

Pavement Designer's Guide
Mn/DOT Flexible Pavement Design
MnPAVE Beta Version 5.1

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Table of Contents

1.0 Introduction

1.1 Design Levels

1.2 Resistance Factors

1.3 Performance Related Specifications

2.0 Start Up

2.1 System Requirements

2.2 Installation Procedure

2.3 Control Panel

2.4 General Operation

2.5 Engineering Units

3.0 Climate Inputs

3.1 Seasonal Design

3.1.1 Definition of Seasons

3.1.2 Season Duration

4.2 Design Level

3.2.1 Basic

3.2.2 Intermediate

3.2.3 Advanced

4.0 Structural Inputs

4.1 Design Levels

4.1.1 Basic

4.1.1.1 Layer Structure

4.1.1.2 Layer Thickness

4.1.2 Intermediate

4.1.2.1 Layer Structure

4.1.2.2 Mechanical Properties

4.1.2.2.1 Design Based on Laboratory Tests

4.1.2.2.2 Design Based on In Situ Tests

4.1.3 Advanced

4.1.3.1 Layer Structure

4.1.3.2 Mechanical Properties

5.0 Traffic Inputs

5.1 Allowable Stress Criterion

5.2 ESAL

5.3 Load Spectrum

5.3.1 Design Level

5.3.1.1 Basic

5.3.1.2 Intermediate

5.3.1.3 Advanced

6.0 Output

6.1 Basic

6.1.1 Damage

6.1.1.1 Damage Functions

6.1.1.1.1 Fatigue

6.1.1.1.2 Rutting

6.1.1.2 Changing the Damage Functions

6.1.2 Life

6.1.3 Maximum Allowable Stress

6.1.4 Exporting Data

6.2 Batch Mode

6.3 Reliability

7.0 References

Appendices

- A. Design Moduli Table and Notes
- B. Calculation of ESALs Using Load Spectrum and HCADT
- C. Example Problems

1.0 Introduction

The Minnesota Department of Transportation (Mn/DOT) and the University of Minnesota have developed a mechanistic-empirical (M-E) design procedure for flexible pavements. Due to the quantity of calculations required when using an M-E design procedure, the MnPAVE software described in this Designer's Guide has been developed. MnPAVE is used to design new flexible pavements and estimates the design life given the expected climatic conditions, pavement structure, material properties, and traffic volumes. Mn/DOT is currently in the process of calibrating and modifying this new procedure based input from district, county, city, and consulting engineers.

Mn/DOT is implementing an M-E design procedure for several reasons. The benefits include the ability to adapt to different distress modes, provide better materials characterization, and quantify the benefit of improved materials and specifications. The M-E design procedure also accommodates future traffic volumes, load limits, and axle configurations. In addition, performance related specifications can be implemented that will allow agreement to be achieved between the material properties used during the design, the properties measured during construction, and the long-term performance of the constructed pavement system. Finally, innovative construction practices and materials can be evaluated and rewarded because the benefits can be quantified in terms of longer estimated pavement life.

The M-E design procedure represents an improvement in our ability to understand and design efficient flexible pavement systems. However, M-E design is not the solution to all the possible problems that affect pavement performance. M-E design is based on the structural response and performance of properly constructed pavement systems (Elliott and Thompson, 1985). Problems arising due to improper mix design, inadequate durability, poor quality control, excessive construction variability, and other factors cannot be overcome by any design procedure. Sound engineering principles must be followed in establishing materials and construction specifications and in monitoring the construction process.

MnPAVE includes both mechanistic and empirical pavement design methodologies. In addition to utilizing traditional empirical methods based on experience, field trials, and material index tests, MnPAVE's mechanistic component models the pavement as a multi-layer structure using a linear elastic theory. This allows different failure modes, which are responsible for pavement degradation, to be modeled by the fundamental laws of physics and material mechanics.

MnPAVE is capable of analyzing up to five-layer pavement systems, which makes it compatible with Mn/DOT's aggregate base frost mitigating design. The output for each trial

pavement design includes the estimated pavement life in years, damage factors for asphalt fatigue and subgrade rutting, percent of damage that occurs in each season, maximum stress, strain, and displacement at critical locations, allowable axle repetitions, and reliability estimates.

MnPAVE utilizes "WESLEA" to perform linear elastic analysis of a multi-layer pavement structure. WESLEA is the U.S. Army Corps of Engineers Waterways Experiment Station, Layered Elastic Analysis method (Van Cauwelaert, et al., 1989), which has been adapted to operate from a Windows platform (Timm, Newcomb, and Birgisson, 1999). Thus WESLEA is the analytic engine that calculates the stresses, strains, and displacements in MnPAVE. Transfer functions are used to translate the mechanistic results into estimated pavement life.

The M-E procedure requires that pavement materials be described by their stiffness and strength at different times of the year. This in turn requires that the stiffness and strength be measured directly in the field or laboratory, or that correlations be used to estimate the stiffness and strength from other tests. By requiring mechanistic input data, MnPAVE implementation will accelerate Mn/DOT's preparation for the new AASHTO M-E pavement design standard.

At this time, MnPAVE should be used in conjunction with Minnesota's existing flexible pavement design procedures (R-Value and Soil Factor) in order to gain confidence in MnPAVE and aid in the development of a statewide database of comparative designs. In spite of this limitation, MnPAVE is currently a valuable tool that takes into account significant climatic conditions, material properties, and traffic variables that have not been included in the past. Mn/DOT's Office of Materials and Road Research conducted verification trials during 1999, 2000, 2001, and 2002 to ensure that MnPAVE's results were reasonable when compared with Mn/DOT's existing design procedures. Some issues remain to be resolved and input from district, county, city, and consulting engineers would be very beneficial as the software is modified.

MnPAVE can be operated in two modes, Standard or Research. This Designer's Guide describes the Standard mode, which currently provides a number of useful features.

- three design levels based on input data quality
- soil and aggregate properties adjusted seasonally
- hot mix asphalt (HMA) modulus based on temperature
- traffic quantified using either ESALs or load spectrum
- English or System International (SI) units
- multiple damage prediction transfer functions based on elastic properties
- maximum allowable stress check for aggregate base

1.1 Design Levels

Three design levels are available based on the quality and quantity of input data available to the designer. The design levels are "Basic, Intermediate, and Advanced." The "Basic" level requires the minimum amount of information and is intended to be sufficient for many low volume county, township, and municipal roads. The "Basic" level can also be used for developing a preliminary design for higher volume roads. The "Intermediate" level requires an amount of information similar to Mn/DOT's current design procedure and is the design level intended for the final design of most trunk highway projects. The "Advanced" level requires detailed traffic and mechanistic material property data and is intended for high volume trunk highways and interstates. Since the Basic, Intermediate, and Advanced levels are available within the Climate, Structure, and Traffic input windows, it is possible for the designer to use a different design level for each type of input data. For example, if the designer has very good traffic data, but no mechanistic material property data they would select the Advanced level for Traffic and the Basic level for Structure.

1.2 Resistance Factors

Resistance factors have been proposed to account for the reduction in mechanical properties resulting from seasonal moisture changes. Resistance factors decrease as the material's resistance decreases and therefore resistance factors less than 1.0 reduce the design moduli. Resistance factors have also been proposed to account for the level of uncertainty associated with the correlations used to estimate mechanical properties from classification data only (Basic Design Level) or other tests such as the R-Value or dynamic cone penetrometer (Intermediate Design Level). Naturally, the final pavement design will have a greater reliability if the input data have high quality and low variability.

Currently these resistance factors are not fully implemented in MnPAVE. Instead the variability in the index tests (Basic Design Level) or the variability in the measured strength tests (Intermediate Design Level) is considered. For example, when the R-Value is estimated from the silt content (Basic Design Level), then the silt content used to estimate the R-Value is the mean value of the historical data for the selected soil type plus one standard deviation. Similarly, if the R-Value is measured in the laboratory, then the design R-Value, which is input and used in subsequent calculations to estimate the design modulus, is the mean of the laboratory measured R-Values minus one standard deviation.

For undisturbed soils, a resistance factor of 0.5 is applied to the engineered soil moduli values when these soils are left in an undisturbed condition (not excavated, blended, and compacted). If the designer believes that the undisturbed soil moduli should be higher or lower, then alternative moduli values can be entered individually in the Advanced Design Level.

Mn/DOT may change this methodology based on additional testing of Minnesota materials and research proposed by Mn/DOT at the University of Minnesota. The appendix of this Designer's Guide contains a Draft Design Moduli Table and Notes that further explain the use of resistance factors that adjust for soil type and moisture condition. Your suggestions would be appreciated.

1.3 Performance Related Specifications

MnPAVE creates the opportunity to develop and implement performance-related specifications. Performance-related specifications are specifications for key materials and construction quality characteristics that have been demonstrated to correlate significantly with long term performance. Performance-related specifications are intended to be more objective than traditional specifications because they are based on quantified relationships between characteristics measured at the time of construction and subsequent performance. They include sampling and testing procedures, quality levels and tolerances, acceptance or rejection criteria, and payment schedules with positive or negative adjustments. These adjustments are quantified using performance models that predict changes in the anticipated pavement life resulting from different quality levels (Chamberlin, 1995).

Performance-"related" specifications describe the desired level of materials and construction quality characteristics that have been found to correlate with fundamental engineering properties. This is somewhat different than performance-"**based**" specifications, which describe the desired levels of the **actual** fundamental engineering properties such as resilient modulus. The actual engineering properties can be used to predict performance because they are used directly in the mechanistic model that predicts pavement stress, distress, and performance based on traffic, environment, and structural conditions (Chamberlin, 1995).

In situ testing at the time of construction needs to strive to directly measure actual engineering properties. This is difficult, but is becoming possible due to the development of new in situ testing equipment. The portable falling weight deflectometer (PFWD), from which moduli can be calculated, is an example of a field test that would be used in a performance-based specification. The dynamic cone penetrometer (DCP), from which moduli can be estimated

based on correlations between moduli and penetration resistance, is an example of a test that would be used in a performance-related specification.

A goal of performance-related specifications is to quantify the quality level providing the best balance between cost and performance and to assure this quality level is attained during construction. Performance-related specifications reflect the best understanding of what determines quality and create a contractual framework that maximizes cost effectiveness (Chamberlin, 1995). However, they require new testing techniques and a greater understanding of the relationships between the fundamental engineering properties and the subsequent performance of the constructed product. This requires that the engineering properties be quantitatively measured during construction.

Construction management has begun to separate the responsibilities of the contractor for controlling quality during construction, from the responsibilities of the owner for judging acceptance of the final product and protecting the public interest. This requires specifications that are more objective and science based. Specifications need to account for variability, recognize the contractor more fully as an equal partner, distribute risk equitably, and provide a basis for accountability (Chamberlin, 1995). Performance-related specifications allow innovative methods to be initiated by the contractor because the specified properties of the constructed product are linked directly to performance rather than to subjective criteria extrapolated from previously used methods.

2.0 Start Up

2.1 System Requirements

MnPAVE is designed for Windows 95/98/2000/XP/NT operating systems, requires 4 MB of hard drive space, and a 200 MHz processor.

2.2 Installation Procedure

Insert the CD or download MnPAVE from the internet at <http://www.mrr.dot.state.mn.us> and run the installation program.

2.3 Control Panel

The "Control Panel" is the first window to appear after MnPAVE has been started. The "Control Panel" includes buttons to select the data input options "Project Information, Climate, Structure, and Traffic" and a button to display "Output". The input options should be completed in this order, beginning with "Project Information" and ending with "Traffic." This is because the seasonal material properties used in "Structure" depend on project location selected in "Climate." Any of these input windows can be selected again later to make changes. All inputs must be completed before "Output" can be selected.

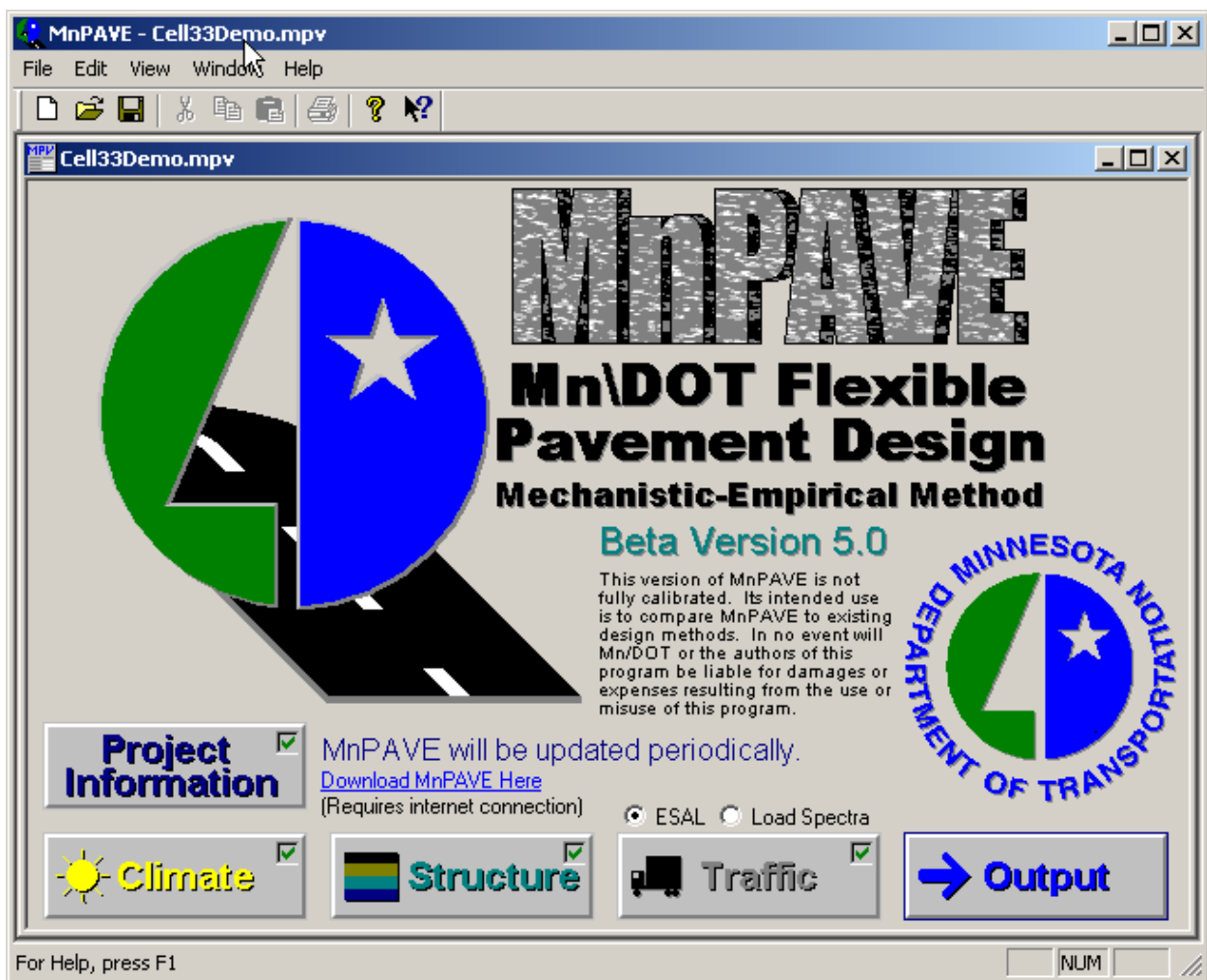


Figure 1. Control Panel Window

2.4 General Operation

MnPAVE uses the pull-down menu and window selection structures common to most of today's software packages. The pull-down menu at the top of the screen includes "File, Edit, View, Window, and Help."

2.4.1 Pull-Down Menus

2.4.1.1. File

Use "File/SaveAs" to name and save your input data files as *.mpv (MnPAVE files).

2.4.1.2. Edit

"Edit" is not currently used.

2.4.1.3. View

"View" contains Tool Bar, Status Bar, Disclaimer, Warnings, and Mode.

View/Disclaimer contains limits on the use of the current version of the MnPAVE software. MnPAVE is intended for evaluation purposes only and the results should be compared to other currently accepted design procedures.

View/Warnings contains "Show HMA Thickness Warning, Show Binder Warning, Always Show Aggregate Base Allowable Stress Results," and "Only Show Aggregate Base Allowable Stress Results if Failed." The HMA thickness warning appears if the designer selects a HMA thickness less than 90 mm (3.5 inches). The allowable stress warning appears if the calculated stress in the aggregate base exceeds the factored aggregate base strength during spring thaw conditions.

View/Mode contains "Standard" and "Research." The Standard Mode should be selected and is intended for general use. The Mode can only be changed from the Control Panel window and must be selected prior to entering climate, structure, or traffic data. This Designers Guide only describes MnPAVE operating in Standard Mode. The Research Mode is available for users to learn more about MnPAVE and its potential application to more complex analyses. Results from the Research Mode are useful for comparing alternative pavement

structures in a relative sense. However, the results are not calibrated and therefore should not be used to determine absolute pavement layer thicknesses.

2.4.1.4. Window

"Window" contains alternate window configurations.

2.4.1.5. Help

"Help" contains "Help Topics, About MnPAVE, and Information on the Web."

Help/Help Topics is not yet completely operational in this beta version and will undergo continued development as the MnPAVE training and implementation process continues.

Help/About MnPAVE contains the software version, release date, team members, and contact information.

Help/Information on the Web contains internet links to current specifications, procedures, and technical memoranda at the Mn/DOT Office of Materials and Road Research.

2.4.2. Data Input/Output Windows

The MnPAVE data input/output windows include "Project Information, Climate, Structure, Traffic, and Output." The Project Information window is shown below. This information will be included in the design summary report created in the Output window.

Project Information

District: 3 County: Wright

City: [Dropdown Menu]

SP Number: 8816-40 Highway: [Dropdown Menu]

Reference Post (RP) from: [Dropdown Menu]

Letting Date: 2/ 5/20

Construction Type: 2360

Designer: Mn/ROAD

Soils Engineer: Mn/ROAD

Notes: [Text Area]

View: All Counties By District

[View Mn/DOT Bituminous Specifications](#)
(Requires internet connection)

Go Back to Control Panel

Figure 2. Project Information Window

Once the project information has been entered, the data used for pavement design are entered using the "Climate, Structure, and Traffic" windows. Data must be entered into these windows in this order to provide MnPAVE with the data necessary for design. To enter data select the "Climate, Structure, or Traffic" windows successively. The output for each trial pavement design will include the estimated pavement life in years and damage factors for asphalt fatigue and subgrade rutting.

2.5 Engineering Units

The default system of engineering units is English, however the system of units can be changed after the "Climate, Structure, or Traffic" window has been selected. System International (SI) or English units may be selected for the "Climate, Structure, and Traffic" data. MnPAVE uses the English system of units during mechanistic analyses and therefore must convert SI input data into English units prior to performing calculations and then convert the English results back to SI to display the output in SI.

3.0 Climate Inputs

3.1 Seasonal Design

The material properties used in each design level are adjusted for seasonal changes in temperature and moisture. For example, the hot mix asphalt (HMA) modulus decreases in the summer when temperatures are higher and the modulus of the aggregate base decreases in the early spring due to near saturated conditions. Seasonally adjusted moduli are important because different failure modes are more prominent during particular periods of the year.

3.1.1 Definition of Seasons

Pavement design should consider the major periods influencing pavement behavior. In Minnesota the year is usually divided into five seasons (Ovik, Birgisson, and Newcomb, 2000). These seasons are "Early Spring, Late Spring, Summer, Fall, and Winter." Early Spring is defined as the time when the aggregate base is thawed and nearly saturated, but the subgrade remains frozen. Late Spring is when the aggregate base has drained and regained partial strength, but the subgrade is thawed, near saturated, and weak. Summer is when the aggregate base is almost fully recovered, but the subgrade has only regained partial strength. By Fall, both the aggregate base and subgrade have fully recovered. Winter is the season when all pavement layers are frozen.

3.1.2 Season Duration

The duration of each season is dependent on the geographic location of the project and the climate it experiences. Therefore each season has a variable duration and the only constraint is that the sum of the seasonal periods must equal one year (52 weeks or 365 days). The typical durations of Minnesota's seasons vary from north to south, but are generally about 2, 9, 14, 13, and 14 weeks for Early Spring, Late Spring, Summer, Fall, and Winter respectively. The criteria used to determine the duration were originally defined by the University of Minnesota (Ovik, Birgisson, and Newcomb, 2000). These criteria have subsequently been modified by Mn/DOT and will undergo additional modification as current Mn/DOT research, related to predicting frost depth and thaw depth from air temperatures, is implemented.

3.2 Design Level

Only the "Basic" design level is available when MnPAVE is operating in the Standard Mode. Recall that Standard Mode was selected during MnPAVE startup using View/Mode/Standard.

3.2.1 Basic

The Basic design level contains "Map" and "Details." The designer uses the Map window to select the project's geographic location in Minnesota by clicking on the approximate position. District, county, and geographic coordinates are provided to aid the designer in selecting the approximate location. It is not necessary to be extremely accurate because a 75 mile radius is used to determine which air temperature data is used to calculate the mean air temperature at the selected location. Generally between four and six weather stations will be included within this 75 mile radius. The air temperature data used by MnPAVE was collected from 47 weather stations located throughout Minnesota and neighboring states between 1971 and 2000.

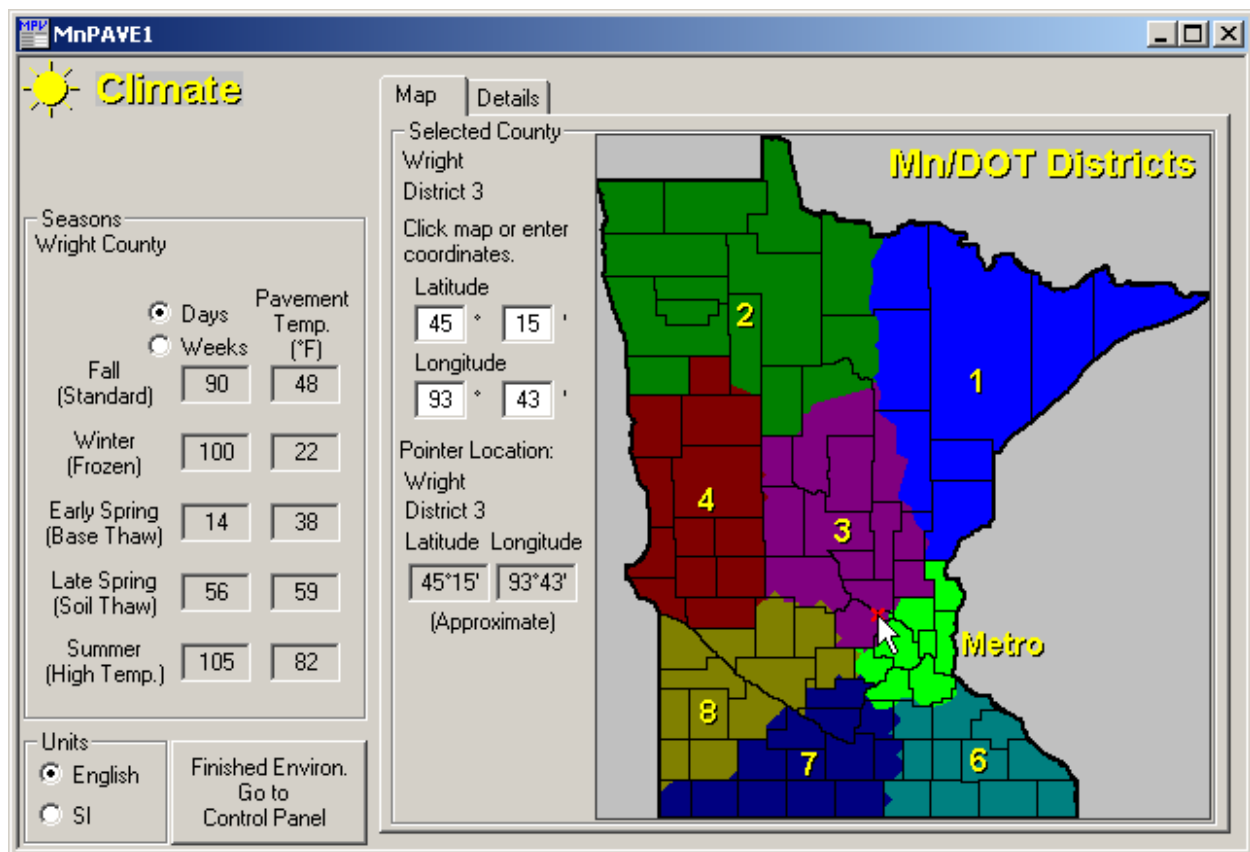


Figure 3. Climate/Map Window

The designer uses the Detail window to view the equation that predicts HMA temperature from air temperature; and also the thaw depth assumed during the early spring season.

The seasonal average daily HMA temperature at one-third the HMA thickness is estimated using the predictive equation that can be viewed by selecting the "View Temperature Equation" box (Ayres, 1997). The equation utilizes the seasonal average daily air temperature for the location selected and the HMA thickness entered by the designer in the "Structure" window.

The "Early Spring Thaw Depth" defines the thaw depth used to determine the moduli of the aggregate base, granular subbase, and engineered soil during the early spring season. Materials above this depth are assumed to be thawed and materials below are assumed to be frozen.

Seasons	Duration	Pavement Temperature	Air Temperature
Fall (Standard)	12	48	41
Winter (Frozen)	15	22	19
Early Spring (Base Thaw)	2	38	32
Late Spring (Soil Thaw)	8	59	50
Summer (High Temp.)	15	83	70
Total	52		

Figure 4. Climate/Details Window

4.0 Structural Inputs

The structural inputs required by MnPAVE's mechanistic model include the number of layers comprising the pavement system, the thickness of each layer, and the elastic properties of each layer. It is the elastic properties, not the material type or R-Value, that are the essential input parameters if the design is to have a high reliability. The "Basic, Intermediate, and Advanced" design levels simply allow the elastic properties to be entered into MnPAVE either directly (Advanced Level), or by correlations to other more commonly used material classifications, material index tests, and material strength tests (Basic and Intermediate Levels).

It is important to consider that an accurate solution requires accurate input data and that attempting to use only material classifications (Basic Level) can result in elastic property estimates that do not accurately reflect the actual elastic properties of the constructed pavement system. Therefore, it is recommended that only the "Intermediate" or "Advanced" design levels be used to provide the structural inputs required. It is anticipated that this approach will encourage greater understanding by the designer of mechanistic material properties as well as a greater appreciation for the implications of selecting good versus poor materials.

The aggregate base, granular subbase, and engineered soil are intended to be stiff enough to enhance HMA compaction during construction as well as provide long term support for the HMA. These materials are independently blended and placed in thin lifts to create homogeneous layers that provide uniform support to the HMA. The aggregate base and subbase must be stiff and strong enough to reduce the stress on the soil and support paving operations, yet be porous enough to provide adequate drainage and have low frost susceptibility. The MnPAVE design procedure does not include any drainage, frost susceptibility, or trafficability criteria. Recommendations regarding these critical design requirements are included in other publications (LRRB Best Practices for the Design and Construction of Low Volume Roads, 2002, Mn/DOT Geotechnical and Pavement Manual, 1994, Mn/DOT Grading and Base Manual, 1996, Mn/DOT Standard Specifications for Construction, 2000).

The mean and coefficient of variation (COV) of the material moduli and layer thicknesses are required to run a reliability analysis when using the Monte Carlo simulation method utilized by MnPAVE operating in the Research Mode. However, since the Standard Mode was selected during MnPAVE startup using View/Mode/Standard, then construction variability is assumed to be included in the design values input at the Basic, Intermediate, or Advanced levels.

The pavement life that will be calculated in the Output/Basic window is based on design moduli estimated from laboratory resilient moduli tests or correlations with other tests. These

design moduli are the mean value of the laboratory or in situ tests reduced by the COV of the tests. Construction variability is not included directly in the pavement life calculated in the Output/Basic window unless in situ performance related tests (DCP or PFWD) are used. Therefore no COVs are shown in the Structure/Advanced window because construction variability must be accounted for in the design values.

There are several options for how the reliability analyses are done. MnPAVE Beta Version 5.1 does not yet have reliability fully implemented.

4.1 Design Levels

4.1.1 Basic

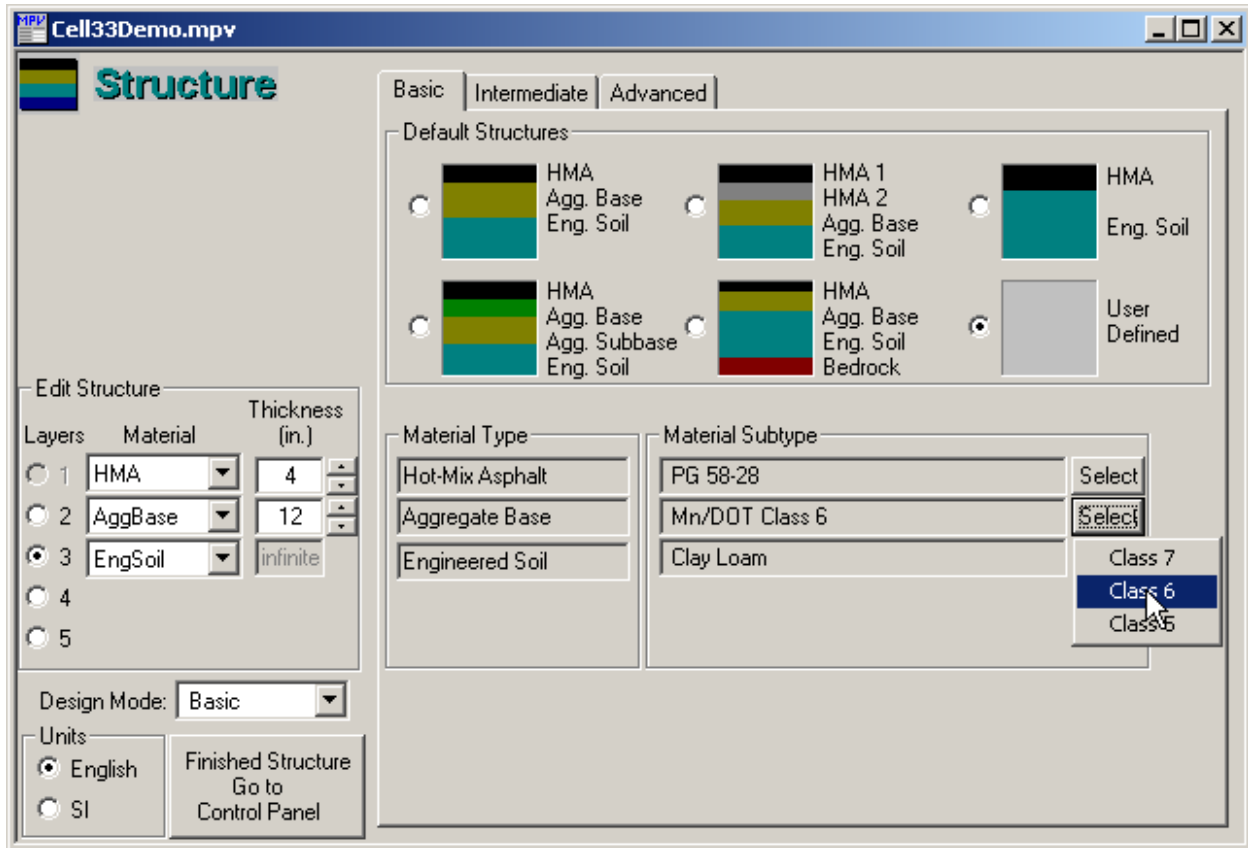


Figure 5. Structure/Basic Window

4.1.1.1 Layer Structure

Select a layer structure from the "Default Structures" provided. It is easy to modify these options, so it is sufficient to select a layer structure that is merely similar to the desired layer structure. The number of layers and their material types will automatically be copied to the "Edit Structure" section of the window. At this point the number of layers and their material type can be modified. Note that MnPAVE is limited to analyzing pavement structures containing 2 to 5 layers. There are several pull-down menus that allow the designer to easily select the material type and material subtype of each layer. Mn/DOT, AASHTO, and Unified soil classification

systems are provided. The appendix contains the Design Moduli Table and Notes that generally explain how the seasonal design moduli are estimated from this classification data.

Layer 1 (the top layer) can be constructed of either "HMA" or "Other". The HMA can be subdivided in up to three lifts with different binder types and aggregate gradations by selecting the "Select" button from the Material Subtype section of the window. The HMA moduli are estimated from HMA temperature and mixture properties using the equation that can be viewed by selecting the "Advanced" button from the "HMA Mix Properties" window (Ayres, 1997 and NCHRP 1-37A, 1999). **MnPAVE Beta 5.1 operating in Standard Mode does not distinguish between different PG binders although there are nine binder types available.** This means that MnPAVE will give the same design no matter what binder type is selected. This is because the majority of existing Minnesota pavements were constructed using AC120/150, which compares to a PG58-28. Currently, there are not enough performance data available on the pavements constructed with other binder types and therefore the performance predicted by MnPAVE is based on pavements constructed with PG58-28.

Generally, the "Other" option should not be selected when MnPAVE is operating in Standard Mode. The "Other" option is included to allow the designer to use materials that have moduli values outside the range allowed by MnPAVE. The "Other" option is used when MnPAVE is operating in Research Mode to view specific responses. Fatigue damage is not calculated if "Other" has been selected.

As the lower layers of the structure are selected, there are more potential material types. These include "Aggregate Base, Subbase, Engineered Soil (EngSoil), Undisturbed Soil (UndSoil), and Other."

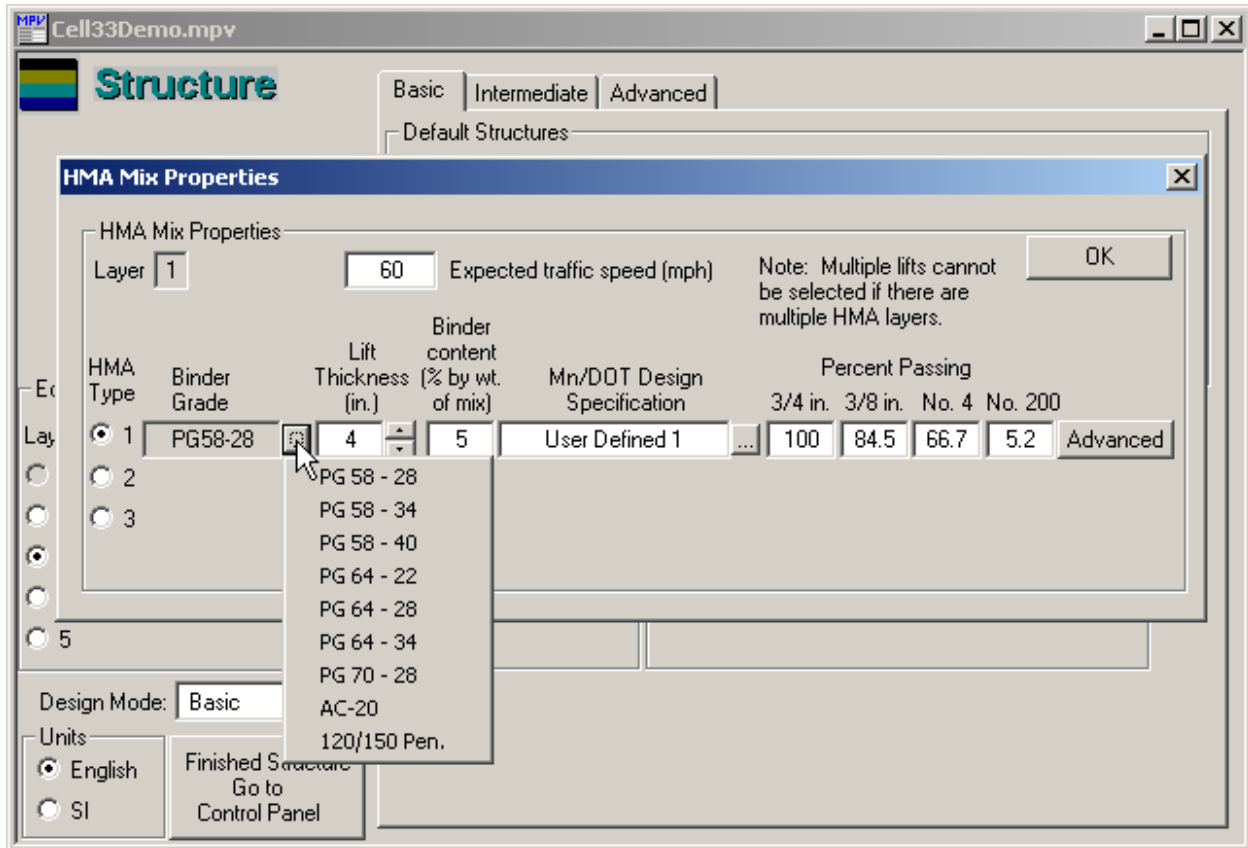


Figure 6. Structure/HMA Window

The "Engineered Soil" is located directly below the aggregate base or subbase and is expected to have relatively well known properties. During the construction process, this soil is excavated, blended, shaped, and compacted in uniform layers to make its properties more uniform and reliable. Some additives may be incorporated into the engineered soil during construction to make its properties even more desirable. Engineered soils become an integral part of the structural system that supports the HMA. The thickness of the overlying layers is based on the expectation that the engineered soil has truly been constructed as intended and therefore has achieved the uniformity, stiffness, and strength properties used during design.

The "Undisturbed Soil" is the in-place soil that existed along the road's alignment prior to construction. This undisturbed soil will not be excavated and not compacted during construction. A resistance factor of 0.5 is applied to the engineered soil moduli estimates when these estimates are used for undisturbed soils. For example, if the summer design modulus for an engineered (compacted) clay loam is 40 MPa (6000 psi), then the modulus of that same clay loam in an undisturbed (not compacted) condition is assumed to be 20 MPa (3000 psi).

The "Other" layer option allows bedrock or soil below the groundwater table to be included in the analysis if either is within about 2 m (6 ft) of the surface. It is recommended that a constant modulus of 350 MPa (50,000 psi) be used for both bedrock and soil below the groundwater table because both materials behave very rigidly in response to dynamic traffic loads. Poisson's ratio is estimated to be 0.15 for bedrock and 0.5 for soil below the groundwater table. The bottom layer of every pavement structure is considered semi-infinite.

4.1.1.2 Layer Thickness

After the basic structure has been defined, a trial thickness for each layer is entered into the boxes next to the "Material". The thickness of each layer has a major affect on the composite behavior of the entire pavement structure and should be chosen to minimize the cost while providing sufficient structural support. It is important to remember that the constructed thickness of some layers may not be constant along the entire project length due to subgrade correction depth and other factors. These factors should be carefully considered before arriving at a particular thickness value.

The thicknesses used by MnPAVE for mechanistic calculations are the design thicknesses entered by the designer. There is no reduction for construction variability. MnPAVE can function with any thickness value between 1 and 25,375 mm (999 in). However the layered elastic analysis is not effected significantly by materials at depths greater than about 3 m (10 ft). MnPAVE allows the layer thicknesses to be changed from the Output window for more rapid comparison of alternate designs. Layer thicknesses can also be varied automatically using the "Batch Mode" option selected in the Output window.

4.1.2 Intermediate

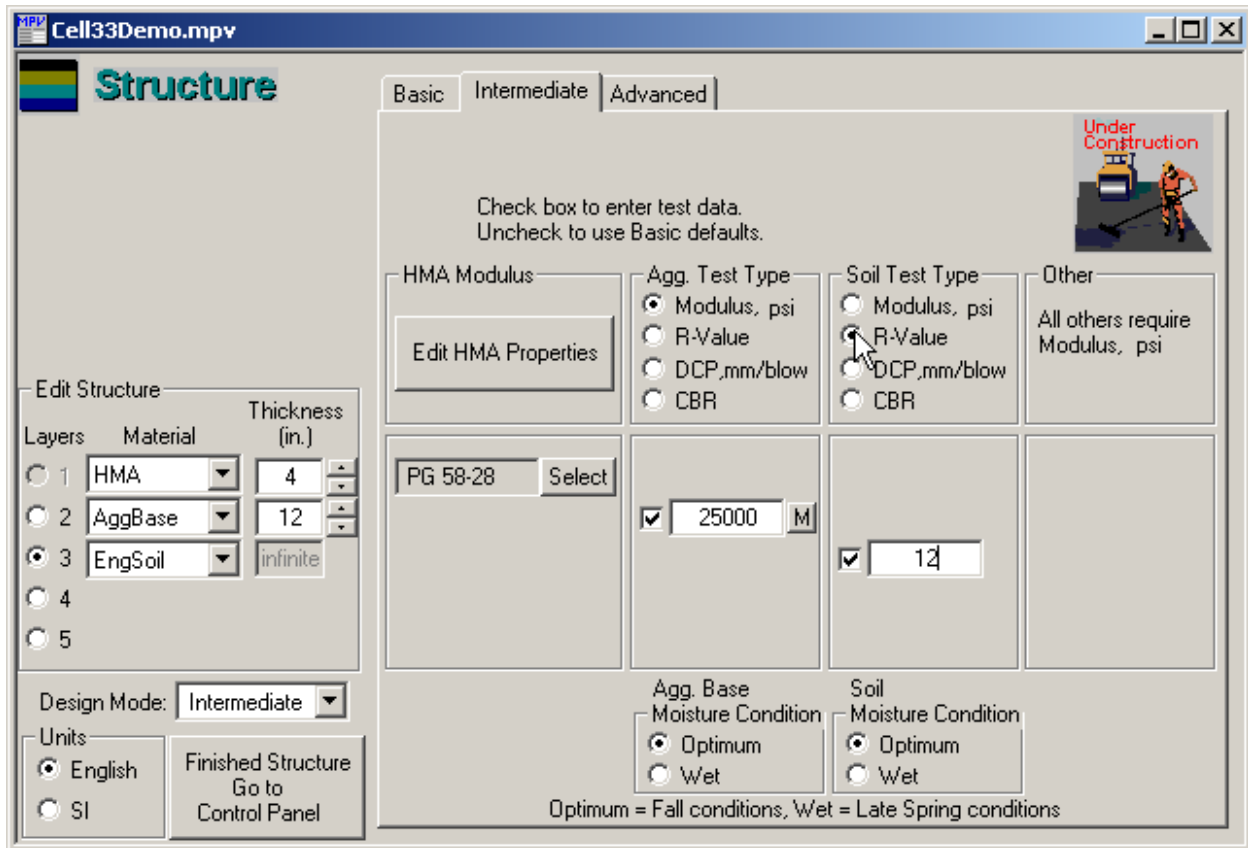


Figure 7. Structure/Intermediate Window

4.1.2.1 Layer Structure

The structure is entered in the "Edit Structure" section of the window. The number of layers is selected followed by the "Material" and "Thickness."

4.1.2.2 Mechanical Properties

At the intermediate design level, a single "design" modulus for each unbound material is used to estimate the seasonal moduli used by MnPAVE. The seasonal adjustments are based on seasonal moisture contents and soil type, which are explained further in "Design Moduli Table and Notes" found in the appendix. The seasonal "Modulus Values" and "Seasonal

Modulus Multipliers" can be viewed by going to the "Structure/Advanced" window. The HMA moduli are estimated from air temperatures using the Witczak equations referenced earlier.

The design modulus from laboratory resilient modulus (Lab Mr) tests performed on each unbound material can either be entered directly or the design modulus can be estimated using correlations to other mechanical property tests. Design moduli can be estimated from the R-Value or dynamic cone penetrometer (DCP). The designer selects the mechanistic test from the "Test Type" section of the window. The test type options include "Lab Mr, R-Value, and DCP."

The values entered here are used for design and therefore should consider variability. There is a mean and coefficient of variation for the laboratory results from Lab Mr and R-Value tests. If in situ DCP tests are used, then the mean and coefficient of variation for the in situ tests must be estimated. The design value entered here is the mean adjusted by the coefficient of variation. This is consistent with Mn/DOT's R-Value design procedure and its treatment of laboratory R-Value data. As a general rule of thumb it is recommended that, if the coefficient of variation exceeds 25 percent (for example the Lab Mr measured at the same stress), then additional tests should be performed (NCHRP 1-37A, 1999).

The design modulus is moisture dependent and therefore the "Moisture Condition" must be specified. Two moisture conditions are available, standard Proctor "Optimum" or "Wet." If the aggregate base and engineered soil are placed during construction at a moisture content near standard Proctor optimum moisture, then the designer should select the "Optimum" moisture condition so that the mechanical properties used for design can be verified during construction. The "Wet" moisture condition would be expected for the aggregate base in early spring and the soil in late spring. The adjustments for moisture condition are included in resistance factors that are explained further in the appendix "Design Moduli Table and Notes." **Currently only the "Optimum" condition may be selected since the available data are confined to moisture contents near standard Proctor optimum moisture. Research proposed by Mn/DOT at the University of Minnesota is intended to better define the effect of moisture on modulus.**

4.1.2.2.1 Design Based on Laboratory Tests

If the designer chooses to characterize the unbound materials using laboratory resilient modulus or R-Value, then these tests are completed prior to design and the designer knows the mean and standard deviation. Therefore the pavement design is completed using the mean

minus one standard deviation of the laboratory results. However, these laboratory tests are performed on samples that may not accurately represent the actual materials at the time of construction because of variations in both the materials encountered during construction and how these materials are blended during construction.

Mn/DOT design procedures have always recommended that the R-Value used for design be verified during construction. This requires careful observation and judgement of the materials placed during construction and possibly requires that additional R-Value tests be performed on samples collected during construction to verify that the mean and standard deviation of the constructed embankment are consistent with the values used for design.

Mn/DOT's R-Value design procedure uses the mean R-Value minus one standard deviation as the "design" R-Value. A reduction of only one standard deviation from the mean was judged to be adequate because it was assumed that the materials in the constructed embankment would have the same mean and standard deviation as the laboratory tests. If the R-Value or resilient modulus is not verified by additional testing at the time of construction or judged to be accurate by qualified inspectors at the time of construction, then the pavement design is at risk of premature failure or may be over-designed and waste resources.

4.1.2.2.2 Design Based on In Situ Tests

If the designer chooses to characterize the unbound materials using an in situ test, such as the DCP, then the mean and coefficient of variation of the in situ DCP tests are not known during the design process. This is not unlike the situation described above where the actual materials used in the constructed embankment are not well known during design. However, when the design is based on in situ tests, these in situ test results can be specified in the contract documents and verified by quality control testing in the field during construction (Frost, Fleming, and Rogers, 2001; McKane, 2000; Nazarian, Yuan, and Arellano, 2002; Siekmeier, Young, and Beberg, 1999; Siekmeier, Burnham, and Beberg, 1998).

Since no tests are available at the time of design, the designer needs to estimate appropriate DCP values based on material type, other tests, and engineering judgement. References available to the designer include the Minnesota Subgrade Atlas (Barnes, 1995) and the Soil Conservation Service maps. The pavement is designed based on the anticipated DCP test results and the contract documents require that the DCP mean and coefficient of variation **be achieved at an appropriate moisture condition**. The contract documents do not necessarily require specific materials or procedures. Rather, the contract documents require

specified mechanical properties **at defined moisture contents**. The drainage and frost susceptibility criteria must still be addressed and eventually these criteria would also be quantified during construction using an in situ test such as the permeameter (drainage) or percometer (dielectric measurement, moisture and frost susceptibility).

4.1.3 Advanced

The advanced design window has two major functions. First, it is used to display the pavement structure and seasonal moduli that result from the data entered at the basic or intermediate design level. Second, the advanced design window allows the designer to enter the moduli for every material and season individually. This second function allows the designer complete flexibility in selecting moduli values that can not be estimated by MnPAVE.

For example, if flyash were added to an engineered soil, then the default seasonal factors used to estimate seasonal moduli for soils may not apply to soil-flyash mixtures. Therefore the designer would need to enter the seasonal moduli for the soil-flyash mixture directly. Seasonal FWD testing or other in situ testing could be used as guidance. Previously constructed projects should be considered for testing and a database created by the Mn/DOT districts.

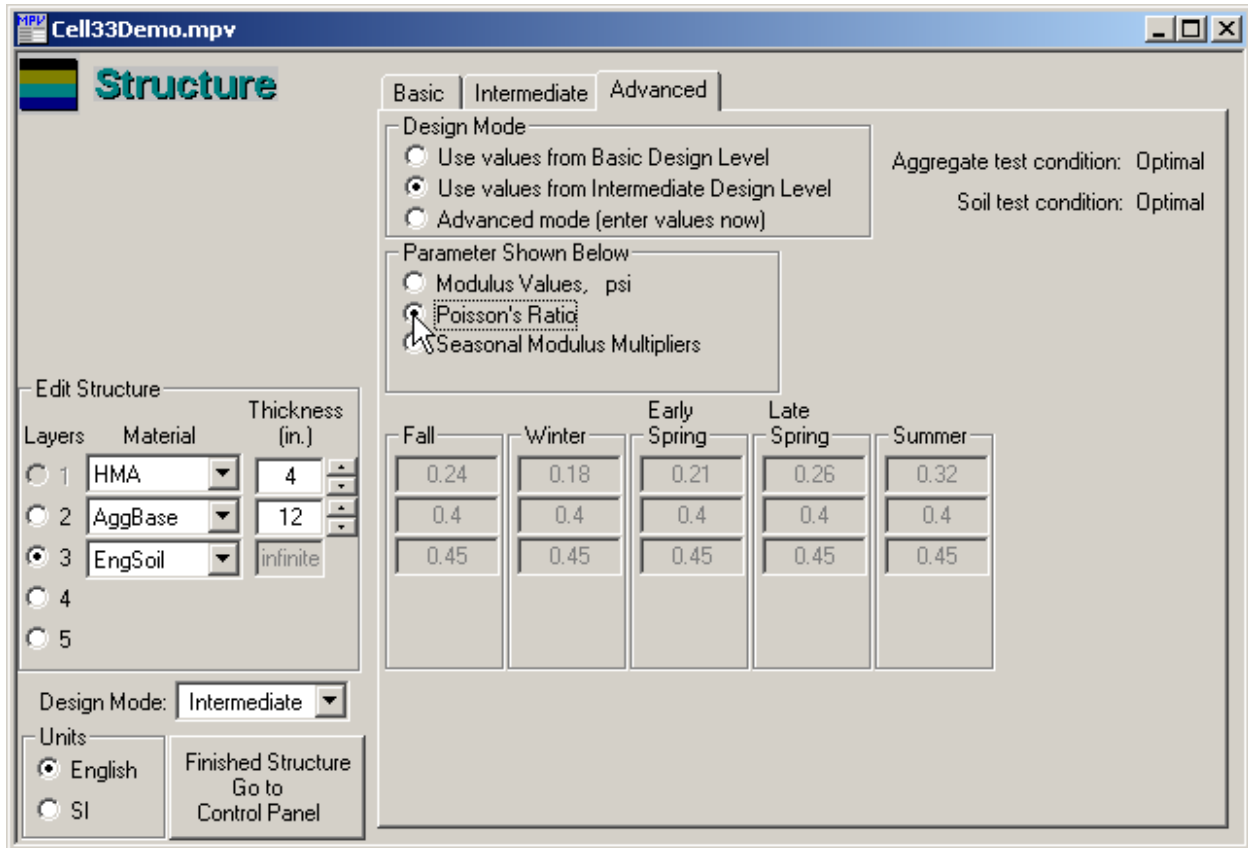


Figure 8. Structure/Advanced Window

4.1.3.1 Layer Structure

The layer structure is either imported automatically from the basic or intermediate design level or entered in the "Edit Structure" section of the "Advanced" window by selecting from the options displayed in the "Design Mode" section of the window. The options include "Use values from Basic Design Level, Use values from Intermediate Design Level, or Advanced mode (enter values now)." The number of layers is selected followed by the "Material" and "Thickness."

4.1.3.2 Mechanical Properties

The seasonal moduli are either imported automatically from the basic or intermediate design level or entered directly in the advanced design window. The parameter that will be displayed or entered is selected from the options in the "Parameter Shown Below" section of the

window. The options include "Modulus Values, Poisson's Ratio, and Seasonal Modulus Multipliers."

5.0 Traffic Inputs

Two types of traffic inputs are required: maximum axle load and traffic volume. The maximum anticipated axle load is required to check whether the aggregate base has the strength required to prevent failure due to a one time worst case loading. The traffic volume is required to quantify the number of repeated loads expected over the design period. These repeated loads are quantified by equivalent single axle load (ESAL) or Load Spectrum.

"ESAL" or "Load Spectrum" is selected above the "Traffic" button on the "Control Panel" window. If the "ESAL" option is selected, then MnPAVE will simulate the quantity of ESALs as the same quantity of 18 kip dual-tire single axles. If the "Load Spectrum" option is selected, then MnPAVE will use the load spectrum defined in the traffic design level selected.

The ESAL concept is integral to the MnPAVE calibration process and therefore the transfer functions are ESAL based. To more fully understand how MnPAVE operates, the designer should first understand how ESALs are calculated. The appendix contains "Calculation of ESALs Using Load Spectrum and HCADT," which provides a useful summary. Additionally, the Mn/DOT Office of Transportation Data and Analysis should be contacted for further information.

The NCHRP 2002 Pavement Design Guide eliminates the ESAL completely and will use the full load spectrum of axle loads applied to the pavement (NCHRP 1-37A, 2001). The NCHRP 2002 Guide is being developed to be consistent with the practices outlined in the FHWA Traffic Monitoring Guide so that road agencies that collect traffic data in accordance with this FHWA protocol will already have the traffic data required for load spectrum. Mn/DOT has been and will continue to collect the required information for the trunk highway system. This type of detailed traffic data is less well developed for the local road network and is now recommended (Skok, et al., 2002).

Traffic volume quantified by either ESAL and Load Spectrum requires an accurate traffic distribution. This was the subject of a study carried out by the Local Road Research Board (LRRB) and Mn/DOT (Timm and Skok, 2000). Local road agencies have traditionally used assumed vehicle distributions provided by Mn/DOT in the State Aid Manual. These vehicle distributions were based on an average traffic distribution for a region and can be used to arrive at an ESAL prediction for a specific roadway. The LRRB study was undertaken to determine whether or not those assumed vehicle distributions accurately predicted the actual vehicle distribution on several roadway sections around Minnesota. The results were surprising even for rural roads where traffic was expected to be relatively constant. In summary, over half of the

ESAL predictions were in error by more than 40%. In 36 of the 53 cases, the ESALs calculated using the assumed distribution fell short of the ESALs calculated using the measured distribution. In one case, an error of 167% was observed. These large errors have a tremendous effect on expected pavement life. The report concluded that vehicle classification studies must be conducted for each project if reasonably accurate traffic loads are desired.

5.1 Allowable Stress Criterion

Aggregate base failure can occur if the axle load transmitted through the HMA exceeds the strength of the aggregate base. Therefore, a maximum allowable stress criterion has been implemented in MnPAVE to protect against aggregate base failure. The failure criterion selected is the traditional Mohr-Coulomb criterion.

This section of the ESAL window should probably be put in its own window since the allowable stress criterion applies to both ESAL and Load Spectrum. It would seem that we may want "Allowable Stress, ESAL, and Load Spectrum" windows from within the Traffic window. This can wait until we get more ideas from users during the training.

5.2 ESAL

The design ESAL can be entered in the "ESAL" section of the window by selecting the "First Year" or "Lifetime" option. Recall that MnPAVE simulates ESALs as the same quantity of 18 kip dual-tire single axles and that these axle loads are distributed through the seasons defined in the Climate window. Therefore, for MnPAVE to calculate the damage that occurs in each season of every year the ESALs per season are needed. This means that the designer may select either the "First Year" or "Lifetime" option, but must still enter the "Design Period Length" and "Annual Growth Rate" regardless of which option is selected.

The design period is typically 20 years, but any number of years can be entered for the design period. The annual growth rate is used to calculate simple growth, not compound growth. Simple growth means that the traffic increases by a constant amount each year for the design period (a fixed number based on a percentage of the first year traffic). Compound growth would mean that traffic volume increases by a greater amount each year of the design period (an increasing number based on a percentage of the previous year's traffic). Simple growth is recommended for most project locations by the Mn/DOT Office of Transportation Data and Analysis based on analysis of traffic growth.

The screenshot shows a software window titled "Example1.mpv" with a sub-header "ESAL". The interface is divided into several sections:

- Axle Configuration:**
 - Tire Pressure: 80 psi
 - Axle Weight: 18000 lbs.
 - Wheel Weight: 4500 lbs.
- Traffic:**
 - Lifetime: 2500000
 - First Year: 97276 (Calculated)
 - Design Life (years): 20
 - Annual Growth Rate (%): 3 (Simple Growth)
- Units:**
 - English
 - SI
- Allowable Stress Failure Criterion:**

	Axle Weight (lbs.)	Tire Pressure (psi)	Wheel Spacing (in.)
Heaviest Single Tire Axle	22000	100	
Heaviest Dual Tire Axle	28000	100	13.5

Additional controls include a "Finished Traffic Go to Control Panel" button and a "Restore Mn/ROAD Defaults" button.

Figure 9. Traffic/ESAL Window

5.3 Load Spectrum

A complete load spectrum is the total quantity of loads in every axle configuration that pass over a roadway during its design life. This total is estimated by counting, classifying, and weighing vehicles for a known period and then estimating the total load spectrum based upon assumptions made about seasonal traffic variations and annual growth factors. Because traffic loads on roads vary considerably from day to day, month to month, and year to year, compiling even a modestly accurate load spectrum requires effort. The same is true for estimating ESALs, however given that automated data acquisition devices are now available the traffic data collection and record keeping functions are greatly simplified.

5.3.1 Design Level

5.3.1.1 Basic

The Basic design level is under development and your ideas are welcome. The following is a possible methodology. When the "Basic" design level is selected, the designer enters the "Average Annual Daily Traffic (AADT)," "Direction Factor," "Lane Factor," " Design Period Length," and "Annual Growth Rate," and then selects between several "Typical Vehicle Distributions." The traffic count and growth data are combined with the "Typical Vehicle Distribution" selected to estimate the load spectrum that MnPAVE would use in the analysis. The typical vehicle distributions would be based on statewide averages, which are not likely to accurately reflect the actual traffic distribution for any specific roadway. Therefore the "Basic" design level should only be used for low volume roads where reliability is not critical.

The NCHRP 2002 Pavement Design Guide is expected to use the following methodology (NCHRP 1-37A, 2001). Basic traffic inputs require the average daily traffic and an estimate of the percentage of buses, multi-trailer, single trailer, and single unit trucks. The designer uses default truck class distributions and axle load distributions to develop the required traffic inputs. The defaults should be developed by the highway agency and may include categorizing the route into one of 17 truck traffic classification (TTC) groups.

- 1 Major single-trailer truck route (type I)
- 2 Major single-trailer truck route (type II)
- 3 Major single- and multi- trailer truck route (type I)
- 4 Major single-trailer truck route (type III)
- 5 Major single- and multi- trailer truck route (type II)
- 6 Intermediate light and single-trailer truck route (I)
- 7 Major mixed truck route (type I)
- 8 Major multi-trailer truck route (type I)
- 9 Intermediate light and single-trailer truck route (II)
- 10 Major mixed truck route (type II)
- 11 Major multi-trailer truck route (type II)
- 12 Intermediate light and single-trailer truck route (III)
- 13 Major mixed truck route (type III)
- 14 Major light truck route (type I)
- 15 Major light truck route (type II)
- 16 Major light and multi-trailer truck route
- 17 Major bus route

In order to select the appropriate TTC the following grouping provides guidance for the types and volumes of heavy vehicles included in the TTC groups. The TTC groups represent distributions observed in the LTPP database and normally expected to occur during design. Since the TTC groups represent only those observed in the data, they do not necessarily address every imaginable situation.

Buses Low to None (<2%) With a Moderate Amount of Multi-Trailer Trucks (2-10%)

- 3 Predominantly single-trailer trucks
- 7 Mixed truck traffic with a higher percentage of single-trailer trucks
- 10 Mixed truck traffic with about equal percentages of single-unit and single-trailer trucks
- 15 Predominantly single-unit trucks

Buses Low to None (<2%) With a Relatively High Amount of Multi-Trailer Trucks (>10%)

- 5 Predominantly single-trailer trucks
- 8 High percentage of single-trailer trucks, but some single-unit trucks
- 11 Mixed truck traffic with a higher percentage of single-trailer trucks
- 13 Mixed truck traffic with about equal percentages of single-unit and single-trailer trucks
- 16 Predominantly single-unit trucks

Busses Low to Moderate (>2%) With Low to None Multi-Trailer Trucks (<2%)

- 1 Predominantly single-trailer trucks
- 2 Predominantly single-trailer trucks, but with a low percentage of single-unit trucks
- 4 Predominantly single-trailer trucks with a low to moderate amount of single-unit trucks
- 6 Mixed truck traffic with a higher percentage of single-trailer trucks
- 9 Mixed truck traffic with about equal percentages of single-unit and single-trailer trucks
- 12 Mixed truck traffic with a higher percentage of single-unit trucks
- 14 Predominantly single-unit trucks

Major Bus Route (>25%) With Low to None Multi-Trailer Trucks (<2%)

- 17 Mixed truck traffic with about equal single-unit and single-trailer trucks

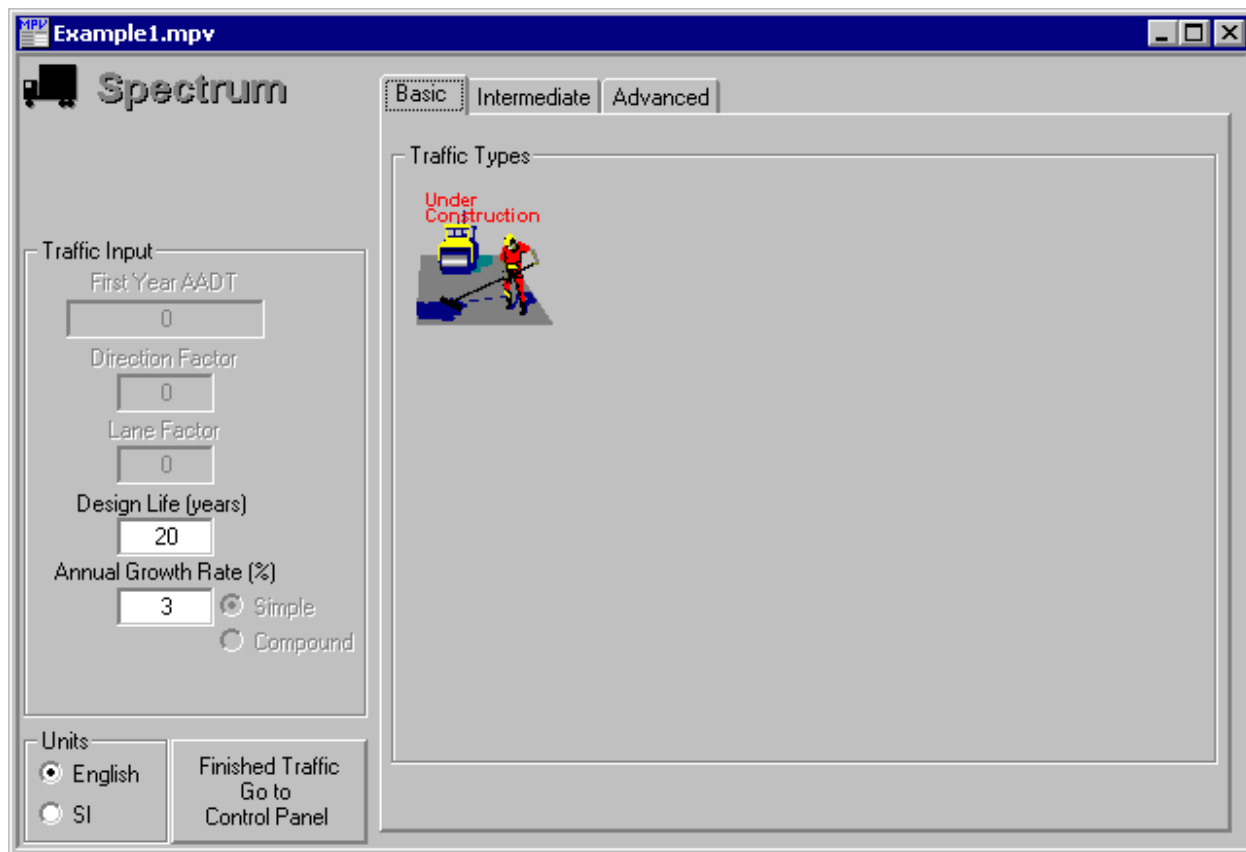


Figure 10. Traffic/Load Spectrum/Basic Window

5.3.1.2 Intermediate

The Intermediate design level is under development and your ideas are welcome. The following is a possible methodology. When the "Intermediate" design level is selected, the designer enters "AADT," "Direction Factor," "Lane Factor," "Design Period Length," and "Annual Growth Rate," and then defines the vehicle distribution by entering the percentage of each "Standard Vehicle Type." The "Standard Vehicle Type" can be defined by selecting either the FHWA or Mn/DOT classification. The traffic count and growth data are combined with the percentage of each Standard Vehicle Type to estimate the load spectrum that MnPAVE will use in the analysis.

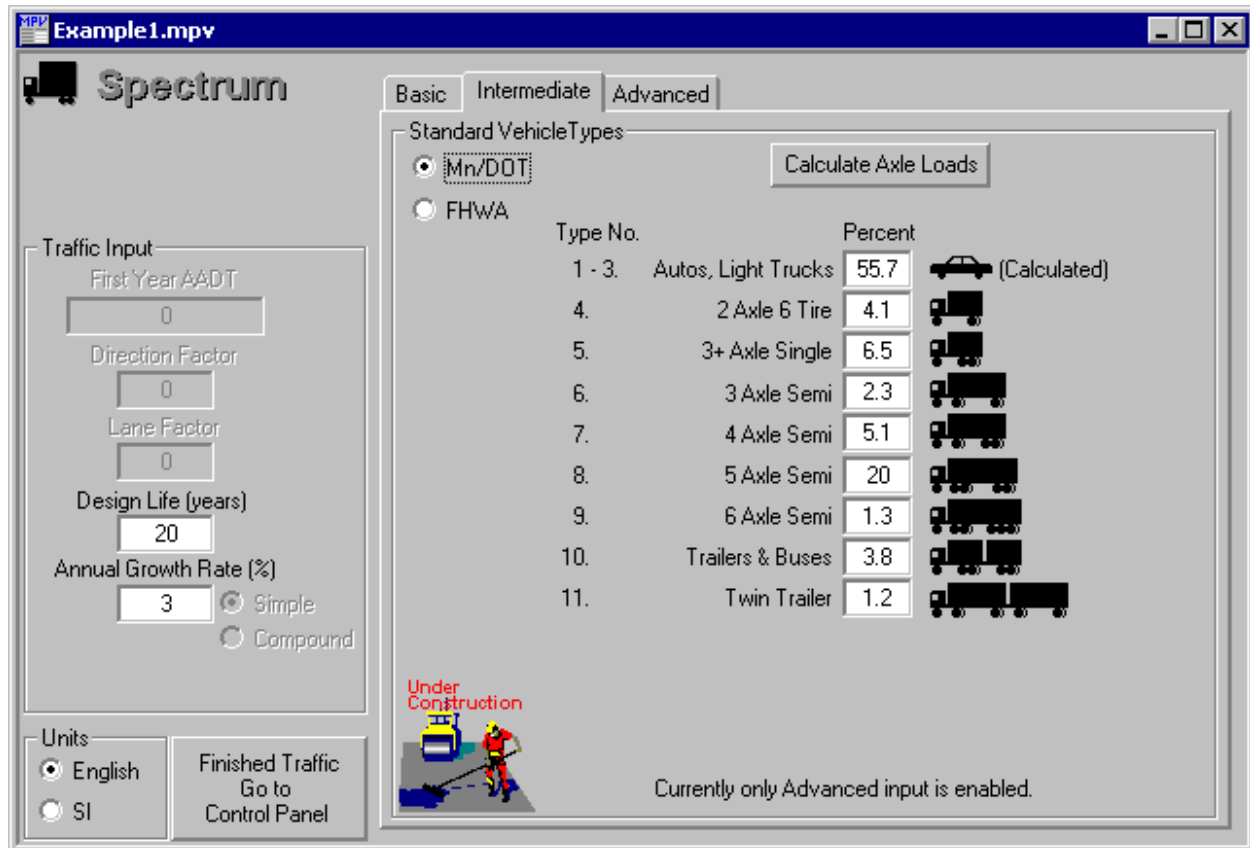


Figure 11. Traffic/Load Spectrum/Intermediate Window

5.3.1.3 Advanced

When the "Advanced" design level is selected, the designer selects the axle configuration and enters the expected number of design period axles under the appropriate load. The "Annual Growth Rate" and "Design Period Length" are combined with design period axles to calculate the complete load spectrum. There are 28 load classes with a 2 kip weight range assigned to each. The mean weight in each range is used in the analysis. For example, if the weight range is 17-19 kips, then 18 kips or 9 tons is actual axle load (9 kip or 4.5 ton dual-tire load) used in the analysis.

Before entering the number of loads in each "Load Class" it is important to make certain that every "Axle Configuration" intended to be included in the analysis has a checkmark in the "Include" box below its picture at the top of the window. Single, tandem, tridem and steer axle types can be selected. The single, tandem, and tridem axles can have either single or dual tires. If any of these configurations is not to be included, click the small box below the picture to remove the checkmark. This "Include" option allows the designer to either include or exclude an entire axle configuration from the load spectrum without entering or deleting dozens of individual axle repetitions.

The screenshot shows the 'Spectrum' software window with the 'Advanced' tab selected. The interface is divided into several sections:

- Traffic Input:** Includes fields for First Year AADT (0), Direction Factor (0), Lane Factor (0), Design Life (years) (20), and Annual Growth Rate (%) (3). There are radio buttons for 'Simple' (selected) and 'Compound'.
- Units:** Radio buttons for 'English' (selected) and 'SI'.
- Finished Traffic:** A button labeled 'Go to Control Panel'.
- Axes:** A section with icons and checkboxes for 'Dual', 'Dual Tandem', 'Dual Tridem', 'Steer', 'Single', 'Single Tandem', and 'Single Tridem'. The 'View' checkbox is checked for 'Dual'.
- Number of Loads Expected During Design Life:** A table with columns for Load Class (kips), Tire Pressure (psi), and Wheel Spacing (in.). The table shows the number of loads for various axle configurations.
- Summary:** A 'Total Number of Selected Axles' field showing 13302734, and buttons for 'Load Sample Data' and 'Clear All'.

Load Class (kips)	19 - 21	21 - 23	23 - 25	25 - 27	27 - 29	29 - 31	31 - 33	33 - 35	35 - 37	37 - 39	39 - 41	41 - 43	43 - 45	45 - 47	47 - 49	49 - 51	51 - 53	53 - 55	55 - 57	57 - 59	59 - 61	61 - 63	63 - 65	65 - 67	67 - 69	69 - 71	71 +
1 - 3	175550	85563	36162	12022	6635	2374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3 - 5	231596	36162	12022	6635	2374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5 - 7	221571	12022	6635	2374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7 - 9	204485	6635	2374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9 - 11	239235	2374	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 - 13	258322	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 - 15	258755	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 - 17	256610	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 - 19	182093	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 12. Traffic/Load Spectrum/Advanced Window

To enter data place a checkmark in the "View" box below its picture at the top of the window. This allows the designer to enter the number of design period loads expected for the axle configuration selected. The tire pressure for this axle configuration must also be entered. The default tire pressure of 100 psi should be used unless the designer provides justification for a different tire pressure. This tire pressure is combined with the load to calculate the radius of the applied load. A circular load is assumed for each wheel, which means that the radius of the applied load will not match the area beneath an actual wheel. The stress applied to the pavement surface is assumed to be equal to the tire pressure. This is known to be incorrect, however the stress differences at the surface are damped out rapidly with depth and therefore the critical strains are not affected greatly. In addition, the current empirical transfer functions are calibrated given that a 100 psi tire pressure equals a 100 psi pavement surface stress.

6.0 Output

Three options exist to perform the calculations and interpret the results; "Basic," "Batch Mode," and "Reliability."

6.1 Basic

Basic output includes the "Damage" and "Life" options. Also, a maximum allowable stress criterion has been included for the aggregate base.

Example1.mpv

Output Life Damage

Traffic Type: ESAL Total Repetitions: 2500000

Expected Life: Thickness Goal Seek

Layer 1: 1 2 3

Years: Fat. 29 MnPAVE Rut. 21 MnPAVE

Adjust Materials (in.):

HMA: PG58-34	6
AggBase: Cl.5	6
Subbase: Gran	15
EngSoil: CL	12
UndSoil: CL	infinite

Recalculate

Units: English SI

Go Back to Control Panel

Basic Batch Mode Reliability

Percent of Total Damage

	Fall	Winter	Early Spring	Late Spring	Summer
	9.2	0.5	0.7	14.7	74.8
	15.1	0.3	0	23	61.7

Export: Design Summary Damage Details

Figure 13. Output/Basic Window

6.1.1 Damage

The damage factors for fatigue and rutting quantify the amount of pavement damage expected during the design period. They are calculated by dividing the traffic predicted to travel

over the pavement during the design period by the allowable traffic estimated by the MnPAVE damage functions. The predicted traffic is provided by the designer in the Traffic window and the allowable traffic is the traffic estimated by MnPAVE based on the pavement structure entered in the Structure window. Therefore the damage factors increase with greater axle loads and greater traffic volume.

For example, if the traffic predicted is greater than the allowable traffic, then the damage factor is greater than 1.0 and the pavement fails prior to the end of the design period. A second example is as follows. If the traffic predicted is based on a 20-year period and the allowable traffic is equivalent to this predicted traffic, then the damage factor would be 1.0 and the expected pavement life would be 20 years.

6.1.1.1 Damage Functions

The damage functions estimate the number of allowable load repetitions based on the calculated strains produced by each loading condition. Damage functions are used to estimate the allowable repetitions for both fatigue and rutting. Typically fatigue failure is defined as 20 percent of the total lane area fatigue/alligator cracked and rutting failure is defined as a 13 mm (0.5 inch) rut. However, the current beta version of MnPAVE uses damage functions that have been calibrated to Minnesota's experience with the Soil Factor and R-Value design procedures. Eventually, the damage functions will be revised based on pavement management data and performance criteria such as these. MnPAVE currently uses the following damage equations.

6.1.1.1.1 Fatigue

Fatigue is based on the Asphalt Institute model (IHR-535, 1998; Finn, F., et al., 1986).

$$N_F = HCSK_{L1} \epsilon_h^{K_{F2}} E^{K_{F3}} \quad (1)$$

or

$$N_F = HCK_{F1} \epsilon_h^{K_{F2}} E^{K_{F3}} \quad (2)$$

where:

N_F = number of repetitions to fatigue failure

H = height adjustment (makes function more severe for thin pavements - Equation 3)

C = correction factor (See Equation 4)

S = shift factor (278 for current MnPAVE calibration)

$K_{L1} = 4.32 \times 10^{-3}$ (Laboratory K_1)

$K_{F1} = SK_{L1} = 1.2$ (Design K_1)

$K_{F2} = -3.291$

$K_{F3} = -0.854$

ϵ_h = horizontal tensile strain at the bottom of the HMA

E = HMA dynamic modulus (psi)

Height Adjustment:

$$H = 1 \quad H_{HMA} \geq 4.5 \text{ in.}$$

$$H = \left(\frac{H_{HMA}}{4.5} \right)^5 \quad H_{HMA} < 4.5 \text{ in.} \quad (3)$$

where:

H_{HMA} = thickness of HMA layer (in.)

Correction Factor:

$$C = 10^M \quad (4)$$

$$M = C_{F1} \left(\frac{V_b}{V_a + V_b} + C_{F2} \right) \quad (4)$$

where:

V_a = volume of air voids (%)

V_b = volume of asphalt (%)

$C_{F1} = 4.84$

$C_{F2} = -0.69$

For MnPAVE calibration, $V_a = 8.0\%$ at bottom of HMA

6.1.1.1.2 Rutting

Rutting is based on the Illinois rutting model (Thompson, M.R., 1987).

$$N_R = K_{R1} \epsilon_v^{K_{R2}}$$

where:

N_R = number of repetitions to rutting failure

K_{R1} = 0.0199

K_{R2} = -2.35

ϵ_v = vertical strain at the top of the subgrade

$$\text{Variable } K_{F1} = \left(\frac{H_1}{4.5} \right)^6 \times 1.6$$

6.1.1.2 Changing the Damage Functions

When operating MnPAVE in the Standard mode, the transfer functions can not be changed. These fatigue and rutting transfer functions are both labeled MnPAVE in the "Expected Life" portion of the Output/Basic window. These are the Mn/DOT standard and shall be used for all Minnesota pavement designs unless documentation is provided to justify other functions. The Mn/DOT Office of Materials and Road Research should be consulted before other functions are used.

When operating MnPAVE in the Research mode, several different transfer functions may be selected and the coefficients in the transfer functions may be edited in the "Transfer Functions" window. This window is reached from the Research mode by selecting the "Transfer Functions" button in the "Expected Life" section of the "Output/Basic" window. This causes a window to appear with the fatigue and rutting transfer functions displayed next to four boxes containing the K-values. These constants may be changed by using the "Add" button to create a user defined transfer function that may be more compatible with agency specific results.

6.1.2 Life

The design life of the pavement is estimated by dividing the design period traffic volume by the damage factors. For example, if the fatigue damage factor is 1.1 and the 20-year design period expects 2,000,000 ESALs, then the predicted fatigue life would be about 18 years or 1,800,000 ESALs. In the same way, the design period traffic volume divided by the rutting damage factor produces an estimate of the rutting life.

6.1.3 Maximum Allowable Stress

A window titled "Allowable Stress Results" appears showing the stress state and the required minimum HMA thickness required if the calculated stress exceeds the factored strength of the aggregate base. MnPAVE always does this check, but whether this window is displayed for non-failing pavement structures can be selected from View/Warnings.

Test sections have shown that aggregate base failure occurs if the HMA layer does not reduce the traffic loads to allowable stress levels in the aggregate base. Therefore, a maximum allowable stress criterion has been implemented in MnPAVE to protect against aggregate base failure. The failure criterion selected is the traditional Mohr-Coulomb criterion, which has the following form.

$$\tau = C + \sigma \tan (\varphi)$$

Where τ is shear strength, C is cohesion, σ is normal stress at failure, and φ is friction angle. The cohesion and friction angle are material properties obtained from laboratory triaxial tests.

The normal stress is calculated by the layered elastic analysis method used by MnPAVE. A failure analysis performed on MnROAD test section 28 indicated that failure of the aggregate base occurred in the middle of the base. It was observed that the lower portion of aggregate base was wetter than the upper portion. Based on that analysis, MnPAVE calculates the maximum principal stress in the middle of aggregate base layer.

Currently, only the Mohr-Coulomb failure criterion for Mn/DOT Class 5 has been implemented in MnPAVE. The Office of Materials and Road Research obtained the default values of cohesion and friction angle for Class 5 from triaxial tests on samples of Mn/ROAD Class 5 Special aggregate base. The triaxial tests were conducted at confining pressures of 4 psi and 8 psi and at the standard Proctor optimum moisture content and two percent above

standard Proctor optimum moisture content. Only one density condition at about 100% percent of standard Proctor density was tested. To guard against aggregate base failure a resistance factor of 0.7 is applied to the material strength obtained from these laboratory tests. This means that the failure strength used in MnPAVE has been chosen to be about 70% of the failure strength of the Mn/ROAD Class 5 Special during spring-like moisture conditions.

It should be noted that the current aggregate base failure criterion used in MnPAVE is only based on a total of ten tests performed on Mn/ROAD Class 5 Special. These ten tests included only one density condition, two moisture conditions, and two stress conditions. More materials collected from around the state need to be tested. Once more data are available the aggregate base failure criterion in MnPAVE will be updated and additional strength-based failure criteria for other materials added.

6.1.4 Exporting Data

Use the "Print Preview" and "Export to File" buttons to view and save the input and output to a file.

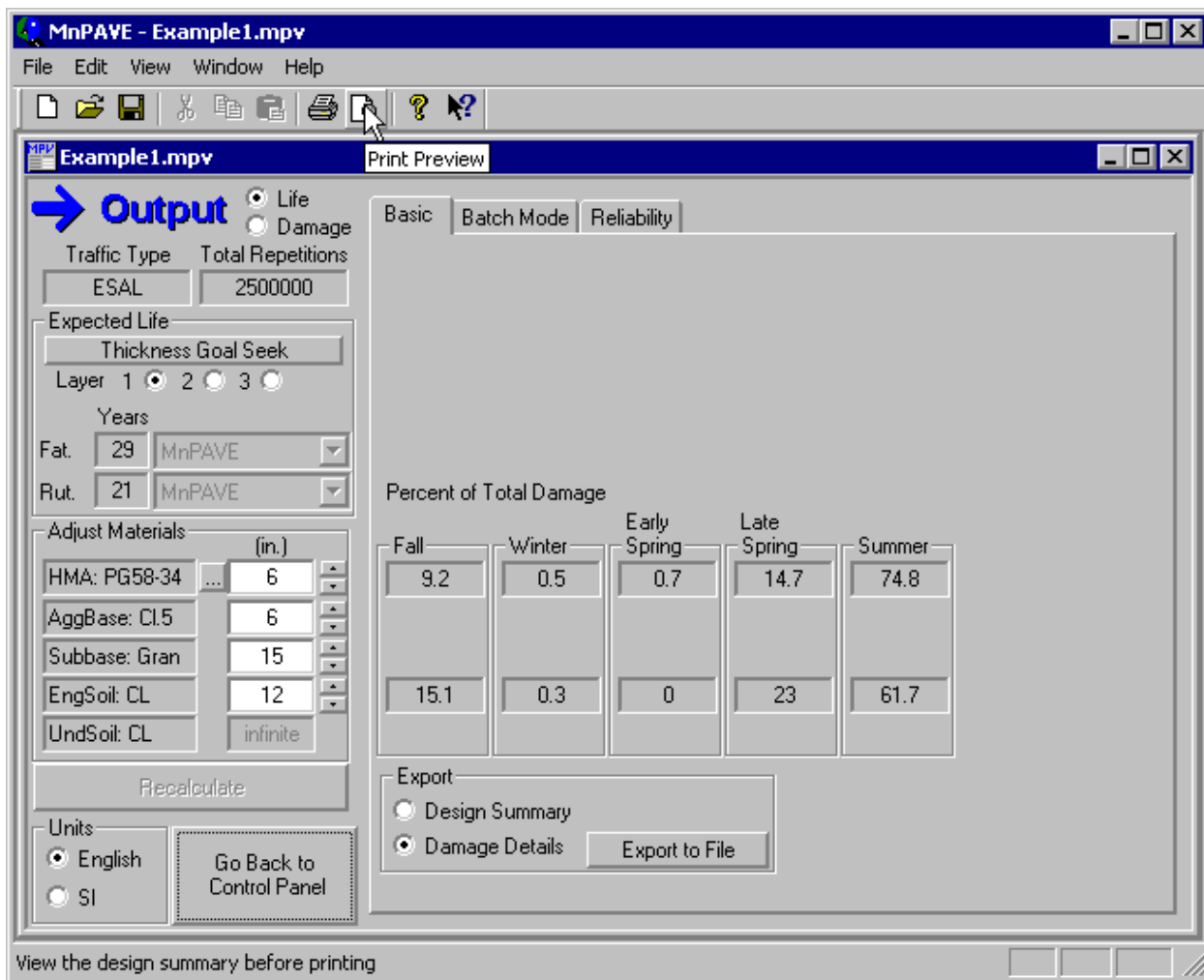


Figure 14. Output/Basic Window Print Preview Option

MnPAVE Design Summary			
MnPAVE 5.1 Simulation			
Input File: Example1.mpv			
Fatigue Life	Rutting Life	Fatigue Damage	Rutting Damage
29 years	21 years	0.40	0.93
Project Information			
District	County	City	
Metro	Ramsey	Maplewood	
SP No.	Highway	Reference Post	
100	10	from 25 to 75	
Letting Date	Construction Type		
02/22/02	2340		
Designer	Soil Engineer		
MnPAVE	MnPAVE		
Climate Information			
Season Mode	Location		
Days	43.0° Latitude, 93.0° Longitude		
Structural Information (Design Level: Intermediate)			
Layer	Type	Subtype	Height (in.)
1	Hot Mix Asphalt	PG 58-34	4.00
2	Aggregate Base	Mn/DOE Class 5	4.00
3	Aggregate Subbase	Mn/DOE Granular	15.00
4	Engineered Soil	Clay Loam	12.00
5	Undisturbed Soil	Clay Loam	
Loading Information			
Load Type	Total Repetitions		
ESAL	2,500,000		
Notes			
<p><small>Disclaimer: The use of MnPAVE is a beta version of the software and is not intended for use in any critical applications. The MnPAVE Design Summary Report is generated by the software and is not intended for use in any critical applications. The user must verify the accuracy of the input data and the output results. The user must also verify the accuracy of the input data and the output results. The user must also verify the accuracy of the input data and the output results. The user must also verify the accuracy of the input data and the output results.</small></p>			
Printed Monday, March 18, 2002 11:45:55			

Figure 15. Output to a File

6.2 Batch Mode

This option allows the designer to run multiple trial designs where layer thickness is varied incrementally.

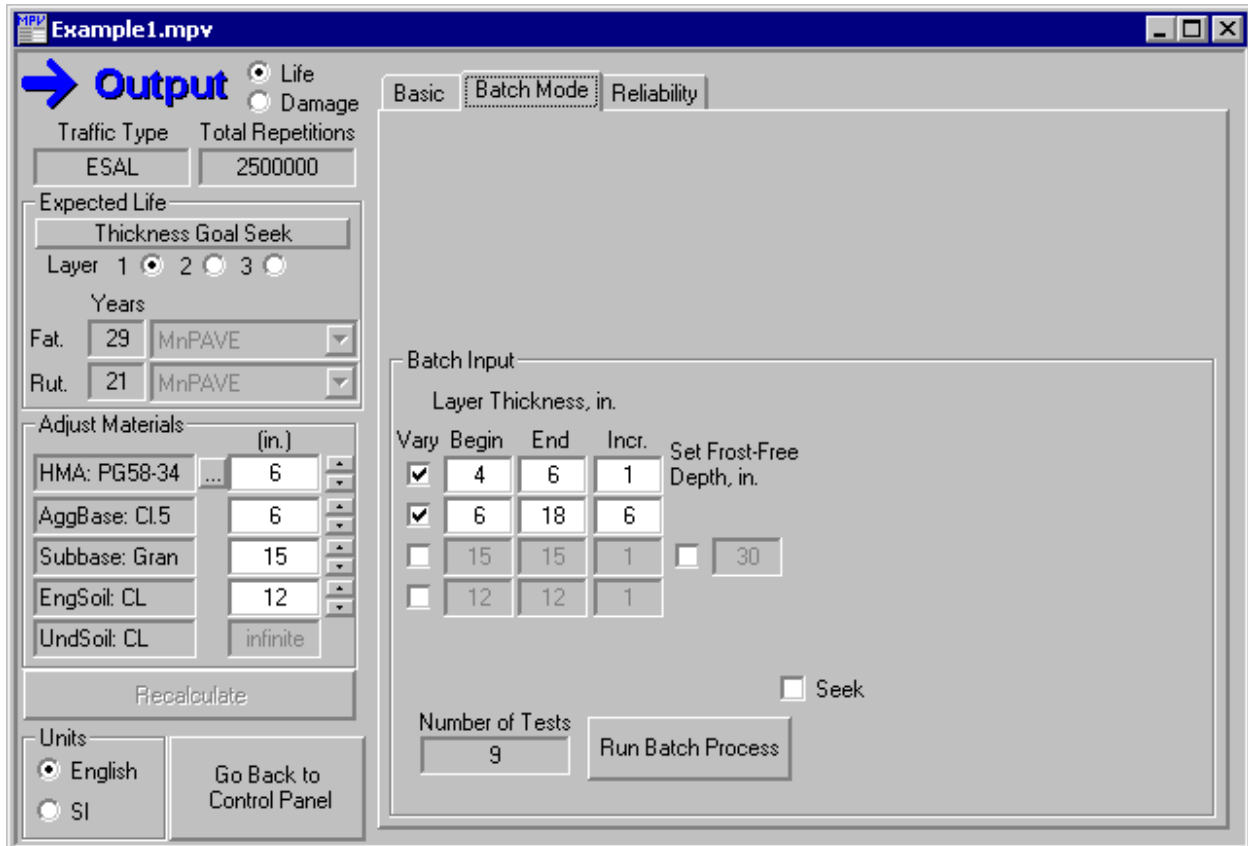


Figure 16. Output/Batch Window

6.3 Reliability

The Reliability design level is under development and your ideas are welcome. The following is a possible methodology. When operating MnPAVE in the Research mode and selecting Output/Reliability, the design moduli and design thickness of each layer have an associated coefficient of variation that is based on the expected variability in the constructed pavement system. MnPAVE uses the variability in moduli and thickness to take real materials and construction procedures into account. Properties and thicknesses vary with location because no pavement layer is completely uniform. Materials change slightly and pavement

layers can not be laid to the exact thickness desired along the entire project. Due to variability, it is better not to assume that both the quality and thickness of a layer will meet their design specifications in all cases because this may result in the premature failure at some locations.

A coefficient of variation (COV) must be entered for each layer thickness or the default percentages used. The COV is a measure of the relative variation and is calculated by dividing the standard deviation by the mean. The resulting number is expressed as a percentage. For example, if the design HMA thickness is 125 mm (5 inches) and the standard deviation is expected to be 12.5 mm (0.5 inches), then the coefficient of variation would be 10 percent. In practical terms, this means that individual thickness measurements would vary by no more than 10 percent from the mean in two-thirds of the cases. Recall that the mean value plus/minus one standard deviation contains about two-thirds of the data.

While a reliability analysis is not required to obtain an estimate for the mean design life of a pavement, a reliability analysis does give an indication as to how often the design life may actually be achieved. For example, if the estimated mean design life is 15 years and the reliability is 50 percent, then it would be expected that only 50 percent of the pavement would achieve this life. If this is not acceptable, then the material quality will need to be improved, the variability reduced, or the thickness increased.

MnPAVE allows the distribution in these parameters to be modeled using either a normal or a lognormal distribution. A normal distribution is a symmetrical distribution of probabilities centered about the mean with 50 percent of the cases above the mean and 50 percent below. The normal distribution is the default setting in MnPAVE for the layer thickness. A lognormal distribution is used if the data points are skewed in one direction. The 'lognormal' name arises because a normal distribution is produced when the natural log of each point is taken. As a result, the standard deviation and coefficient of variation used with this distribution are assigned only after the normal distribution is produced.

A previous Mn/DOT study by Stroup-Gardiner and Newcomb (19) found that HMA modulus was more accurately modeled when treated as a lognormal random variable when large temperature variations were present. This allowed coefficients of variation of 2 to 6% to be used as opposed to the 5 to 15 % required for normal random variables. It has also been found that the modulus calculated from FWD measurements was lognormal (Barnes, 19). Further explanation of how variability can be incorporated into an M-E design procedure can be found elsewhere (Tanquist, 2002; Timm, Newcomb, and Galambos, 2000; Timm, et al., 1999).

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Appendices

- A. Draft Design Moduli Table and Notes
- B. Calculation of ESALs Using Load Spectrum and HCADT
- C. Example Problems

A. Draft Design Moduli Table and Notes

Insert table here.

Notes for **DRAFT** Design Moduli Table

1. AASHTO soil class A-5 is not included as a possible equivalent class in Minnesota because it is extremely rare.
2. The soil ribbon formed for field identification should be about 15 mm wide and 3 mm thick. The length given defines the point at which the ribbon breaks under its own weight when held in a horizontal position. The moisture content should be 80 to 100 percent of standard Proctor optimum moisture and be such that the soil can be rolled to a 6 to 8 mm diameter rod (pencil size) before ribboning.
3. The "Rating" and "Soil Factor" ranges shown in this table have been modified slightly from previous Mn/DOT publications. Comments regarding the proposed ratings and soil factors would be appreciated.
4. The data set used for the Index Tests contained 2610 soil samples grouped by the Mn/DOT Textural Classification System and tested by the Mn/DOT Maplewood Lab from 1993 through 1998. The ranges shown for the standard Proctor tests are the mean of the data minus one standard deviation and plus one standard deviation.
5. The plastic limits for Mn/DOT's sandy clay and silty clay are estimated pending additional laboratory results.
6. The standard Proctor saturation is calculated using a specific gravity of 2.65.

7. The R-Value is estimated in three ways; from the mean plus one standard deviation of the percent passing the #200 sieve, percent silt content, and plastic limit using data from Mn/DOT Inv. 183. These correlations will be verified using the soils tested by the Mn/DOT Maplewood Lab from 1993 through 1998.

$$\text{R-Value} = 367 / (\text{mean percent passing \#200 plus one std dev})^{0.78} \quad R^2 = 0.62$$

$$\text{R-Value} = 200 / (\text{mean percent silt plus one std dev})^{0.7} \quad R^2 = 0.??$$

$$\text{R-Value} = 51.66 * e^{(-0.06 * (\text{mean plastic limit plus one std dev}))} \quad R^2 = 0.73$$

8. The R-Value used by Mn/DOT is at a 1.65 MPa (240 psi) exudation pressure and after a 16 to 22 hour soaking period. This approximates conditions near or about ??? percent greater than 100 percent of standard Proctor density and about ??? percent less than standard Proctor optimum moisture.

9. The plate load modulus (MPa) is estimated from the R-Value using data from Mn/DOT Inv. 183. These plate load tests were generally performed during the months of June through September.

$$E = 9.58 * (\text{R-Value})^{0.4} \quad R^2 = 0.46$$

10. The E_{RIMN} is the laboratory resilient modulus defined by the University of Illinois between 1976 and 1989 based on 50 Illinois soils. The two E_{RIMN} (MPa) values presented in the table are normalized to a deviator stress of 10 psi, near 95 percent of standard Proctor density, and a moisture content near standard Proctor optimum. They are estimated in two ways. The first estimate uses the Illinois data exclusively and the relationship between E_{RIMN} and the silt content. This first estimate includes a 25 MPa reduction in the estimated modulus to account for uncertainty in the estimate. The second estimate uses the Illinois data combined with the Minnesota R-Value estimated from the silt content. The second equation is used in MnPAVE's intermediate level to estimate E_{RIMN} from R-Value.

$$E_{RIMN} = 75 - 0.7 * (\text{mean percent silt plus one std dev})$$

$$E_{RIMN} = 0.0018 * (\text{R-Value})^3 - 0.19 * (\text{R-Value})^2 + 7.02 * (\text{R-Value}) - 20$$

11. The California Bearing Ratio (CBR) is estimated from the R-Value using the data from Mn/DOT Inv. 183.

$$\text{CBR} = 2.52 * e^{(0.03 * \text{R-Value})} \quad R^2 = 0.77$$

12. The CBR from Mn/DOT Inv. 183 was measured at conditions near ??? percent of standard Proctor optimum moisture and near ??? percent of standard Proctor density.

13. The Dynamic Cone Penetrometer Penetration Index (DPI) for the soils and the granular subbases is estimated in two ways.

The first DPI estimate is based on the CBR and the correlation developed by the US Army Corps of Engineers.

$$\text{When CBR is less than 10, then DPI} = (3452 / \text{CBR})^{0.5} \quad R^2 = 0.41$$

$$\text{When CBR is greater than 10, then DPI} = (292 / \text{CBR})^{0.893} \quad R^2 = 0.76$$

The second DPI estimate is based on the E_{RIMN} estimated using the silt content and correlation developed by CSIR Transportek, Council for Science and Industrial Research, South Africa.

$$\log Mr = 3.04758 - 1.06166 * \log \text{DPI} \quad R^2 = 0.76$$

$$\text{therefore} \quad \text{DPI} = 1 / 10^{((\log E_{RIMN} - 3.04758) / 1.06166)}$$

14. The Dynamic Cone Penetrometer Penetration Index (DPI) for the aggregate bases is estimated from the CBR using the correlation developed by CSIR Transportek, Council for Science and Industrial Research, South Africa.

$$\text{DPI} = (410 / \text{CBR})^{0.787} \quad R^2 = 0.??$$

15. The seasonal design moduli (MPa) are estimated using the laboratory E_{RIMN} for clay loam modified by three resistance factors that adjust for soil type and moisture content. These resistance factors increase as the material's resistance increases. Resistance factors that are greater than one 1.0 increase the design moduli. Resistance factors that are less than 1.0 reduce the design moduli. Design moduli for frozen conditions have a default value of 350 MPa (50 ksi).

16. The seasonal moisture resistance factors are estimated using moisture data from the Mn/ROAD test sections constructed from a Mn/DOT clay loam subgrade with a design Mn/DOT R-Value of 12 (240 psi exudation pressure). The moisture data was acquired between 199? and 199? using time domain reflectometry (TDR) moisture sensors. The TDR data was interpreted using travel time transfer functions that were rough approximations. Research proposed by Mn/DOT at the University of Minnesota is intended to better define these transfer functions and allow more accurate determination of seasonal moisture content of the Mn/ROAD subgrade and aggregate base materials.

The seasonal moisture resistance factors are applicable to the clay loam subgrade at Mn/ROAD and must be modified by the pore suction resistance factors to account for the ability of difference soils to draw water into open pore spaces. A seasonal moisture resistance factor equal to 1.0 means that the in situ saturation of the clay loam is expected to be nearly equal to the standard Proctor optimum moisture. If the seasonal moisture resistance factor is less than 1.0 then the in situ saturation during that season is expected to be greater than the standard Proctor optimum moisture. Recall that when resistance factors are less than 1.0, that they reduce the design moduli. Therefore a lower resistance factor is consistent with increasing saturation and decreasing design moduli.

17. The pore suction resistance factors are used to modify the Mn/ROAD seasonal moisture resistance factors for different soil types. These pore suction resistance factors are based on unsaturated pore suction and therefore on the moisture conditions that typically exist when the ground water table is deeper than about 1.5 m (5 feet) from the pavement surface. The pore suction resistance factors are important because they modify the seasonal moisture resistance factors that are based on the Mn/ROAD test sections constructed on a clay loam subgrade.

The pore suction resistance factors are currently based on the relationship between the difference in the laboratory percent saturation near standard Proctor optimum moisture and the in situ saturation expected for Minnesota soils (Swanberg and Hansen, 1946; Kersten, 1944). The pore suction resistance factors account for the ability of different soils to draw water into open pore spaces. These pore suction resistance factors are currently normalized to clay loam, which therefore has a resistance factor of 1.0. The pore suction resistance factors are under development and will be modified by research proposed by Mn/DOT at the University of Minnesota. This research is intended to define the soil moisture characteristics for a sample of Minnesota soils and aggregate base materials.

18. The susceptibility resistance factors are used to modify the laboratory E_{RIMN} estimated for clay loam for different Minnesota soils. These susceptibility resistance factors are currently under development and will be modified. They currently attempt to account for the influence of both soil type and moisture on moduli. Research proposed by Mn/DOT at the University of Minnesota is intended to better define these susceptibility resistance factors and allow more accurate determination of the relative stiffness of Minnesota's subgrade and aggregate base materials.

19. If the pavement surface will not be greater than 5 feet from the ground water, then the late spring design moduli should be used for the summer and fall seasons also.

Appendix B

Calculation of ESALs Using Load Spectrum and HCADT

Final Report

September 17, 2001

**by
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**Mn/DOT Office of Materials and Road Research
Mn/DOT Office of Transportation Data and Analysis**

Preface

This report describes and compares the ESAL definitions, ESAL calculation procedures, and traffic forecasting procedures used by the Office of Transportation Data and Analysis and the Office of Materials and Road Research. In addition, this report describes the three procedures that have been used by Mn/DOT to convert HCADT data into ESAL values. Finally, the report makes several recommendations relevant to the M-E design process and the ESAL calculation procedure. This report was produced by Peter Davich of the Office of Materials and Road Research and reviewed by John Siekmeier of the Office of Materials and Road Research and George Cepress of the Office of Transportation Data and Analysis.

A great deal of help was provided during the compilation of this report by George Cepress, Curt Dahlin, Tom Nelson, and Mark Levenson at the Office of Transportation Data and Analysis. They volunteered a good deal of time to explain the procedures and concepts they use during the ESAL calculation procedure. In addition, Maggi Chalkline at the Office of Materials and Road Research provided much of the information related to ESAL calculation at Mn/ROAD.

Table of Contents

1.0	Introduction
2.0	Definitions
2.1	Average Daily Traffic
2.2	Annual Average Daily Traffic
2.3	Axle Load Equivalency Factor
2.4	ESAL
2.6	Serviceability Indices
2.7	Structural Number
2.8	Weigh-In-Motion Instrument
3.0	ESAL Calculation from HCADT
3.1	Mn/DOT Investigation 183
3.2	Transportation Information System
3.3	Comparison of Formulas
3.4	Assumed Average Vehicle Distributions Method
4.0	Spectra
4.1	AASHTO Procedure
4.2	Mn/ROAD ESAL Calculation Procedure
4.2.1	Low Volume Roadway
4.2.2	Mainline
4.3	State-Wide Office of Transportation Data and Analysis Procedure
5.0	Traffic Forecasting
5.1	Introduction
5.2	TDA Traffic Forecasting Procedure
6.0	Recommendations
6.1	Implications for M-E Design
6.2	Other Recommendations
7.0	References

1.0 Introduction

The calculation of ESAL values can be a highly complicated and sometimes counterintuitive process despite the apparent simplicity of the ESAL concept. The Office of Materials and Road Research (MRR) and Office of Transportation Data and Analysis (TDA) use different procedures depending upon the origin of their data: the low volume test site at Mn/ROAD, the mainline at Mn/ROAD, or outstate sites. These procedures are based on the results of the AASHO Road Test, which took place in Illinois in the late 1950s. However, the original procedure has been modified in several ways based on the type of traffic data available and to fit each office's particular needs. The following report is intended to specify the procedures used by each Mn/DOT office and explain the origin of each procedure.

2.0 Definitions

2.1 Average Daily Traffic

Average Daily Traffic (ADT), as defined by Mn/DOT's 1998 State Aid Manual (Section 5-892.705), is "the total volume during a given time period in whole days greater than one day and less than one year divided by the number of days in that time period." Cars and trucks of all configurations and weights are included in this count.

One problem with this definition is that the State Aid Manual does not make it clear whether the "total volume" to be measured is one-way or two-way traffic. However, Mn/DOT Investigation 183 and Mn/DOT's Office of Transportation and Data Analysis (TDA) agree that ADT should be measured in two directions. Therefore, ADT values should be divided by two to calculate the traffic in one lane of a highway with one lane in each direction.

2.2 Annual Average Daily Traffic

Annual Average Daily Traffic (AADT), as defined by Mn/DOT's 1998 State Aid Manual (Section 5-892.705), is "the traffic volume on a segment of road in one year divided by 365." For most applications, the AADT is more representative of the traffic that a road will experience than the ADT because the AADT is intended to include all of the traffic fluctuations throughout a year. As a result, AADT values are preferred to ADT values whenever they are available. AADT values are recorded by the Transportation Data and Analysis (TDA) Office wherever ESAL estimates are desired using tube counters and other methods. After the TDA Office collects this data, it is entered into the "MNESALS" program to make traffic estimates.

As was the case with the ADT, the AADT considers traffic moving in two directions according to the TDA Office. All AADT values should be divided by 2 (or another factor for a multi-lane road) to obtain the amount of one-way traffic on any road where two-way traffic data was collected.

2.3 Axle Load Equivalency Factor

Axle load equivalency factors (LEFs) are used in the AASHTO ESAL calculation process, which is the process used by Mn/DOT. When these factors are multiplied by the

number of axle configurations that they represent, the result is the number of ESALs that particular axle configuration applied to the road. These factors are functions of pavement type, pavement thickness, terminal serviceability, axle configuration, and axle load. They can either be calculated by using the equations in Appendix MM-1 (See Section 4.1 of this report for full equation) or the summary tables in Appendix D of the 1993 AASHTO Guide for the Design of Pavement Structures. General axle load equivalency factors that are independent of pavement-related variables and axle configuration have been proposed by others (Hajek, 1995).

2.4 ESAL

Almost every road construction project or study currently underway in the United States involves the concept of ESALs in some form. All traffic load estimates provided by Mn/DOT's Office of Transportation Data and Analysis are given in units of ESALs. However, in some cases there may be a misconception concerning the definition of an ESAL. Some users of this data believe that an ESAL is simply a load. As a result, one ESAL may be erroneously defined as "one pass of an 18 kip single axle with dual wheels". There is a subtle yet important difference between this definition and the official AASHTO definition. AASHTO defines an ESAL as one "18-kip single axle load application which will have an equivalent effect upon the performance of the pavement structure." As a result, all ESAL values currently being produced by Mn/DOT's Office of Transportation Data and Analysis (TDA), by the weigh-in-motion (WIM) sensors at Mn/ROAD, and by all other current applications are functions of pavement type, pavement thickness, and the terminal serviceability value (p_t) being used as a failure criterion (even if the terminal serviceability concept is not being used to evaluate the pavement). (See Section 4.1 of this report for full equation) Therefore, an ESAL should be thought of as a damage factor rather than a load.

Although the variations in the ESAL values caused by variable pavement structure and terminal serviceability index values are small in most cases, their cumulative effects could change a particular ESAL value in the AASHTO guide by more than 200% under the heaviest axle loads. However, the heaviest axle loads listed in AASHTO's table are unreasonably heavy (80 kips) and would not be found on Minnesota's roads. Using more common load spectrum values, the difference between the perceived definition of an ESAL and the actual definition is often 10 to 20%. (AASHTO Guide for the Design of Pavement Structures Manual, 1993). This may be a relatively small amount compared to some other unknowns in traffic data, such as the

variability of some assumed vehicle distributions and the ability to forecast traffic 20 years into the future.

Despite these misconceptions, the ESAL is widely accepted and most users share a general understanding of its limitations. However, the engineers who use ESALs in the pavement design process must clearly understand every aspect of the ESAL's definition. One reason for this is that the ESAL may not be completely compatible with mechanistic-empirical (M-E) design procedures or other procedures that do not use present serviceability indices (PSI) as pavement performance indicators. Many M-E design procedures, such as Mn/DOT's MnPAVE, use the tensile strain in the bottom of the HMA surface and the vertical strain applied to the subgrade as failure criterion instead of PSI. As a result, an ESAL, which has a different failure criterion incorporated in its calculation, may be unsuitable for use with an M-E procedure.

2.5 Heavy Commercial Average Daily Traffic

Heavy Commercial Average Daily Traffic (HCADT) is defined in several different ways by the various offices that make use of it, but each official definition is consistent with the others. To begin, Investigation 183 defines HCADT as "the number of heavy trucks expected to use the highway." "Heavy trucks" are defined as all large, industrial trucks with the exception of 4-tired, 2-axle (FHWA Type 0) trucks. Mn/DOT's Geotechnical and Pavement Manual defines HCADT as "all commercial vehicles with six or more tires (FHWA Type 4 and above)." Finally, the Mn/ROAD ESAL values are calculated using the FHWA classifications. These define HCADT as "vehicle types 4 through 13", which are all of the vehicles with 6 or more tires.

None of these HCADT definitions contain any information relating to axle weights, axle configurations, or the "relative damage" to the pavement. As a result, HCADT values are simply a count of the six-tired vehicles that pass over a road. HCADT data becomes much more useful when combined with an average traffic distribution and average axle configuration weight data because together they can be used to calculate ESALs. When the exact number of axle configurations and their weights are known, the AASHTO equations can be used to calculate ESALs accurately for a specific project. As a result, an accurate traffic distribution is very important (Skok and Timm, 2000).

Lastly, the HCADT counts traffic moving in both directions on the road, therefore, the design lane HCADT is one half of the commonly reported two-way HCADT value for roads with a single lane in each direction.

2.6 Serviceability Indices

AASHTO recommends the use of serviceability indices to evaluate pavement degradation. A pavement will have its maximum present serviceability index (PSI) value (usually 4.5 to 5.0) immediately after construction. The “serviceability” of the road slowly decreases because of increasing rut depths, the onset of cracking, and a general decrease in rideability. Depending upon the importance of the roadway, a terminal serviceability (p_t) is chosen at which the pavement would require rehabilitation of some sort. The default value for the terminal serviceability used by Mn/DOT is 2.5. The terminal serviceability is one of the variables in the AASHTO ESAL equation contained in Appendix MM-1. The summary tables in Appendix D contain separate tables for p_t values of 2.0, 2.5, and 3.0.

2.7 Structural Number

The structural number (SN) is an index value that generally quantifies the stiffness of a particular pavement structure and it is another important variable in AASHTO’s flexible ESAL calculation procedure. The structural number and the weight of a particular axle configuration are used to determine the axle load equivalency factor for a particular axle configuration located in Appendix D of the 1993 AASHTO Guide for the Design of Pavement Structures. The structural number is determined using the following equation:

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

where:

D_x = the thickness of a particular pavement layer in inches

a_x = an empirically determined factor that represents the strength of the material used to construct the layer.

The factors from the AASHO Road test were $a_1 = 0.44$ for HMA, $a_2 = 0.14$ for crushed rock base, and $a_3 = 0.11$ for granular subbase. Methods for estimating this factor for other materials are found in the 1993 AASHTO Design Guide.

2.8 Weigh-In-Motion Instrument

The mainline pavement sections at Mn/ROAD contain two weigh-in-motion (WIM) instruments that record the load spectra data that is used to calculate ESALs. As the cars and

trucks in the traffic stream pass over the WIM instruments, the weight of every axle is recorded. The data from the cars (FHWA classifications 1 – 3) is saved in binary form but not analyzed because the axles are too light to cause significant damage to the pavement. However, the data from the heavy commercial vehicles (FHWA classifications 4 – 13) is saved, converted from binary to ACSII, and stored in the Mn/ROAD database.

3.0 ESAL Calculation from HCADT

3.1 Mn/DOT Investigation 183 (1968)

Every aspect of the pavement design process was studied in a large research project undertaken by Mn/DOT and the University of Minnesota from 1963 to 1968 (Kersten and Skok, 1968). Chapter VIII of the final report (Kersten and Skok, 1968) contains a process for converting heavy commercial average daily traffic (HCADT) into ESALs. The equations used in this process were empirically derived from the results of testing that took place over a two-year period. They are listed below.

A computer program named “TRUFAC” was used during this testing to convert load spectra data into 18,000-pound single axles (N_{18} axles). This process involved several steps. To begin, the program calculated truck factors for each of the six vehicle classes that existed at the time (Mn/DOT Types 0 – V). This was accomplished by dividing the axle data into 2,000 pound weight classes for single and tandem axles, multiplying the number of axles in each weight class by the “load equivalency factor” for that weight class, summing the products, and dividing by the number of trucks in the truck type classification. The “load equivalency factors” used in this analysis were derived from the results of the AASHO Road Test. (Ref 26. Inv. 183). The structural number was not used in this method. These truck factors were corrected for seasonal and yearly traffic variations and all of the resulting truck factors were displayed in Investigation 183 is a series of graphs and tables.

This analysis was performed for three different vehicle distribution classes. Class A was comprised of highways with “interstate trucks and very few local trucks”. Class B was a medium traffic road with an even distribution of both types of trucks, and Class C was comprised of “low traffic roads with almost all local trucks”. These vehicle distributions were the only traffic variables entered into TRUFAC.

For various roads around Minnesota, N_{18} (ESAL) values were calculated using these truck factors and the measured count (actual vehicle distribution). These ESAL values were then plotted against the HCADT values for the road and compared. These graphs are included as Figures VIII-5 – VIII-7 in the Inv. 183 report (Kersten and Skok, 1968). Two empirical equations were created from these graphs with the intention of making it possible to directly convert HCADT values into ESALs. More than one equation was necessary because there were different trends for low and high volume roadways (the cutoff between “low” and “high” volume occurred at 150 HCADT). The structural number was not included in this calculation process.

Equation VIII-3 in Investigation 183 is:

$$\log N_{18} = -0.816 + 1.307 \log (\text{HCADT}) \quad \text{for HCADT values under 150}$$

Equation VIII-4 in Investigation 183 is:

$$\log N_{18} = -0.671 + 1.317 \log (\text{HCADT}) \quad \text{for HCADT values over 150}$$

where:

N_{18} = an abbreviation for ESALs

HCADT = one-way value

It should be noted that the HCADT values used in these equations are one-way values, while HCADT values are normally reported as two-way values. As a result, two-way HCADT values should be divided by two (or an appropriate distribution factor) before using these equations.

3.2 Transportation Information System (1995)

The Transportation Information System (TIS) is a database that has a procedure and accompanying software that takes statewide traffic volume data and uses a variety of techniques to roughly estimate ESAL values. One of its functions is to convert past HCADT values into ESAL values because traffic data was primarily recorded as HCADT before the 1970s.

An equation that converts HCADT values into ESALs is provided in Chapter 8 of the TIS User's Manual. The equation also appears in Mn/DOT Investigation 231, (Skok, et al, 1971). The source of these equations was not cited in either document, however, the TDA Office has made it clear that the results from the TIS method are approximate and should not be used for applications where accuracy is important.

The “ESAL Formula” used by TIS takes the form:

$$\text{ESALs} = \text{DAYS} * \text{DC} * \text{HCADT} * ((\text{C}_1 * \text{Y}) - \text{C}_2)$$

where:

DAYS = the number of days in the year or portion of year.

HCADT = two-way heavy commercial average daily traffic. (Inv. 183 uses only one-way HCADT)

Y = year where data was taken in full form. (Example: “1950”)

DC = design constant. This constant is a function of the driving surface width and whether or not

the highway is divided. The value is always between 0.20 and 0.50, and tables are provided in the TIS User’s Manual.

C₁ = A constant. It is a function of the type of pavement (flexible or rigid), the year of computation, the HCADT for the roadway, and whether the roadway is urban or rural. Tables are provided in the TIS User’s Manual.

C₂ = A constant. It is a function of the same values as C₁ and it is looked up in the same tables.

The TIS User’s Manual does not provide any additional information concerning when and where this equation should be applied for new applications. It is included in the User’s Manual to inform the readers how previous ESAL estimates were made by TIS so that this data can be properly analyzed. Mn/DOT’s TDA Office recommends that the TIS ESAL values should be used only for approximations and not for design applications.

3.3 Comparison of Formulas

A large section of Chapter VIII of Mn/DOT Investigation Number 183 is devoted to determining the equation used to convert HCADT values into ESALs. Due to this, it is possible to understand the origin of the HCADT-to-ESALs equation contained in Inv. 183. Unfortunately, this type of documentation is absent from the TIS User's Manual (as well as Mn/DOT Investigation 231). As a result, it is necessary to compare the equations in the two documents and determine if their results are similar.

A very simple series of tests was set up to determine the relationship between the equations. An Excel spreadsheet was created that contained one column of HCADT values that could be found on Minnesota's roads. These values were entered into both ESAL calculating equations for a direct comparison. The results of this comparison are included in Figure 1

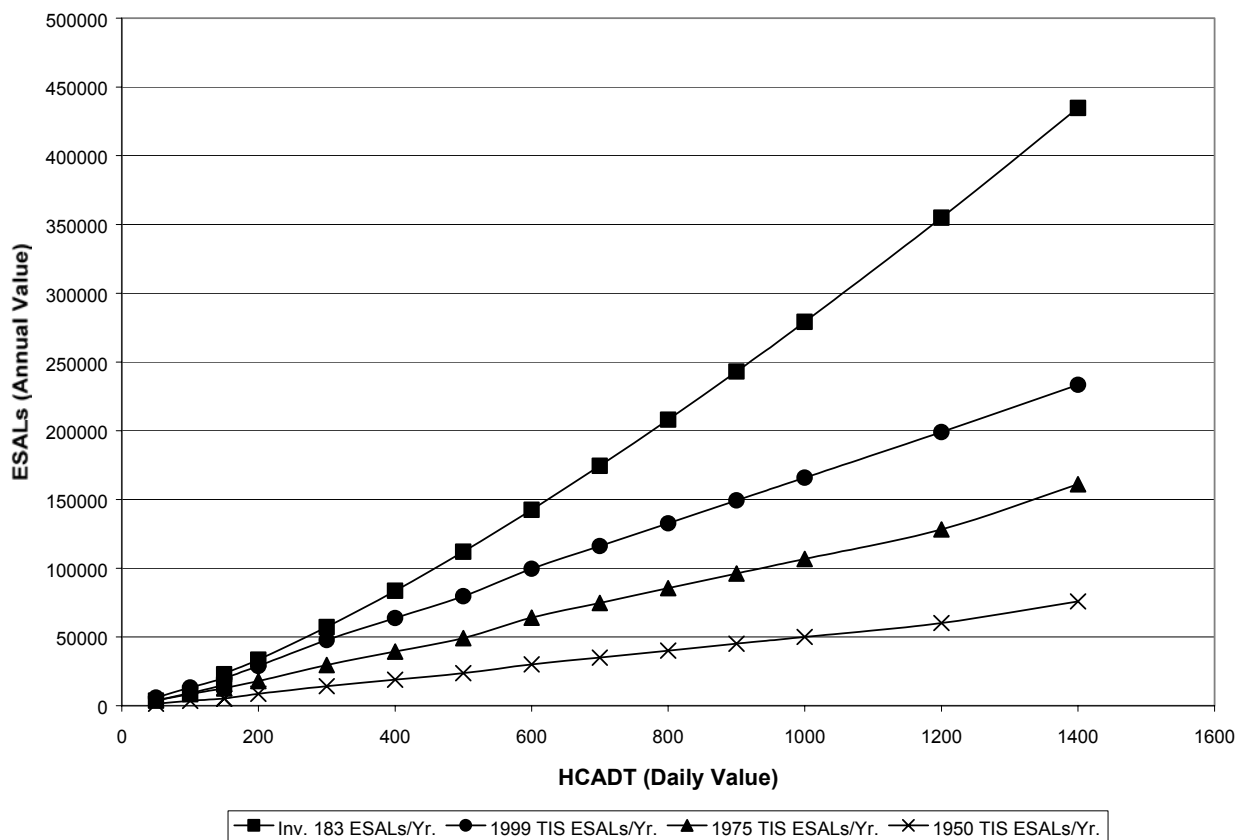


Figure 1. Results of Comparison

This testing clearly shows that there is little correlation between the two ESAL calculation methods no matter which year's ESALs are analyzed. The value produced by the equations in Mn/DOT Investigation 183 are consistently larger than the values produced by the TIS method. Both curves plot relatively close together for low HCADT values, however, they diverge for large HCADT values. The TIS results produced using the tabular data from 1999 are considerably closer to the Investigation 183 method than the TIS results from 1950. Nevertheless, the two methods give significantly different results in all cases and they should be further researched before using the results from either. However, because the TIS equation is calibrated through the year 2000, it can be assumed that it will provide a reasonable estimate of ESALs for applications where accuracy isn't required. For all important calculations, the TDA Office recommends that HCADT be converted into ESALs using the MNESALS program and a measured average vehicle distribution. Refer to Sections 4.3 and 5.2 of this report for a more complete description of MNESALS.

3.4 Assumed Average Vehicle Distributions Method

After reviewing the problems with the two methods described above, it was decided to investigate a third method for HCADT to ESAL conversion. The basis of this method is that average vehicle distributions be created by the TDA Office based on data collected within Minnesota and used to provide an estimate of the axle configuration data needed to calculate ESALs. With this estimate, any individual HCADT value could be distributed into vehicle classes using the average distribution. The resulting estimated vehicle counts could then be used to estimate the volume of any particular axle configuration using average axle configuration load data. This data is then used in Appendix D of the AASHTO Design Guide to estimate the axle load equivalency factors. The axle configuration load data would be provided by the TDA Office as a single table based on state-wide data. ESALs equals the number of repetitions of any particular axle configuration multiplied by the LEF.

This method could be used to produce a reasonably accurate range of ESALs from HCADT values if both "heavy" and "light" truck distributions are used within the MNESALS program. However, it should be remembered that this method will still produce an estimate and the results should be used accordingly. However, if a vehicle distribution can be provided for a specific project location and pavement design, then the measured vehicle distribution should be used to make the HCADT-to-ESAL conversion.

4.0 ESAL Calculation from Load Spectra

4.1 The AASHTO ESAL Calculation Procedure

The AASHTO ESAL calculation procedure is contained in the 1993 AASHTO Guide for Design of Pavement Structures. In this guide, ESALs are either calculated using the load equivalency factor (LEF) equation derived during the AASHO Road Test or using several tables that approximate the results of that equation. ESALs are calculated by multiplying the LEFs by the number of repetitions of the axle configuration that they represent.

In Appendix MM, equation MM.1 is used for flexible pavements and takes the form:

$$\log_{10} [w_{tx} / w_{t18}] = 4.79 \log_{10} (18+1) - 4.79 \log_{10} (L_x + L_2) + 4.33 \log_{10} L_2 + G_t/B_x - G_t/B_{18}$$

where:

$$G_t = \log_{10} [(4.2 - p_t) / (4.2 - 1.5)]$$

$$B_x = 0.40 + [(0.081(L_x + L_2)^{3.23}) / ((SN + 1)^{5.19} * L_2^{3.23})]$$

L_x = load on one single axle or one tandem axle set (kips)

L_2 = axle code (1 for single axle and 2 for tandem axle)

SN = structural number

p_t = terminal serviceability

B_{18} = value of B_x when L_x is equal to 18 and L_2 is equal to 1

w_{tx} / w_{t18} = an alternate notation for a load equivalency factor. The 'x' and '18' that appear within

the notation show that each axle configuration is being compared to an 18 kip axle configuration.

Equation MM.4 is used for concrete pavements and takes the form:

$$\log_{10} [w_{tx} / w_{t18}] = 4.62\log_{10} (18+1) - 4.62\log_{10} (L_x + L_2) + 3.28\log_{10} L_2 + G_x/B_x - G_t/B_{18}$$

where:

$$G_t = \log_{10} [(4.5 - p_t) / (4.5 - 1.5)]$$

$$B_x = 1.00 + [(3.63(L_x + L_2)^{5.20}) / ((D + 1)^{8.46} * L_x^{3.52})]$$

D = slab thickness

Appendix D of the guide provides tables with specific solutions to these equations. Tables D.1 through D.18 provide “axle load equivalency factors” for a flexible or rigid pavement for terminal serviceabilities of 2.0, 2.5, and 3.0. The first step in using the flexible pavement charts is locating the table that is based on the desired axle configuration and terminal serviceability index (p_t). Next, the user finds the axle load on the vertical axis, the structural number on the horizontal axis, and reads the axle load equivalency factor from the table. The number of ESALs attributed to that axle configuration, axle load, terminal serviceability, and structural number is calculated by multiplying the number of passes over the pavement by this axle load equivalency factor.

4.2 Mn/ROAD ESAL Calculation Procedure

4.2.1 Low Volume Road

Converting load spectra data into ESALs is relatively straightforward for Mn/ROAD’s low volume road. The traffic on the low volume road is precisely controlled and measured, therefore, the exact load spectrum is known. The traffic and structural data are stored in several of the Mn/ROAD database tables. The ESAL calculations are performed using the data contained in these tables. The traffic (the Mn/ROAD trucks) data, including the specific truck used, the mass placed on the truck, and the number of loadings of the pavement (laps) is included in the database table LVR_DAILY_LOG. When test sections are reconstructed it becomes necessary to enter a new structural number into the databases so that the AASHTO load equivalency factors can be adjusted. Other traffic loads (such as construction vehicles, snowplows, and personal transportation vehicles) are recorded in a separate spreadsheet, however, this data is not currently loaded into the database.

A different AASHTO load equivalency factor has been calculated for each of the test sections and each of the truck's different loading configurations since 1994. These factors are estimated from Appendix D of the 1993 AASHTO Guide for the Design of Pavement Structures assuming a terminal serviceability index of 2.5. The load equivalency factors for each of the different trucks, truck configurations, and test sections is included in the database table LVR_ESAL_FACTORS.

Lastly, the ESAL values calculated for the LVR at Mn/ROAD are located in the LVR_ESALS table. This table contains a variety of information for each day: the truck used, the number of truck loadings, and the number of daily ESALs for each test section. The daily ESALs for each test section are calculated by multiplying the ESAL factors from the LVR_ESAL_FACTORS table by the number of passes the truck made over the pavement test sections that day. When the test sections are reconstructed, the daily ESAL values are calculated with the new structural factors continue to be tabulated in the same table in the database. These ESAL values can be summed to determine the cumulative number of ESALs applied to a specific pavement over any time period.

4.2.2 Mainline

ESALs are calculated for the mainline at Mn/ROAD using the same equations as the low volume road. However, the traffic volume is not controlled on the mainline so another variable is introduced into the calculation process.

The traffic on the mainline is measured by two weigh-in-motion (WIM) instruments imbedded in the pavement. These instruments record each vehicle's speed, axle spacing, length, gross vehicle weight, and individual axle weights. This data is stored on a computer in a cabinet next to the road until it is downloaded by the Mn/DOT Office of Transportation Data and Analysis over a modem. This data is subsequently placed on the Office of Materials and Road Research's network by TDA, converted into ASCII files by Maggi Chalkline, and loaded into the Mn/ROAD database tables. The data appears in one of two tables: WIM_RAW_VEHICLES or WIM_RAW_AXLES. For a more complete description of this process refer to [ESAL Calculation for the Mn/ROAD Mainline \(Draft Report\)](#) by Maggi Chalkline.

Before the raw data in the database can be used to calculate daily ESAL values, it must pass through several screening processes. Curt Dahlin from the Office of Transportation Data and Analysis performs a cursory analysis of the data, formulates a weight adjustment factor, and decides whether the data is "good" or "bad" for each day of the week. The decision process for deciding whether any particular data is "good" or "bad" is based upon the average weekly

values of FHWA Type 9 trucks which make up the majority of the HCADT, knowledge of traffic switches at Mn/ROAD, and personal judgement. Curt Dahlin also proposes substitute data sets from “good” days that could be substituted for suspect data. However, at this time these substitute data sets are not loaded into the database. Maggi Chalkline performs a similar analysis graphically to determine whether the total traffic volume for each day is abnormally high or low due to either instrument error or traffic switches. Lastly, a subprogram within the database loader program identifies WIM records in which the axle spacing or weight of a vehicle is unrealistic and does not load these records into the database. The data that is flagged as “bad”, abnormally high or low, or unrealistic is not included in any calculations. However, it is saved with the rest of the raw data for possible use in the future. The data that passes this screening is transferred into two new tables entitled WIM_ADJ_VEHICLES and WIM_ADJ_AXLES. A report currently being prepared by Maggi Chalkline at the Materials and Road Research Office will contain more information about this process (Chalkline, 2001).

After these analyses have been performed, the data is suitable for the calculation of ESALs. All of the data stored in the WIM_ADJ_VEHICLES and WIM_ADJ_AXLES tables is transferred to a program named ESALCALC (Chalkline, 2001). This program was originally created by Professor Randal Barnes at the University of Minnesota in a joint project with Mn/DOT. ESALCALC automates the ESAL calculation procedure that is used for the low volume road. The pavement variables needed to use this program are contained in the WIM_PARAM table and the axle weight data from the mainline is distributed into weight classes that span 2-kip ranges (1-3, 3-5, 5-7, 7-9, etc up to 90 kips). AASHTO equations MM.1 and MM.4 are used to create axle load equivalency factors for every combination of axle configuration and weight recorded by the WIM instrument. The axle load equivalency factors calculated by this process are multiplied by the number of axle configuration repetitions recorded within each 2-kip range and the resulting ESAL value is placed in the WIM_ESALS table. This table is checked for accuracy but because of the large volume of data contained in the table, it must be summarized prior to further analyses. WIM_ALL_DAYS contains the traffic data that was recorded by the WIM instrument in each lane over the course of a day and CELL_ESALS lists total daily ESALs for each test section and lane.

There is a second source of mainline ESAL data available to the Office of Materials and Road Research. The electronics for the WIM instruments imbedded in the mainline pavement contain a program that calculates ESAL values for the traffic that passes over the instruments. The data produced by this program is referred to as the “IRD” data in reference to the makers of the instrument: International Road Dynamics. The Office of Materials and Road Research

would like to use the values produced by this program to backup and potentially calibrate the ESALCALC program. However, the actual methods, equations, and variables used in the IRD program are kept confidential by International Road Dynamics, so this is not possible. At this time the IRD data is simply stored in the WIM_RAW_VEHICLES and WIM_ADJ_VEHICLES tables and is not used for any analysis.

4.3 State-Wide Office of Transportation Data and Analysis Procedure

The TDA Office uses the 1993 AASHTO procedure and equations to calculate ESALs. However, they assume a single statewide average value for the variables that would normally be dependent on the road structure. These values are a terminal serviceability of 2.5, a structural number of 5 for flexible pavements, and a concrete depth of 8 inches for rigid pavements. The traffic data needed for this analysis is acquired using several methods. The most common data sources include vehicle classification counts, WIM instruments, tube counters, and other smaller scale counts. The TDA Office stores this data.

The TDA Office's ESAL calculation procedure is contained in the most recent (1999) version of the "MNESALS" program, which was created by the Transportation Research & Investment Management Division of Mn/DOT. This program is based upon the AASHTO ESAL calculation formula and uses all of the AASHTO LEFs, however the TDA Office has limited access to much of the road structure data that is necessary for a complete AASHTO analysis. As a result, the program assumes that most pavements in Minnesota can be adequately modeled using the values above: a terminal serviceability of 2.5, a structural number of 5 for flexible pavements, and a concrete depth of 8 inches for rigid pavements. This method is supported by others including Hajek (1995) and Skok et al (1971).

The MNESALS program does all of the ESAL calculations automatically. The only required inputs are the files containing the traffic data obtained from the roadway and a list of the desired analyses. The data is manually entered into the program, the program enters it into the AASHTO equation (using the default input values described above), and the desired output appears on one of the formatted sheets. Refer to Section 5.2 for a more complete description of the traffic forecasting procedure. More information about the MNESALS program is provided in a document prepared by the TDA Office entitled "MNESALS, An Electronic Spreadsheet for Traffic and ESAL Forecasting".

5.0 Traffic Forecasting

5.1 Introduction

The Office of Transportation Data and Analysis does Mn/DOT's traffic and load forecasting for project design purposes. The forecasting procedure described in this section is based upon the Procedures Manual for Forecasting Traffic on the Rural Trunk Highway System, the documentation of the MNESALS program, and conversations with several of the TDA Office's employees. Each of Minnesota's eight district offices has an employee in charge of traffic forecasting. The Mn/DOT Office of Transportation Data and Analysis (TDA) supplies these forecasters with a procedure and training for formulating their predictions. In addition, the TDA Office has the results from hundreds of vehicle classification counts conducted at many sites throughout Minnesota. However, each district forecaster is allowed to use the individual vehicle counts that they believe to be the most appropriate for their project. All of the resulting district traffic forecasts are sent to the TDA Office so that the district methods and results can be reviewed by the State Forecasting Engineer. The forecasts from throughout the state are reviewed and compared to the results produced by TDA using their vehicle counts. In most cases the results are similar, however, if the districts' forecasts show significant differences from the forecasts of the TDA Office the district may be asked to perform another analysis or get more data. In the majority of cases the forecasts are approved and returned to the districts with a memo detailing any differences between the traffic forecasts.

The advantage of allowing the district offices to make their own forecasts is that the district forecasters have a better understanding of the traffic on the road that is being designed. For example, the district offices would be more likely to know if there will be additional traffic on a roadway resulting from a new gravel quarry or distribution center. This minimizes the TDA personnel involvement and the decentralized procedure with review by the TDA Office is considered to be the most effective forecasting method available.

5.2 TDA Traffic Forecasting Procedure

The Office of Transportation and Data Analysis makes traffic forecasts by fitting a least squares line through measured traffic counts. The entire analysis is programmed into the "MNESALS" program, so the actual ESAL calculation formula is hidden although the variables are known.

The first step of the MNESALS program is to input the data needed for the analysis. The TDA Office uses annual average daily traffic (AADT) measurements combined with one or more vehicle classification counts to make their forecasts. These AADT counts are collected on weekdays over 48 hour periods and weighted so that the count is representative of the entire year. HCADT values are measured using either vehicle classification studies or using tube counters. All of this data is needed before MNESALS is used.

When a forecast is desired for a particular section of road, the AADT measurements for all nearby sites are collected by the forecaster. Before using this data to make a traffic forecast, this person makes certain that the data is suitable for a least squares line fitting technique. For example, if ten AADT values exist for the past twenty years, the forecaster may use judgement to select five of these ten that best model a smooth, steady increase in traffic. These selected points are then used in a least squares curve estimation analysis. Any curve with an R^2 value in excess of 0.75 is considered acceptable by TDA, however the forecasters usually try to obtain an even better fit. Lastly, if the traffic on the road appears to be holding steady or declining, the TDA Office assumes a minimum growth percentage of 1%.

The least squares curve estimation provides future traffic forecasts in the form of AADT. These values are provided for the base year (the year in which construction ends) until the end of the design year (20 years for hot mix asphalt (HMA), 35 years for PCC). To convert these AADT values into ESAL values, vehicle classification information is needed for the roadway. If this information is not readily available for the region, the forecaster will order a vehicle classification count. These counts document which vehicle types exist at which proportions in the AADT: cars, 2 axles, 6 tire vehicles, 3+ axle single units, 3 axle semis, 4 axle semis, 5+ axle semis, buses, and twin trailers. The raw numbers provided by this count are weighted to account for the time of day, day of the week, month, year, and the length of the count to produce the "adjusted raw" numbers. The percentage of trucks (HCADT) observed in the count is recorded and this value is varied depending upon existing and anticipated traffic patterns. For example, if there is an exit along the road which leads to a gravel quarry, it is likely that the percentage of trucks passing along the main roadway will change significantly at that point.

Finally, the AASHTO ESAL calculation procedure is used on the adjusted raw vehicle counts for each year to be considered. The TDA Office assumes a terminal serviceability value of 2.5, a structural number of 5 for HMA, and slab thickness of 8 inches for PCC pavements. The final report produced by the MNESALS program includes the following values for both the base year and design year of the pavement: the two-way AADT value, the design lane factor, the two-way HCADT (based upon the vehicle classification counts or a WIM count), the two-way

single unit value, the two-way Tractor Semitrailer (TST) value, and the flexible and rigid ESAL values. Additional ESAL forecasts are provided for every five-year period during the design life of the pavement and for several years afterwards.

6.0 Recommendations

6.1 Implications for M-E Design

6.1.1. The transfer functions in MnPAVE can be roughly calibrated using Mn/DOT's experience and traffic data quantified using ESALs. This is a practical approach that will achieve reasonable results.

6.1.2. The transfer functions in MnPAVE must eventually be calibrated using load spectra. ESALs should not be used in this calibration because ESAL data already has "equivalent" damage embedded, which is precisely what the calculated strain, empirical transfer function, and Miner's hypothesis are attempting to predict.

6.1.3. The same traffic data used to calculate ESALs should be used to estimate the load spectrum required by MnPAVE. Both ESAL calculation and MnPAVE require a total count, a measured or assumed vehicle distribution, and the measured or assumed weight of each axle configuration. MnPAVE should not use ESALs as input but rather the data currently used to calculate ESALs.

6.1.4. Regarding the comparison of MnPAVE to the State Aid Soil Factor Design Method, the procedures proposed in (Investigation 183 and TIS) for converting HCADT values into ESALs produce very different results. As a result, these equations should not be used. Rather, the MNESALS program should be used. The inputs would be HCADT, a "heavy" and "light" vehicle distribution provided by TDA, and a single table of average axle configuration weights based on vehicle type provided by TDA.

6.1.5. The Office of Transportation Data and Analysis should continue to provide traffic forecasts with both ESALs and load spectrum for M-E design for all projects.

6.1.6. The Office of Materials and Road Research and the Office of Transportation Data and Analysis should continue to cooperate to insure that the data needs for effective design of pavement structures are adequately and efficiently met so that the best possible pavement designs are built.

6.2 Other Recommendations

6.2.1. The load study that is currently being completed by Dr. Snyder, formerly with the University of Minnesota, should be put to use to make certain that the ESAL values being calculated for Mn/ROAD are reasonable. While it is unlikely that the results of this testing will alter AASHTO's official ESAL definition, this testing should give a clear indication whether the results from the AASHTO Road Test, which was undertaken in Illinois, are applicable in Minnesota. Several M.S. and PhD theses have been written about this subject. They should prove to be valuable resources for Mn/DOT.

6.2.2. Determine which equations and values are being used in the IRD ESAL calculation method. Without knowing exactly how the values were calculated, the results of this method are unusable.

6.2.3. Encourage more counties to obtain vehicle distributions for their projects. A good method for doing this would be to place a safety factor on any ESAL inputs into MnPAVE. This would reward the counties that took the time to measure the distributions and would result in better pavement designs.

6.2.4. Support the TDA Office in their collection, storage, and analysis of project specific axle configuration weight data (the load spectrum).

7.0 References

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C. Example Problems