watson, and T. Clyne, *MnROAD Study of RAP and Fractionated RAP*, LRRB Report No. 2012-39, December 2012.

This pooled-fund study investigated the construction of several test sections at the MnROAD facility incorporating recycled asphalt pavement and fractionate recycled asphalt pavement (FRAP). The project scope included development of specifications, construction evaluations, and testing of materials in the field and in the laboratory.

Reported Conclusions

1. Extracted binder grades met or exceeded design values.
2. Fracture energy from semicircular bend (SCB) data was useful in categorizing expected mixture performance in terms of recycle percentage.
3. The process of fractionating the RAP into two different sizes resulted in less blending than anticipated as determined from qualitative comparisons of dynamic modulus tests to their counterpart predicted using the Hirsch model.
4. Pavement performance evaluations at MnROAD has shown that the RAP, FRAP, and other mixtures performed very well after four years of service. During the fourth year of service, several non-overlay study cells began to exhibit some transverse cracking.
5. Additional cracking is anticipated as the pavements are continually exposed to typical low temperature conditions.

Recycled Asphalt Pavement: Study of High-RAP Asphalt Mixtures on Minnesota County Roads [7]

Johnson, E.N., M. Watson, R. Olson, K.H. Moon, M. Turos, and M. Marasteanu, *Recycled Asphalt Pavement: Study of High-RAP Asphalt Mixtures on Minnesota County Roads*, LRRB Report No. 2013-15, May 2013.

This project was conducted by the MnDOT Materials and Road Research Section. The objectives of this project included the following.

- Determine the performance of local roadways built with typical RAP levels (less than 30 percent).
- With the help of the asphalt industry, investigate the activation of RAP asphalt in a plant setting.
- Investigate the extent of RAP asphalt activation in a laboratory setting.
- Develop high-RAP mixtures, and test them for low-temperature performance.

The project considered several issues of RAP performance and design, including the following.

- Virgin and mixture binder grade
- Binder modification (polymer, other)
- Percent recycled material in design
- Recycled material type (RAP, shingles, other)
- RAP fractionation
- Warm asphalt

Reported Conclusions

The project reported the following conclusions.

- Pavement performance of Minnesota county highways containing an average of 20 to 26 percent RAP showed that a 40 percent improvement occurred in transverse cracking per mile along with a 34 percent improvement in crack spacing when low PG -34 asphalt binder was used instead of low PG -28.
- Asphalt binder activation was investigated with RAP and virgin aggregate mixtures produced in a batch plant and in the laboratory. No asphalt binder was added to the blends during production. It was found that coarse aggregates from plant mixing achieved a more uniform coating and were subjected to less abrasion than those from laboratory mixing. Temperature, mixing time, and heating time of RAP were the most influential parameters for complete coating. The percentage of RAP was an important variable in explaining the amount of partial coating.
- Eight mixture designs were produced for laboratory evaluations. The designs used PG 58-28 and PG 58-34 asphalt binders with RAP contents ranging from 0 to 55 percent. Indirect tensile (IDT) and SCB testing were performed at the low temperatures. IDT results showed that creep stiffness increased along with RAP content. RAP mixtures had slightly higher IDT strength values than non-RAP mixtures, except for the 58-34 binder mixtures tested at PG temperature. IDT critical temperature (Tcr) analysis showed that the addition of RAP significantly increased the critical temperature for the PG 58-34 binder, predicting less crack resistance. SCB fracture testing showed that the addition of RAP lowered the fracture energy and increased the fracture toughness of the mixtures, and the highest RAP content appeared to have the most reduced fracture performance.

Recommendations

The following recommendations are derived from the conclusions and recommendations in the above-referenced projects and reports. They are made primarily from an implementation perspective.

1. **Develop a practical classification method for RAP products.**
   Some of the reports summarized above mentioned the effect of the RAP source and other properties on the potential performance of the pavement layers in which it is used. An evaluation should be conducted to determine if the state of the practice is such that a classification method (with the associated sources, binder types and proportions, etc.) could be developed for use in Minnesota.

   The practical application of such a classification system would require additional testing and evaluation of a particular RAP material to determine the best way to incorporate it in pavement construction (new or rehabilitation).

2. **Develop training for local agency pavement design engineers and/or technicians.**
   Engineers at local agencies and MnDOT districts have heard of research conducted at the state and national level, and have seen presentations at various conferences about RAP. At times the sources of information seem to contradict each other. A unified training

program should be developed to establish MnDOT's position on RAP and its potential uses. Such a training program should incorporate the following components.

- Results of the research conducted to date, both at the state and national levels.
- Pros and cons of using RAP, including the variability inherent in the material, additional construction effort that may be required, and tighter construction controls (density, temperature, etc.)
- Additional design considerations
- Performance expectations

3. **Establish common testing protocols for evaluating RAP materials.**
   Since RAP material properties are inherently highly variable, common testing methods, frequencies, and other aspects should be established to evaluate specific RAP materials for use in pavement design and construction. Only in this way can design and performance be compared among various projects across the state.

4. **Establish a link between design and performance for pavements constructed with RAP.**
   Important aspects of pavement design, construction, and performance should be linked so that lessons learned through observation of performance can be developed into future design and construction practices to improve future pavement performance.

   This should include all aspects of the design ↔ construction ↔ performance process, including the following.

   - Design procedures
   - Materials testing and evaluation
   - Construction specifications and practices
   - Performance evaluation and reporting
   - Future research to make corrections or adjustments in the design procedures.

Chapter 3. Implementation of Vehicle Classification Update

In 2006 the LRRB began the "Update of Vehicle Classification for Local Roads" project, conducted by MSU Mankato, which was completed in 2009 [8]. The two objectives of this project were to update the recommended vehicle classification for local (CSAH and CR) pavement design and to develop a procedure for local agencies to conduct individual vehicle classification studies on specific highways they plan to construct. During that two-year project, over 200 counts were done on about 55 roadways in 15 counties across the state, averaging about 12 days per count. Significant changes have been found in the statewide vehicle classification, which are discussed in the next section. After the first phase of data collection, the LRRB asked MSU to extend the project for an additional phase to verify the data observed.

Evaluation

This section provides a short description of the evaluation that was conducted, and some of the basic results found. For greater detail about this information, see LRRB Report 2010-17 [8]. Based on the vehicle classification study, an updated statewide classification was developed to revise the values in Table 4-4.2, Vehicle Classification Volumes (revised February 1, 1997) of the current MnDOT Pavement Manual [9]. The information in Table 1 is from the 2007 MnDOT Pavement Manual [9]. The column to the far right in the table is specified for pavement designs on rural CSAH and county roads.

The classification values in Table 2 are those measured across the state and include data from the 15 counties, counted over three seasons (Spring, Summer and Fall) for periods of about two weeks each. The information provided in this table includes the average value for each classification type, along with the minimum, maximum, and 95th percentile.

Table 1. Vehicle Classification Percentages from 2007 MnDOT Pavement Manual.

VEHICLE CLASS PERCENT OF AADT Analysis of 1983-1989 Data							
Vehicle Classes	Trunk Highways Greater Minnesota			Trunk Highways Mpls/St. Paul Seven County Area			Rural CSAH or County Road
	Average	Min/Max	95% of data sites	Average	Min/Max	95% of data sites	Average
Autos, pickups	89			93			94.1
2 ax, 6 tire SU	2.7	.4 / 9.3	< 4.9	2.2	.8 / 7.6	< 3.6	2.6
3+ ax SU	1.5	0 / 28.7	< 4.1	1.0	0 / 8.9	< 2.8	1.7
3 ax TST	.1	0 / 1.1	< .3	.2	0 / 1.2	< .4	0.0
4 ax TST	.2	0 / 1.6	< .6	.2	0 / 1.1	< .6	0.1
5+ ax TST	6.1	0 / 31.0	< 15.5	3.2	0 / 22.6	< 10.6	0.5
Buses, Trucks w/Trailers	.4	0 / 3.9	< 1.2	.3	0 / 2.7	< .9	1.0
Twin Trailers	.1	0 / 1.0	< .3	.0	0 / .4	< .2	0.0
Total Number of Sites	N = 837			N = 239			1977 County Road Study

Table 2. Updated Statewide Classification Percentages.

Vehicle Class	Average %	Maximum %	95% of data
Autos, pickups	88.9		
SU (2axle, 6 tire)	3.7	35.6	8.8
SU (3+ axle)	1.9	27.7	6.1
TST (3 axle)	0.8	15.3	2.7
TST (4 axle)	0.2	4.5	1.0
TST (5+ axle)	2.2	34.7	8.3
Buses,Trucks w/ Trailers	2.3	37.1	9.6

Based on the statewide data collection efforts, the proportion of 5+ axle tractor-semi-trailers (TST) has increased from 0.5% to 2.2%, almost a four-fold increase. In many cases the proportion of 5+ axle TSTs exceeded 10% and in a few cases it has exceeded 20%.

Recommendations

1. **Update the default vehicle classification data in the Pavement Design Manual.** The first step in releasing an official update of the vehicle classification for local roadway pavement design is to conduct an internal review and validation of the data developed by MSU in the LRRB INV-844 project. Once this data is validated and/or modified based on the validation analysis, a new “default” table for vehicle classification should be released to the local agencies, and encouraged for use. Action on this recommendation for using the updated statewide default classifications should be done in consideration of the other recommendations in this section, particularly the encouragement to conduct individual roadway counts. For pavement designs where no other information is known, agencies should be advised to use the “average” column in the updated table.

2. **Encourage individual roadway counts.** A better method for determining traffic volumes and vehicle classifications at the project level is to conduct the counts on the actual roadway of interest. Many local agencies own the equipment to conduct such counts, and otherwise can obtain the proper equipment from the district state aid offices. While the data analysis is most often conducted at the district state aid offices, the local agencies have the knowledge and the desire for more detailed information when conducting pavement designs in their jurisdiction. In the cases where less information is desired by the local agency, the default traffic maps and vehicle classification tables are available. As mentioned in the next recommendation, additional information should be provided to local agencies regarding the interpretation of the data they collect, for adjustments such as seasonal adjustment factors, etc.

3. **Provide additional guidance/training on collecting and interpreting classification data.** There is a need for additional guidance from the state aid office in collecting and interpreting traffic and classification data. Many county engineers are interested in how the county traffic maps are produced, or how to use the seasonal adjustment factors, for example. A training program should include the basics of data collection, but also special considerations for prediction of future loads.

Potential topics for guidance and/or training could include the following.

- Selecting of individual count locations
- Conducting volume and classification counts (setting up the hardware, obtaining and analyzing the raw data, etc.)
- Adjusting analyzed data using proper MnDOT techniques
- Using the resulting data in standard and advanced pavement design methods.
- Consideration for future vehicle usage by local industries (farming, timber, etc.) and the potential for increased axle loads and vehicle counts.

Chapter 4. Ten-Ton Pavement Design Charts

The update of the state aid pavement design charts has been considered for several years. This section of the report provides a summary of meetings and activities related to the development and implementation efforts for the new 10-ton designs. The information presented here is derived from meetings and discussions with local agencies (end users), MnDOT Office of Materials personnel (developers), and industry representatives (advocates). Based on the information below, several recommendations are suggested, focusing on potential implementation efforts, and additional development and research.

Evaluation

This section is divided into two sections – a summary of some of the meetings and discussions that have taken place since early 2007 regarding the 10-ton design chart implementation and a discussion of perceived industry concerns. Much of the information provided in the summary section is taken directly from documented meeting minutes and other sources.

Concrete and Bituminous Pavement Charts – Revision Work Plan (Early 2007)

Objectives of the Work Plan

Revise the existing concrete and bituminous paving charts and make available to designers. The charts must be technically acceptable and be reviewed by technical experts, industry representatives, and city and county engineers. Primary issues of the chart are:

1. Are minimum bituminous thicknesses shown mean "inches of GE" or literally "inches"?
2. What is the best minimum thickness for doweled and non-doweled concrete pavements?
3. Should the bituminous and concrete design information be combined into a single chart or be shown separately?
4. Typically flexible pavement is designed for 20 year life while rigid pavements are designed for 35 or 50 year life. Currently the concrete pavement chart thicknesses are for 20 year equivalent thicknesses. Should the chart show the actual thicknesses needed for 35 or 50 year. (On the other hand, should a bituminous chart be developed for an ultimate life of more than 20 years?)

Secondary Objective

Identify all concrete and bituminous pavement issues (materials, design, construction practices, education, web data, etc.) that are controversial, unreliable, or appear to be weak links. Capture the essence of the issues for possible future investigation effort. Some of the issues identified by the steering committee included the following.

- Traffic counts
- Accurate ESAL estimates
- Design vehicles of the future
- Farm vehicles
- Design life target
- Ordinary compaction vs. 100% compaction vs. intelligent compaction
- Future use of Soil Factor? Future use of G.E.?

- Look at pavement design starting with "buildabilty" and backing into design process
- Law concerning 10 ton roads within 3 miles of TH
- RAP Specs
- Incentive / disincentive use
- Should a pavement selection process be developed?

Comments from Industry Representatives

Concrete Paving Association of Minnesota (14 May 2007). This summary of comments refers to version #3 of the 10-ton design charts.

- When comparing pavement designs (bituminous and concrete) a common analysis period should be used. CPAM prefers pavement thickness design based on 20-yr design, but agreed to both 20- and 35-year design columns.
- Suggested that MnDOT study some of the thin concrete pavements that have been built in the past.

Minnesota Asphalt Paving Association (24 May 2007). This summary of comments refers to version #4 of the 10-ton design charts.

- Would like to eliminate the Soil Factor method in favor of the R-Value method.
- Prefer to have separate pavement design charts (bituminous and concrete) since so many conditions in pavement design and construction are different (such as staged construction).
- What happens after the service life? Concrete is difficult to remove while asphalt is recyclable.
- The chart should cite the source of the Material Type information.
- Remove the 2331/2340 Granular Equivalent (GE) notation
- What is the basis for the GE changes at <1000 Average Daily Traffic (ADT)?
- What is the basis for the assessment of pavement life?
- What about overloads? The Geotechnical manual describes issues for bituminous. Not sure what to consider for concrete.
- Incorporate PG binder?
- What about constructability and minimum soil strength at low volumes?
- A 4-inch Class 5 pavement platform should be noted for concrete.
- “Reliable designs are preferable to ‘doing it on the cheap’”.

Comments from MnDOT Personnel (October 2009)

Discussions were held with several MnDOT and Minnesota County engineers during October 2009 to determine the status of the 10-ton design charts and their recommendations for moving forward with implementation. The notes in this section are the aggregated comments from all discussions.

- When discussing with both industries, need to determine what they believe are the correct inputs and methods for pavement design (for their industry).
- 70% of the roads are <1000 ADT

- Need a way of evaluating the reliability of the designs in the new charts.
    - R-value
    - Soil Factor
    - PCC (-2σ for flexural strength) to try to get to 95% reliability
    - Variability of the inputs in the charts
- Can the minimum PCC design be 6” with dowels?
- Should look at the practicality of some of the designs.
- What is designed vs. what is constructed?
- Differences between some designs (increment of thickness or GE) are often too fine for practical construction/inspection purposes (for example, 4.5 and 5.0 inches).
- Perhaps go back to separate charts?
- Perhaps use MnPAVE to analyze / validate existing (new) charts
- How much of the existing CSAH system is already at 10-ton?
- Counties are good at pavement design, but likely need help with the pavement type selection process.
- Can a 5-inch concrete pavement without dowels be equivalent to 6-inch with dowels?
- For SF 130, the minimum concrete thickness should be 6 inches; minimum bituminous should be 23 inches GE.
- How well will thin concrete sections hold up with low volume, but heavy trucks?
- FWD-based pavement strength (spring load limit) is based on INV-183, but design chart is based on soil factor.
- ADT breakdown for geometric design is <50, <150, <500, and >500. Should similar divisions exist for pavement design? What is the minimum design for pavements? To what ADT does this correspond?
- Look into making the smallest ADT category <400, and adding a 400-1000 ADT category.
- R-value chart shows a minimum bituminous thickness at 3 inches. Is there a discrepancy between that and the new 10-ton chart?
- Look at 5-inch minimum concrete section more closely
    - 6.5” has performed better in the past?
    - Look at practicality of designs
    - 6” with dowels as a minimum section?
- Should specify that the design charts are not to be used for pavement type selection.
- Need to make sure that what is constructed is what was designed
- Look in to the variability of inputs (in reality, not just theoretically) to the design charts.

<u>Summary of State Practices</u>

ACPA Database of State DOT Concrete Pavement Practices [10]

No state reported minimum “Typical Thickness Range” less than 6 inches
Two states reported minimum “Typical Thickness Range” of 6 inches
One state reported minimum “Typical Thickness Range” of 7 inches
All others were 8 inches or greater

Washington [11]

For Design ESALS < 5,000,000, the minimum slab thickness is 8 inches.

California [12]

The thinnest slab (for best soil conditions, lowest traffic, with edge support) is 0.70 ft (8.4 inches) with an allowance for future grinding of 0.03 ft (3/8 inch), leaving a minimum slab thickness of 8 inches.

Kentucky [13]

The minimum slab thickness is 8 inches, assuming 1,000,000 design ESALs, the strongest soil classification, and a dense graded aggregate base.

Illinois [14]

The minimum slab thickness is 6.5 inches for less than 40 heavy commercial vehicles per day, with 12.5-ft joint spacing. A design limitation states that "once all pavement thickness adjustments have been made, the final design thickness must be 6.5 in or greater."

North Dakota [15]

A design note in the pavement design manual states that "because of North Dakota's climate, the NDDOT's minimum acceptable concrete pavement design thickness is 8 inches."

Colorado [16]

The minimum thickness for highway and bicycle path is 6.0 inches for up to 1,000,000 ESALs. A design note in the pavement manual states that "the minimum thickness requirement may be changed on a project-to-project basis depending upon traffic, soil conditions, bases, etc."

Recommendations

1. **Maintain a single design chart.**
   Dividing the draft 10-ton design chart into two separate charts will likely not change any local agency's use of the charts for pavement type selection. It would only make comparisons a little more difficult.
2. **Provide training on how to conduct a proper pavement type selection.**
   Without proper training, any design chart or set of design charts <u>will</u> be used for selection and design. Pavement type selection is not a new concept, and MnDOT has encouraged it in Technical Memos, research, and other methods.
3. **Validate the designs.**
   This can be done by selectively recruiting county engineers to design pavements with the draft chart, and to construct and then observe these pavements over a period of time. A procedure for monitoring all pavements for performance vs. design should be developed. Much of the data is already being collected for pavement management purposes. An important part of continuous review is to analyze this data to compare the design (and predicted performance) to the actual performance in the field.

4. **Investigate the potential benefit of dividing the minimum ADT range for pavement design.**
   Since about 70% of the statewide CSAH miles have less than the smallest (1000 ADT) design category, an evaluation of the minimum pavement section for each type should be conducted and correlated with this minimum ADT range. If a category with a smaller ADT level is justified, this is recommended to be at about 400 ADT (which corresponds to about 40% of the statewide CSAH miles).
5. **Consolidate the “5.0u-6.0” concrete thickness recommendations.**
   Address the implication that a 5-inch undoweled section is equivalent to a 6-inch doweled concrete pavement section in the top two boxes on the left side of the chart. A single recommendation should be given. The less expensive option of the two would be the 5-inch undoweled section. If this pavement section is acceptable in some cases, an analysis of conditions under which it would be considered appropriate should be conducted. In cases where dowels are required as part of the design, the 6-inch section is needed.
6. **Evaluate practicality of 0.5-inch GE value increments.**
   In the current draft (Draft #7) GE is listed in 0.5-inch increments. This is an improvement over the current 9-ton chart (which has precision to 0.1-inch, although this seems to be due to a conversion from metric, rather than a desire to design to a 0.1-inch precision). However, some questions arise due to this level of precision.
   a. What is the basis of the GE factors, and what is their inherent variability in terms of relative quality as a pavement material?
   b. What is the effective difference in load-carrying capacity, for example with a SF of 50, between designs for <1000 ADT and < 150 Heavy Commercial Average Daily Traffic (HCADT)? The difference in GE required is only 0.5. (In this case, accounting for the minimum bituminous thickness, required layer thicknesses are 3.5” bituminous and 4.5” Class 5 for <1000 ADT, and 4.0” bituminous and 4.0” Class 5 for <150 HCADT.) Comparisons between other designs have GE differences of 1 or 2.
   c. With what precision are the base and subbase layers constructed? Can contractors reliably place and compact these layers to the nearest 1/2 inch? Assuming that base layers are placed according to blue-top elevations, this should not be an issue.

7. **Define “standard paving platform” for concrete designs**
   Consider augmenting note #6 in the draft design chart to define “standard paving platform”. For example, a Google search for this term (on 22 January 2010) did not return a single result.

8. **Evaluate improved methods for evaluating subgrade soil strength**
   Consider a related research project to consolidate and recommend a unified method for evaluating and determining subgrade soil strength. One of the objectives of such a project should be the evaluation of the feasibility and practicality of utilizing R-value for pavement design (at a minimum) and resilient modulus (as a preferred option). A unified method for pavement design and soil characterization has the potential to improve greatly

the network-level evaluation and comparison of pavements in the many local roadway systems in the State.

Additionally, it is important to use soil strength that will be achieved in the field, rather than in small-sample laboratory tests. A system should be developed to evaluate soil support in the subgrade after it is constructed, and then to be able to adjust pavement designs – at least materials and/or thickness – after this information is known. This could require changes in the design process, construction specifications, and the relationship between the agency and the contractor. One suggestion is to develop *probable* and *worst-case* pavement designs, such that highway geometrics (clearances, etc.) can be considered in the worst-case (that constructed soil support is not adequate and either needs to be reconstructed or that additional pavement layer thickness is necessary) during the design phase. Some other implications to this concept include possible required adjustments to cost, schedule, quantities, production rates, etc. Specifications could be developed to encourage the contractor to prepare the soil support adequately so that these additional requirements would not need to be implemented.

Chapter 5. Update of FWD Viewer Tool

The original FWD Analysis tool is a Microsoft Excel spreadsheet that provides county engineers with the FWD data collected in their county as part of the statewide FWD collection effort funded through the MnDOT State Aid Division. The tool was originally developed by Erland Lukanen in the Office of Materials and Road Research. The tool incorporated the evaluation of allowable spring axle loads determined by four different methods – AASHTO, TONN, INV-183, and Soil Factor. As of March 2010, the tool had been distributed to all 43 counties for which the FWD testing was completed in 2009. By May 2011, the initial update of the tool, described in this chapter, was delivered to all counties participating in the MnDOT State Aid FWD testing program of 2009-2010.

Evaluation

The tool has been updated several times since the initial 2011 update described in this chapter. As final modifications were made and submitted, the initial implementation phase was conducted. The implementation phase included presentation and instruction on the use of the tool at each of the districts, as indicated below.

- District 1 Carlton, 23 September 2010
- Districts 2 and 4 Detroit Lakes, 8 October 2009
- District 3 Pierz, 3 December 2009
- Metro District Blaine (Bunker Hills), 25 August 2010
- District 6 Rochester, 18 December 2009
- District 7 Mankato, 24 November 2009
- District 8 Ivanhoe, 22 October 2009

The initial update of the tool allows county engineers to view the results of the four allowable axle load analyses using the FWD data collected on their own highways. It also allows them to try “what-if” scenarios by modifying traffic inputs. At the time that Version 1.0 of the tool was almost complete, several features were suggested that are included in the recommendations section of this topic, many of which were included in Version 2.0 of this tool, described in the next chapter.

Incorporation of TONN 2010

The original TONN analysis had been included in the first version of the tool and in the initial update, but was replaced with the TONN 2010 analysis developed by Khazanovich at the University of Minnesota [17]. The incorporation of the TONN 2010 analysis into the FWD Viewer Tool is described in detail in a separate report [18].

FWD Viewer Tool Implementation

A screen capture of the initial update of the FWD Viewer Tool is shown in Figure 1. At the time, the current version of the tool was Version 1.24, dated 27 May 2011. Figure 2 shows the summary tab of the tool. By May 2011 the development of the initial update was complete, and 86 counties for which FWD data has been collected were provided a copy of the tool with their own data.

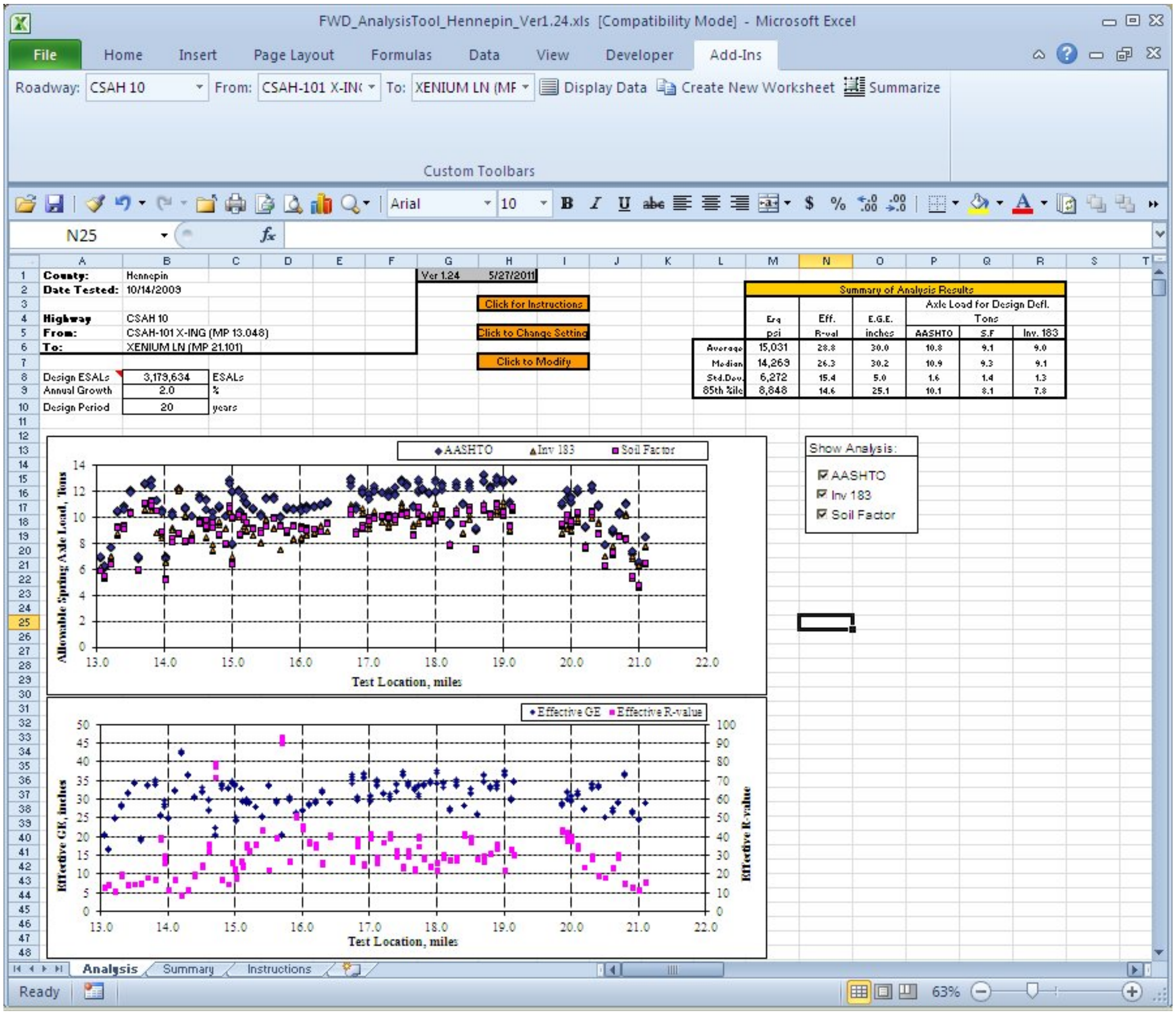

Figure 1. FWD Analysis Tool – Analysis Screen.

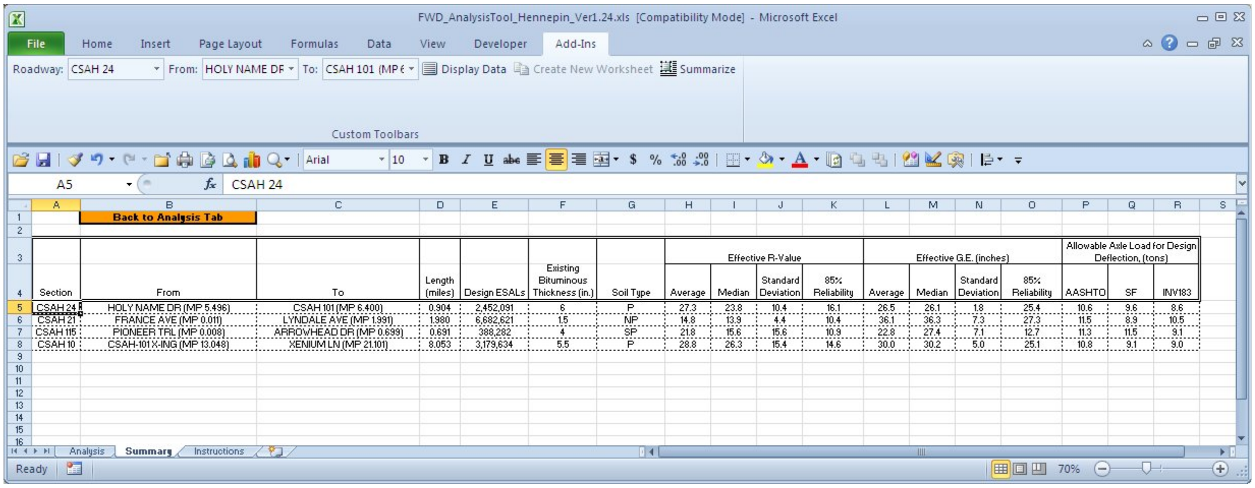

Figure 2. FWD Analysis Tool – Summary Screen.

User Information

The following information is taken from the User's Guide (the Instructions tab in the spreadsheet tool).

FWD Analysis Tool Version Ver 1.24 User's Guide
Released May 2011

1. *The user may not change any inputs in the spreadsheet itself.*
   a. To change traffic inputs, click on the orange "Click to Modify Default Traffic" button. See Item 4 below.

2. *To view the allowable spring axle load calculations and effective GE and R-values, proceed with the following steps.*
   a. For Excel 2007 and later, select the "Add-Ins" menu item. You may need to adjust Excel macro security settings.
   b. Select a highway from the "Roadway" drop-down box.
      Some divided highways were tested in both directions. These are noted by appending an "I" or "D" to indicate "Increasing" or "Decreasing" stations.
   c. Select the beginning terminus from the "From" drop-down box.
   d. Select the ending terminus from the "To" drop-down box.
   e. The data and graphs will be automatically updated.
   f. To hide particular analyses in the Allowable Spring Axle Load graph, check or uncheck the box next to the appropriate name in the Show Analysis box.

3. *To conduct an analysis, and to save the analysis parameters, proceed with the following steps*
   a. Modify the segment displayed and the traffic inputs as desired.
   b. Press Summarize in the Add-Ins toolbar.
   c. Click on the Summary tab to view the saved data.
   d. For each analysis, click the Summarize button and a new set of analysis parameters will be saved to the Summary tab.

4. *Entering Traffic Data*
   a. Click on the orange cells labeled "Click to Modify Default Traffic".
   b. In the "General Information" section of the pop-up user form, enter the Annual Growth, Design Period, and ADT value to recalculate Design ESALs.
   c. Select the type of region where the roadway exists (Urban or Rural).
   d. Select to use "Default" or "User-Entered" Values for traffic. Default will use the State Aid recommended classification definitions and AADT values supplied by Traffic Data Analysis.
   e. Select "HCADT" or "Vehicle Classification", to determine the level of inputs required to calculate Design ESALs.
   f. For HCADT, enter the HCADT for the current year.
   g. For Vehicle Classification, enter the percentage of each vehicle classification, if known, or use the default values.

h. Press OK to save entries and return to the spreadsheet or Cancel to return without saving changes.

5. *User-Defined Settings*
   a. Click on the orange cells labeled Click to Change Settings.
   b. In the pop-up user form, user settings for the summary worksheet and graphs can be modified.
   c. Press OK to save entries and return to the spreadsheet or Cancel to return without saving changes.

6. *Miscellaneous Items*
   a. Using multiple copies of the window at one time is not recommended, but you can save copies of the tool elsewhere.
   b. The section of roadway selected is assumed to be one continuous roadway for graphing purposes.
   c. Selecting a new roadway will clear previous selections in the "From" and "To" fields in the toolbar.
   d. The user is strongly advised against deleting rows or any cells of data that appear in the "Analysis" worksheet, the tool assumes original location and integrity of these cells.
   e. The "Export to Analysis" button will erase all data previously in the analysis tab and replace it with original data.
   f. "Create New Worksheet" will export the current state of the analysis tab to another tab named by the roadway.
   g. Hidden worksheets are hidden to preserve the functionality of the tool and are therefore not recommended to be altered by the user.
   i. If data in the "Analysis" tab or other created worksheets is overwritten or altered, the user can reload the data using the Roadway toolbar.

Recommendations

Suggested recommendations in this section include those for improvement to the tool, from both a technical and a user-interface perspective, as potential improvements to the tool in a future version. The recommendations below were received during the panel meetings and other meetings with the state aid and FWD testing firms. These include technical, user interface, and implementation recommendations. Some of these recommendations were addressed with the future possibility of developing a "design" version of the FWD analysis tool.

1. Technical
   - Provide additional support and guidance for the implementation of the "Drought Adjustment" and "Seasonal Adjustment" factors. Currently, the drought adjustment factor has been set to 1.0, as recommended by those familiar with FWD testing and analysis. Future versions of the analysis tool may allow input of a drought adjustment factor, although any change to this factor should only be made by persons knowledgeable in FWD testing and analysis. Technical evaluation of these factors should be conducted to verify their appropriate range of values for various conditions.

- Additional (or replacement) analyses should be considered, such as the updated allowable axle load analysis currently under development. Other uses for the FWD data contained in the tool could be implemented, such as an R-value pavement design module.
- The capability of displaying multiple data sets (FWD taken in the same approximate locations at different times) should be implemented. Users could then see the effect of time/traffic over long periods of time, or of changes in moisture content over shorter periods of time.
- The ability to predict deflections relative to potential construction activities (e.g.: how the FWD deflection basin might change if an overlay was constructed) should be considered. This would allow local agencies to try several "what-if" situations as they attempt to use their construction and maintenance funding most effectively.
- Consider adding the ability for users to define pavement thickness at each FWD drop location, perhaps based on GPR data.

2. User Interface
   - Consider developing a user interface similar to the MnPAVE software. While this would require the users to install a full software package, it could be more stable and could interface with local (user's computer) or web-based databases.
   - Automatic incorporation of "Previous Day Temp" should be implemented.
   - The ability to import additional data by the user should be considered.
   - Customizable user reports and charts (titles, axes, legend, etc.)

3. Implementation
   - Conduct additional demonstration and training as needed at the district and individual county level.
   - A request from MnDOT State Aid should be sent to the counties that have received the tool for additional suggestions for future improvements to the tool, the data, and the analyses included in the tool. With a large pool of users, many suggestions for improvements to the user-friendliness and stability of the tool are likely.

Individual County Summaries of FWD Data

In November 2013, the project team created data summaries for each county that participated in the FWD data collection. The data summaries contain graphical and tabulated information with the analyzed FWD data, including Effective Granular Equivalent, Effective R-value, and the spring load rating information computed by the FWD Viewer Tool. These summary reports were provided in electronic and hard copy format to each county.

Chapter 6. Overlay Design Method for FWD Viewer Tool

This chapter describes the development of an overlay thickness design method as an addition to the updated FWD viewer tool that was described in the previous chapter. This effort focused on the development of the overlay method and its implementation into the FWD Viewer Tool. This chapter describes the method's development, and the resulting modifications to the FWD spreadsheet tool. The overlay method that is added to the tool utilizes the TONN 2010 method to evaluate a future bituminous overlay by predicting the recommended load rating with the additional bituminous thickness. A screen capture of the overlay method page in the spreadsheet tool is shown in Figure 3.

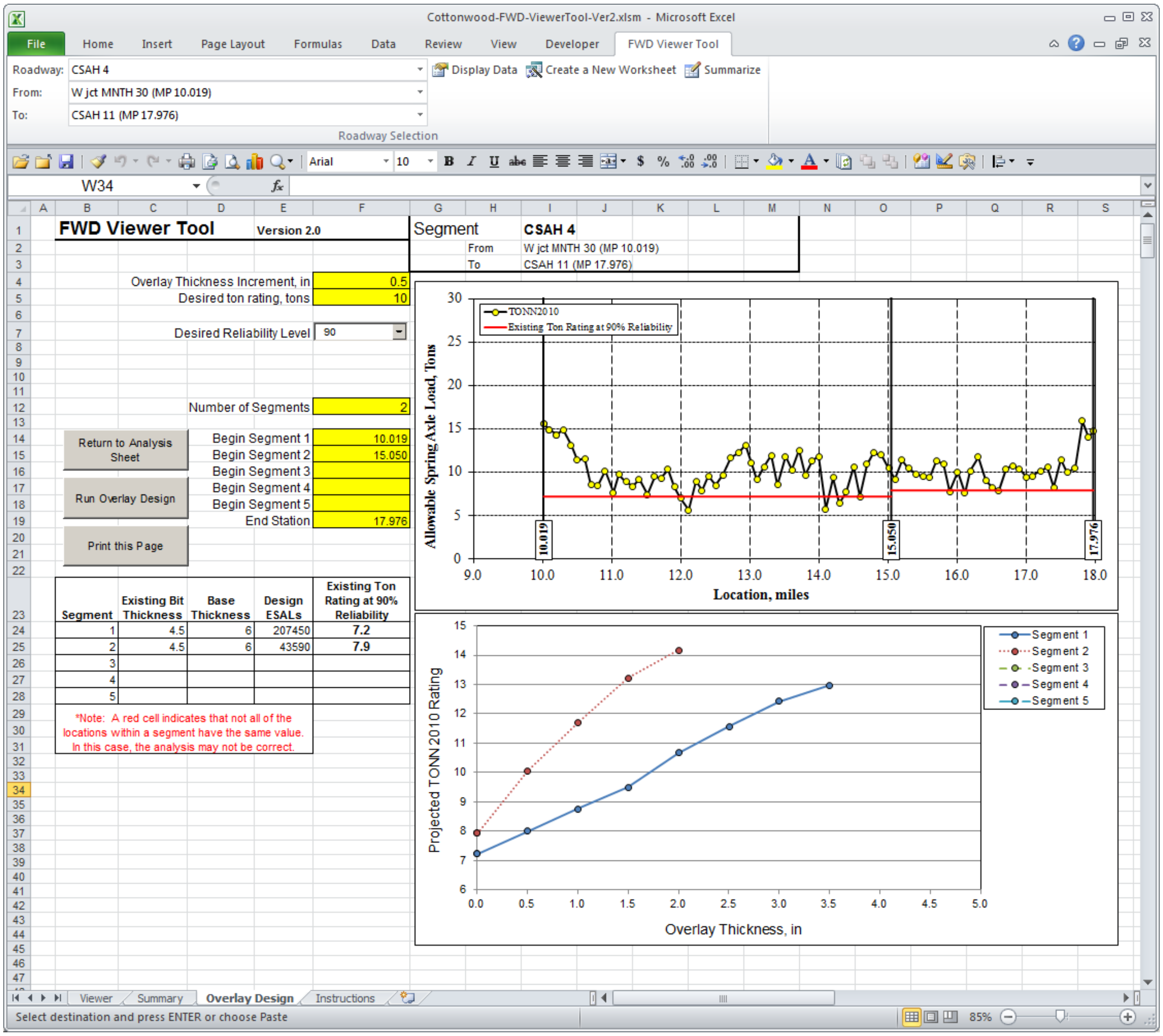

Figure 3. Sample screen capture of overlay method tab in the FWD Viewer Tool.

Overlay Method Development

The basic analysis method directing the overlay design process includes the simulation of added bituminous thickness with an overlay, prediction of a new FWD deflection basin using the added surface thickness using the MnLAYER routine, and subsequent analysis using the TONN2010 analysis method. These and other intermediate steps are described in this section.

Normalize and Consolidate

One decision that was made in order to reduce the computation time of the overlay analysis method was to normalize the four typical FWD drops at each location and to consolidate the into a single drop with deflections normalized to a drop weight of 9,000 lb.

The normalization for each drop location proceeded as follows.

1. Each deflection sensor is normalized to a weight of 9,000 lb

$$dn_i = d_i \frac{9{,}000}{W}$$

where:

dn_i = normalized deflection for at sensor location *i*, in,
d_i = measured deflection at sensor location *i*, in, and
W = drop weight.

2. The average of the normalized deflections at each sensor location is computed.
3. A single normalized and consolidated deflection basin is then available to use in the TONN2010 computations with a high good comparison to the TONN2010 values that were computed with the four individual drops. The information shown in Figures 4 and 5 are the original (as measured) deflections for the four drops at a single location, and the normalized deflections for the same location, respectively.

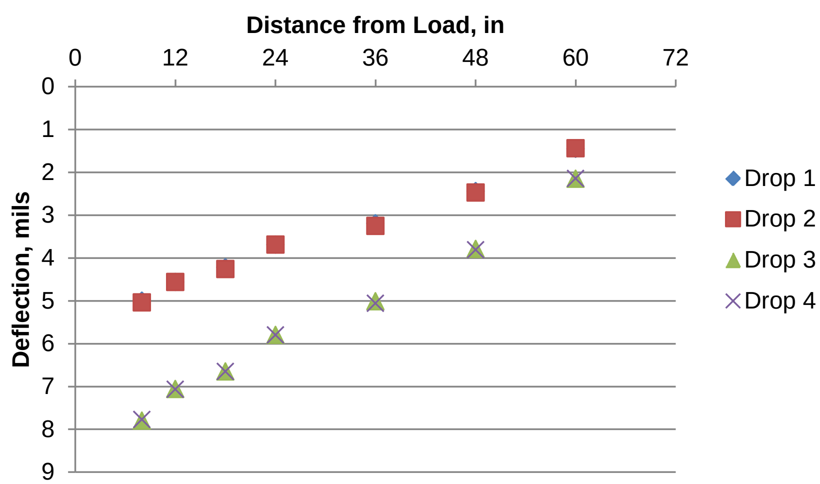

Figure 4. Sample of original deflection basin data.

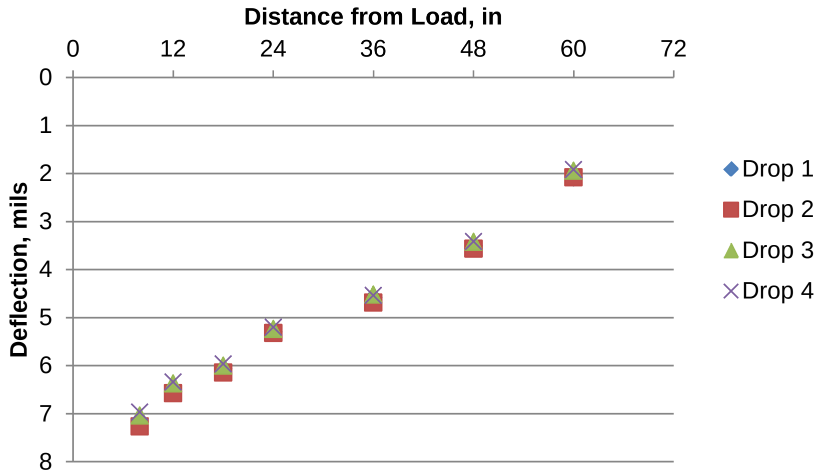

Figure 5. Sample of normalized deflection basin data.

4. At the same time, the TONN2010 values that had been computed for the individual drops are averaged, which gives the spreadsheet a normalized TONN2010 value to use in the subsequent analyses.

Statistical Characterization

For the segment chosen by the user (shown in the example in Figure 6), the computed resilient modulus for each layer, produced by the TONN2010 analysis, at each location is used to determine the average and standard deviation of these properties.

Using the reliability level selected by the user, the appropriate level of resilient modulus and TONN 2010 Load Rating are calculated by the routine. The level of the load rating is shown by the horizontal lines in Figure 6. In the example in this figure, the user had selected a reliability level of 80%. The horizontal line is computed to be at the 20th percentile, corresponding to an 80% reliability. The equation below describes how this is computed for both the TONN2010 value and the resilient modulus of each layer.

$$TONN_{x\%ile} = TONN_{ave} \pm z_{x\%ile}\sigma$$

where:

$TONN_{x\%ile}$ = computed TONN rating at the reliability selected by the user,
$TONN_{ave}$ = computed average TONN rating for all data points in the segment,
$z_{x\%ile}$ = standard normal deviate corresponding to the reliability level, and
σ = standard deviation of TONN ratings for all data points in the segment.

Predict New Deflection Basin

With the statistical characterization of the material properties at the selected reliability level, the overlay method begins by computing a predicted deflection basin for the pavement with the addition of the *Minimum Overlay Thickness* (chosen by the user). Given the layer thicknesses and moduli, and the additional bituminous thickness at the surface, the MnLAYER routine included in the TONN2010 analysis is used to determine this new deflection basin. This component of the analysis is repeated for each overlay thickness, increasing by the *Overlay Thickness Increment* selected by the user.

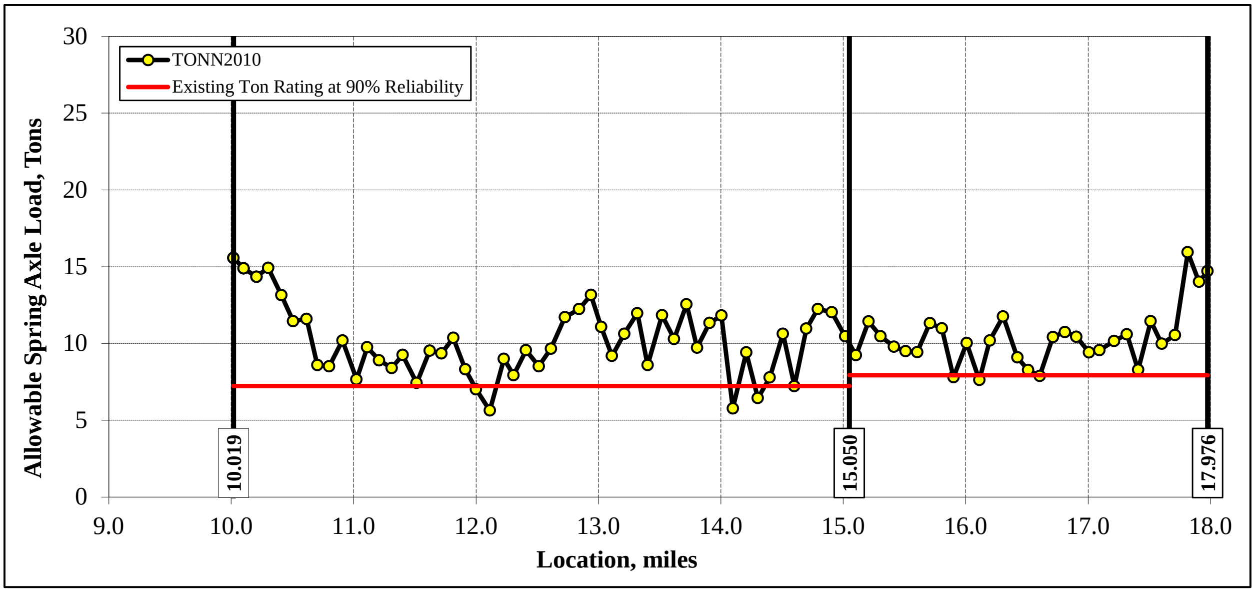

Figure 6. Example of overlay analysis segment selection.

Compute Predicted Load Rating

With the new deflection basin computed in the previous step, the analysis computes the predicted load rating obtained by the addition of bituminous thickness at the surface of the pavement. This is plotted in the overlay analysis sheet of the tool, as shown in the example in Figure 7. In this figure, the two segments defined in Figure 6 are plotted with increasing overlay thicknesses, beginning with the thickness of the existing layer, or no overlay thickness. Since only two segments are defined in this example, Segments 3 through 5 are not shown in the results graph.

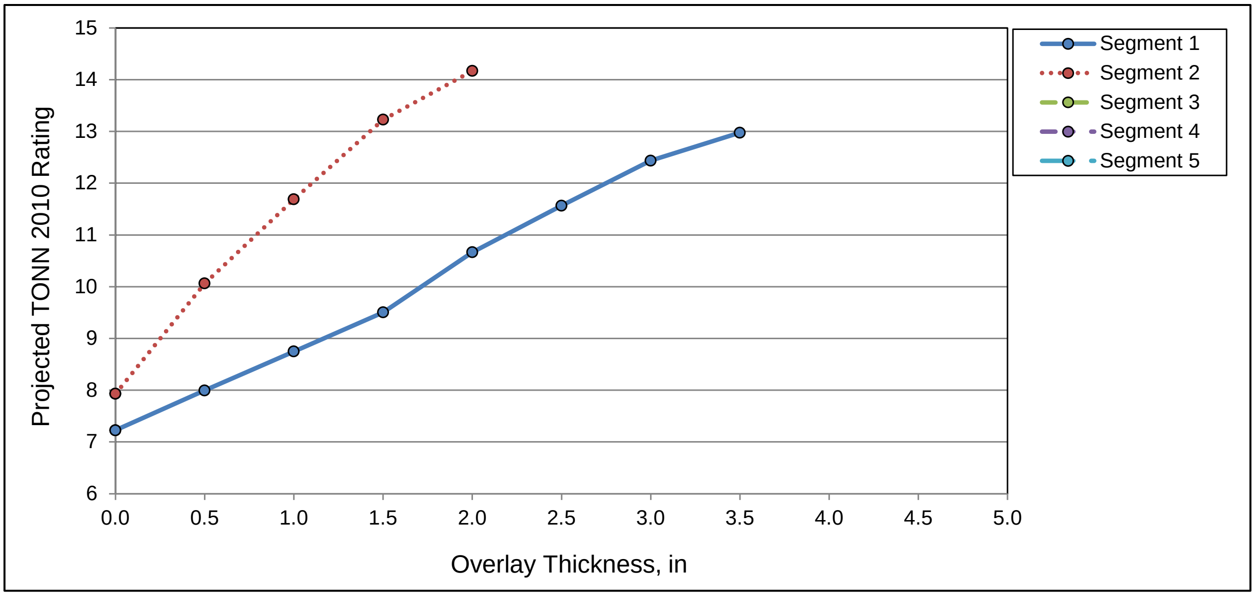

Figure 7. Example of overlay analysis results.

Implementation

This section presents a short step-by-step guide to conducting an overlay analysis with the FWD Viewer Tool.

1. Conduct roadway section selection as normal.
   The user selects a roadway and defines the beginning and ending points with the pull-down boxes in the menu ribbon.

2. Run TONN 2010 analysis, or use the pre-computed data that is loaded with the spreadsheet tool. This is done by pressing the "Recompute TONN 2010" button.

3. Push "send to overlay analysis" button.

4. Select number of segments, reliability level, and other inputs
   Enter the *Overlay Thickness Increment* and the *Desired Load Rating*
   Select the *Desired Reliability Level* in the pull-down box
   Change the number of segments to analyze in the *Number of Segments* cell.
   Then change the beginning mile point for each segment. Adjust the *End Station* point if desired.

5. Press the *Run Overlay Design* button to execute the analysis routine and view results in graph.

Training

The training component was developed under the Implementation of TONN 2010 project. The delivery of that training is included in this project. The training program includes basic instructions on installing and running the analyses, a review of the background and technical aspects of the method, and several case studies where participants are led through individual analyses in a step-by-step manner. The training presentations were conducted to county engineers and their assistants at the district state aid level between November 2013 and February 2014.

As the training sessions were conducted, several ideas were presented for future improvements to the tool. These include the following.

- Provide the failure modes computed by the TONN 2010 analysis so that future maintenance can be planned, or so that appropriate pre-overlay repairs can be completed.
- Since the TONN 2010 routine only considers base layers below the bituminous, can some credit be given for stiff subbase layers?
- Provide a method for agencies to eliminate suspect data from the analysis.
- Improve the tool to be used on 64-bit versions of Microsoft Office
- Allow agencies to add new FWD testing results to the tool for comparisons and new analyses.

Chapter 7. Conclusions

This report contains descriptions of several pavement-related topics of interest to the State Aid Division of MnDOT and to the Minnesota Local Road Research Board. Conclusions and recommendations for the individual topics are included in their respective chapters and are summarized below. In the time between the individual evaluations and the date of this report, some of the recommendations may have been implemented or become less relevant. Each set of recommendations, however, was submitted in the form of task summary reports as the evaluations were completed.

Use of RAP in Local Pavement Design

The general need for the greater and more beneficial use of RAP may include the following recommendations with more detail provided in Chapter 2.

- Develop a practical classification method for RAP products.
- Develop training for local agency pavement design engineers and/or technicians.
- Establish common testing protocols for evaluating RAP materials.
- Establish a link between design and performance for pavements constructed with RAP.

Implementation of Vehicle Classification Update

Much of the recommendations from the vehicle classification update chapter have been implemented by various MnDOT offices. These included the following with more detail found in Chapter 3.

- Update the default vehicle classification data in the *Pavement Design Manual*.
- Encourage individual roadway counts.
- Provide additional guidance/training on collecting and interpreting classification data.

Ten-Ton Pavement Design Charts

Some of the results of the evaluation, interviews, and other discussions have become less relevant but could still be implemented in the future, under the right circumstances. Some of the recommendations suggested below should be implemented regardless of other impediments to full implementation, including training, design validation, and defining standards. Full details regarding these recommendations can be found in Chapter 4.

- Maintain a single design chart.
- Provide training on how to conduct a proper pavement type selection.
- Validate the designs.
- Investigate the potential benefit of dividing the minimum ADT range for pavement design.
- Consolidate the “5.0^{u}-6.0” concrete thickness recommendations.
- Evaluate practicality of 0.5-inch GE value increments.
- Define “standard paving platform” for concrete designs.
- Evaluate improved methods for evaluating subgrade soil strength.

Update of FWD Viewer Tool

Recommendations for an updated FWD Viewer Tool were made in Chapter 5. Most of these recommendations were completed as part of this project and are included in detail in that chapter. Some suggestions for improvement to the tool have been made by users (engineers at individual counties and MnDOT's State Aid Division. These include the following.

- Provide additional technical support on an ongoing basis to help users understand and utilize the tool for pavement analysis.
- Add the capability of displaying multiple data sets at one time (primarily at the same location but tested at different times).
- Add the ability to predict load rating with the addition of a structural overlay. This capability was added and is described in Chapter 6.
- Add the capability for users to make corrections to the data if new information becomes available.
- Consider developing a user interface similar to the MnPAVE software.
- Add the ability to import additional data by the user.

Overlay Design Method for FWD Viewer Tool

The overlay design method was added to the FWD Viewer Tool as part of this project. The suggestions for improvement from users are included in those suggested for the update of the FWD Viewer Tool described in Chapter 5.

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