



UPDATES TO SOFTWARE FOR ESTIMATING DAMAGE DUE TO SUPERHEAVY LOADS

Conducted for:

**Texas Department of Transportation,
Louisiana Department of Transportation and Development
New York Department of Transportation and
Federal Highway Administration**

**Research Report 9-1502-01-7
Project Number 9-1502-01**

October 2007

Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, TX 79968
<http://ctis.utep.edu>

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-05/9-1502-01-7		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Updates To Software for Estimating Damage due to Superheavy Loads				5. Report Date October 2007	
				6. Performing Organization Code	
7. Authors C. Tirado, C. Carrasco, S. Nazarian and R. Osegueda				8. Performing Organization Report No. 9-1502-01-7	
9. Performing Organization Name and Address Center for Transportation Infrastructure Systems The University of Texas at El Paso El Paso, Texas 79968-0516				10. Work Unit No.	
				11. Contract or Grant No. 9-1502-01	
12. Sponsoring Agency Name and Address Texas Department of Transportation. Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080				13. Type of Report and Period Covered Technical Report 9/05– 8/06	
				14. Sponsoring Agency Code	
15. Supplementary Notes Research Performed in Cooperation with TxDOT and FHWA. Research Study Title: Model Calibrations with Local Accelerated Pavement Test Data and Implementation for Focused Solutions to NAFTA Problems					
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17. Key Words Pavement Response, Rutting, Finite Element Analysis, Superheavy Vehicles.			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161, www.ntis.gov		
19. Security Classified (of this report) Unclassified		20. Security Classified (of this page) Unclassified		21. No. of Pages	22. Price

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Model Calibrations with Local Accelerated Pavement Test
Data and Implementation for Focused Solutions to NAFTA
Problems**

**Performed in cooperation with the Texas Department of
Transportation and the Federal Highway Administration**

The Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, TX 79968-0516
Research Report 1502-1
October 2006

ACKNOWLEDGEMENT

The successful progress of this project could not have happened without the help and input of many TxDOT, LADOTD and NYDOT personnel. The authors acknowledge Dar Hao Chen and John Bilyeu from TxDOT, Masood Rasoulia from LADOTD and Julian Bendaña of NYDOT for their guidance and valuable input.

ABSTRACT

The implementation of North American Free Trade Agreement (NAFTA) opened the borders to international traffic coming from both Canada and Mexico. As a consequence, highway networks will be subjected to trucks with new axle configurations and heavier axle loads, causing concern on the impact of super-heavy vehicles on highway's infrastructure. This pooled fund study is aimed at providing these tools.

A software package with the capacity to calculate pavement distress for flexible pavements under any type of traffic load, and to make a comparison of the level of distress caused by a standard and a non-standard truck has been developed and reported in the previous reports. In this report the refinements to that software including the addition of damage to rigid pavements are described.

IMPLEMENTATION STATEMENT

This study is aimed at addressing the possible premature failure of flexible and rigid pavements caused by changes in size and weight requirements as the results of the NAFTA agreement. The outcomes of the finite element models developed here can readily be used to more accurately assess the magnitude of the damage that can be anticipated.

The software is ready for limited implementation by the participating states.

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CHAPTER ONE - INTRODUCTION

PROBLEM STATEMENT

The implementation of the North American Free Trade Agreement (NAFTA) among Canada, Mexico, and the United States has called the attention of some state departments of transportation along the border to understand the impact of heavier axle loads and new axle configurations on their highway networks. Highways designed to carry vehicle loads of 80 kips (350 KN) could be trafficked with gross vehicle loads of over 120 kips (500 KN), by trucks with different tire and axle configurations. For example, specialized haulage vehicles in Mexico are equipped with “super-single” tires, and tridem-axles and triple trailers are used on many long haul routes in Canada. The use of these heavy loads and new vehicle configurations will have a major impact on the performance of the US highway network. Hence, highway agencies urgently need tools to predict the additional damage and the economic impacts of allowing such trucks in the US highway system.

To assess the impact of super heavy loads on the existing roads, a software package based on finite element models has developed as reported in Tirado et al. (2006). That software package was primarily geared toward flexible pavements based on the algorithm suggested by VESYS. In this report, the improvements to the software are discussed.

OBJECTIVE AND APPROACHES

The main objective of the work conducted under this research project is to develop a tool with the capacity to calculate pavement distress under any type of traffic load, and to make a comparison of the level of distress caused by a standard and a non-standard truck for both flexible and rigid pavements.

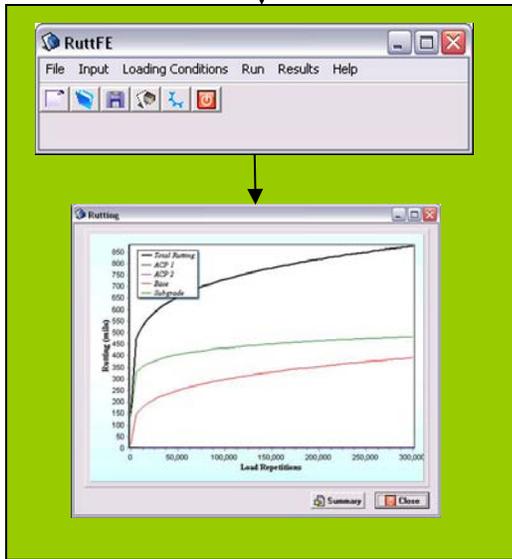
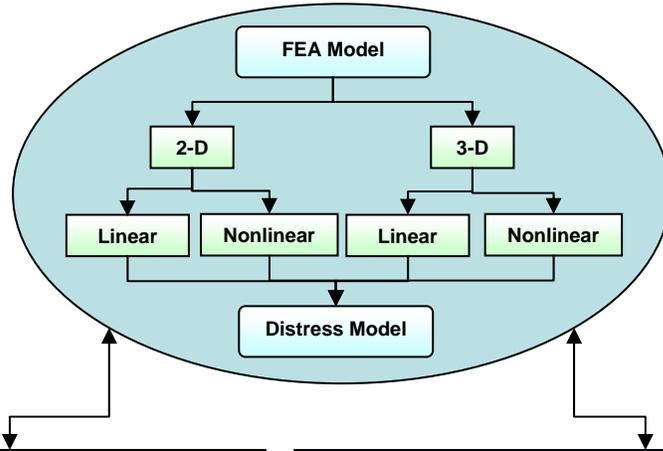
The pavement distress evaluation tool consists of three main modules. Figure 1.1 illustrates the connection between these three modules. The first is a stand-alone Finite Element program with the capacity to load an input file and produce an output file with the pavement distress calculations. The input file contains the geometric pavement section information, material properties and their variation as a function of temperature, and traffic loading characteristics. The output file contains the distress calculations for all the pavement layers as a function of traffic load repetitions. This module is the processor (engine) used in the other two modules. The next module is a graphical user interface (GUI) that functions as a pre and post processor for

the stand-alone finite element program. This module provides an interface to enter all the pavement section information, material properties and traffic information in a user-friendly manner. This user interface generates the input file used by the processor and reads the output and displays the results in a graphical, easy-to-interpret form. Furthermore, the developed program has the capability of analyzing and comparing pavement damage based on different distress models, for both flexible and rigid pavements. This module has been updated to determine damage for both flexible and rigid pavements using different distress models. The last (third) module is a Geographic Information System (GIS)-based tool that allows the calculation of pavement distress and makes comparisons between trucks on a road network. Instead of just doing the distress calculations at one pavement section, this tool can be used to calculate the pavement distress generated by a truck as it moves through a network of roads, thus generating a “profile” of pavement distress. This module is not discussed in this report since it was already covered in Tirado et al. (2006).

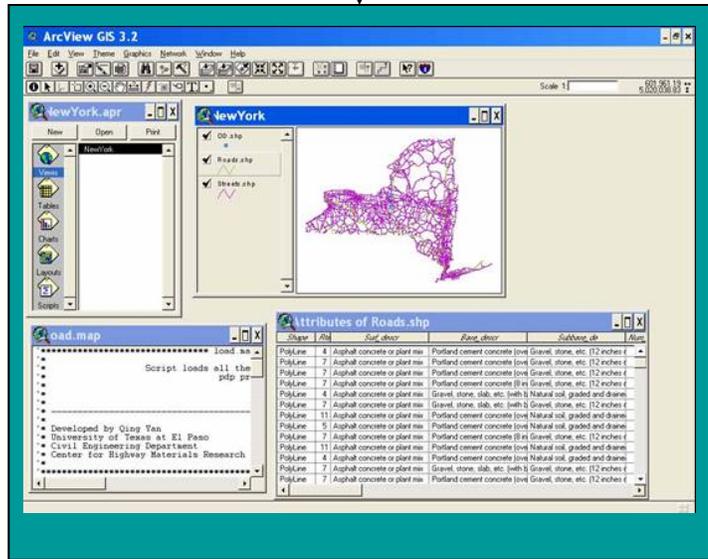
ORGANIZATION OF REPORT

Chapter 2 of this report contains a brief review of the literature. In chapter 3, a brief description of the tools used to compute the pavement responses, for both flexible and rigid pavements, is included. Chapter 4 discusses the different performance models incorporated into the graphical user interface program. Finally, chapter 5 includes the summary of the work accomplished and the status of the project.

Pavement Distress Processor



Pavement Distress GUI



GIS Pavement Distress GUI

Figure 1.1 - Summary of methodology used in project

CHAPTER TWO - BACKGROUND

INTRODUCTION

The implementation of the North American Free Trade Agreement (NAFTA) opened the borders to international traffic coming from both Canada and Mexico. As a consequence, highway networks has been subjected to trucks with new axle configurations and heavier axle loads, causing concern on the impact of super-heavy vehicles on highway's infrastructure. This issue has been the subject of federal and state research for the past decade.

This chapter briefly includes further content of surveyed publications that complements the background shown in Tirado et al. (2006).

PAVEMENT PERFORMANCE PREDICTION

Great effort has been aimed to develop tools for pavement damage prediction. Models have been developed to predict pavement performance based on layer deformation and fatigue cracking. One of these models, VESYS, is based on the elastic model of layered homogeneous material in half infinite space with some viscoelastic-plastic theory applications. The layer rutting model estimates the permanent deformation in each finite layer as the product of the elastic compression in that layer and the layer material permanent deformation law associated with that layer. It is suitable to for analyzing the primary response and predicting the performance for different pavement materials under daily traffic loading and different climatic seasons (Zhou and Scullion, 2002). However, despite the success in these models, new or more advanced constitutive models cannot be easily incorporated into them. On the other hand, finite element (FE) techniques possess flexibility for adopting these new models. Finite element modeling of rutting and permanent deformations has already been documented before.

Zaghloul and White (1994) developed a procedure for permitting overloaded trucks in Indiana. Load Equivalency Factors (LEF) for asphalt pavements with granular base as well as for full depth asphalt pavements were developed. As a part of this study a three-dimensional, dynamic finite element program (3D-DFEM) was used to develop load equivalency factors. Truck loads moving at different speeds were included in the analysis and a number of material models were used to represent the actual pavement materials behavior under moving loads.

In a similar manner, research has been carried on by various researchers to evaluate mechanistic models to calculate pavement responses for predicting pavement performance. Gillmann (1999) developed a procedure for evaluating the effect of axle spacing on pavement damage in terms of Load Equivalency Factors (LEF) for both rigid and flexible pavements.

Wang et al. (2006) evaluated the prediction quality of three response models commonly used in concrete pavement analysis: ISLAB2000, JSLAB2004 and EverFE2.22. The theoretical evaluation involved simulations, sensitivity trials and comparisons of calculated slab stress, strain, and deflection responses of a number of hypothetical pavement systems.

Tirado et al. (2006) provides a further list of research that has been done related to the implementation of finite element modeling to predict pavement damage.

CHAPTER THREE - PAVEMENT RESPONSE

INTRODUCTION

A number of computer programs have been developed for analyzing the structural response of pavement systems based on linear elastic theory; however, these programs fail to consider the nonlinear behavior of the pavement material since some granular materials may exhibit nonlinear behavior under actual traffic loads. In order to take into account this behavior, other programs, such as ABAQUS, may be used to model pavement considering nonlinear behavior. However, both the licensing of the program and the necessity for training personnel to manage this program makes it difficult to implement, especially when a limited budget is available.

A finite element program was developed to calculate the primary response of a flexible pavement using two- and three-dimensional models and incorporated into a graphical user interface that enables pavement distresses calculation. On the other hand, the analysis of rigid pavements requires the use of the processor of JSLAB2004, a finite element program developed for jointed concrete pavements.

PAVEMENT DISTRESS GRAPHICAL USER INTERFACE

A graphical user interface (GUI) called Integrated Pavement Damage Analyzer (IntPave) was developed to facilitate the user the process of input of pavement section properties data. This software integrates the finite element programs to calculate both flexible and rigid pavement response. The graphical user interface was developed based on Visual C++ code. See Appendix A for a thorough description of IntPave's interface.

STAND-ALONE FINITE ELEMENT PROGRAM FOR FLEXIBLE PAVEMENTS

Distress models for flexible pavements make use of the parameters obtained from the primary response of pavement such as the layer deformation or the tensile strain at the bottom of the asphalt-concrete layer. A finite element (FE) program was developed in Matlab[®] and compiled into an executable file that allows IntPave to send to and retrieve data from the FE program once the user has gathered and input the necessary pavement information. The finite element program has the capability of performing an analysis in both two- and three-dimensions. The analysis is based on a generalized Hooke's law to model the properties of pavement structure. Using an open source preprocessor called GMSH, it was possible to create a 2-D mesh with triangular

elements for an axisymmetric model, as shown in Figure 3.1, and a 3-D mesh using four-node tetrahedral elements, as shown in Figure 3.2, suitable for analyzing axle configurations and saving computation time. In both cases the mesh becomes more refined as it gets closer to the load application points, namely the tire contact areas.

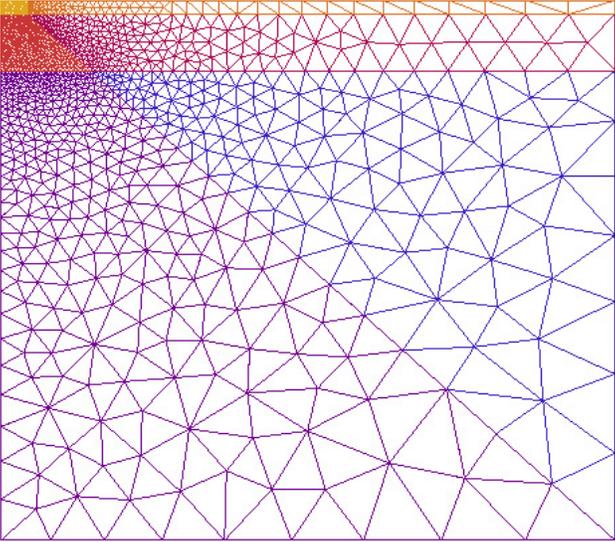


Figure 3.1 - 2-D mesh with element refinement transition, load applied at upper left corner.

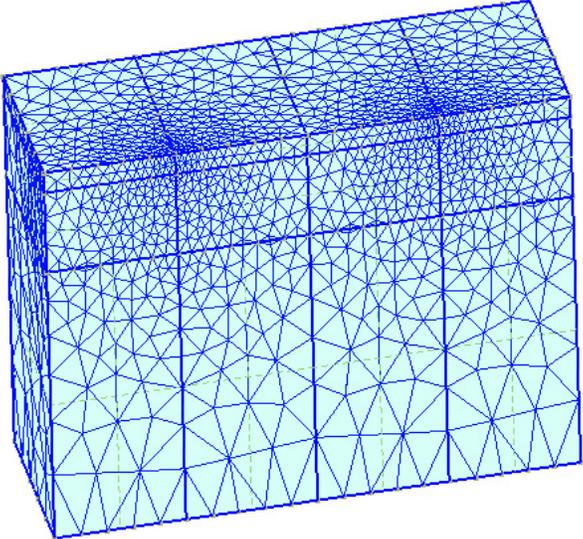


Figure 3.2 – 3-D mesh, tandem axle, dual tire load condition.

Nonlinear Model

The finite element program has the advantage of analyzing problems using either a linear analysis based on the generalized Hooke's Law, or a nonlinear analysis for both 2-D and 3-D models. For the latter approach, the nonlinear model used in the FEA program considers a load-induced nonlinear behavior based on the static linear elastic layered theory with a simple modification of the isotropic linear relation. An iterative process is employed to consider the nonlinearity of the pavement materials. The constitutive model developed by Barksdale, et al. (1994) has endorsed a universal relationship for both fine and coarse grained base and subgrade materials in the form of,

$$E = k_1 \sigma_c^{k_2} \sigma_d^{k_3} \quad (3.1)$$

where E is the resilient modulus, σ_c and σ_d are the confining pressure and the deviatoric stress, respectively; parameters k_1 , k_2 , and k_3 are coefficients statistically determined from the results of laboratory resilient modulus tests. The resilient modulus refers to the unloading modulus during a triaxial test in which loading, unloading and reloading are simulated under cyclic loading conditions. A resilient modulus is defined as the ratio of the repeated deviatoric stress to the recoverable part of the axial strain. Since the state of stress can only be known if the material properties are known, an iterative process is necessary to implement this stress-modulus relationship shown in Equation 3.1.

FINITE ELEMENT MODELING FOR RIGID PAVEMENTS

In order to evaluate damage caused by traffic on rigid pavements, it is necessary to obtain the pavement response making use of mechanistic models to predict pavement performance. One of the finite element-based models available in the public domain that can be obtained at no charge is JSLAB, a finite element program developed for jointed concrete pavements. This program was initially developed by the Portland Cement Association (PCA) and then modified and upgraded by the Federal Highway Administration (FHWA) in 1992 and 2004 (FHWA, 2004a). JSLAB is a 2-D structural finite element rigid pavement analysis program that uses a mesh of four-node, 12 degrees-of-freedom elements. The program has the capability of handling multiple wheel and axle loads using rectangular loading areas. The load transfer can be modeled with either aggregate interlock between slabs or dowel bars. Besides it has the capability to calculate the response time history under step-moving axle loads. However, the number of slabs is limited to a maximum 3×3 (FHWA, 2004b).

Integrating the finite element process of JSLAB2004 into the pavement distress graphical user interface required separating the JSLAB processor from its own graphical user interface. IntPave incorporated a simplified interface to send to and receive data from JSLAB. The obtained pavement response (i.e. pavement stresses) were later used at the distress models to calculate damage. To simplify the input process IntPave creates a 3×2 slab system where the size of the centered slab is defined by the user while the adjacent slabs are automatically defined similar to the central slab or larger if needed in order to accommodate the total truck length, as shown in Figure 3.3. A dynamic analysis is performed by moving the truck every foot from the first slab

to the third one, passing through the middle one where the maximum stresses are obtained throughout the slab or at user specified location in order to calculate damage using the distress models explained in the next chapter.

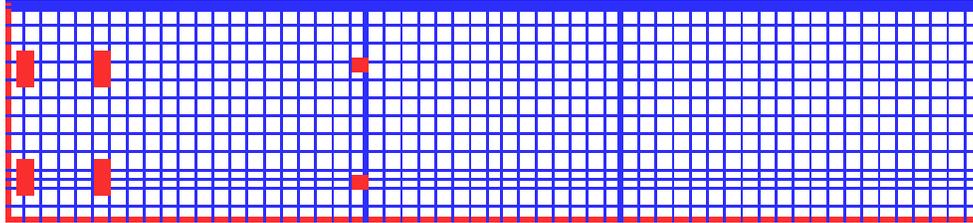


Figure 3.3 – 2-D mesh for 3-slab system for a truck consisting of a tandem dual axle and single axle single tire combination.

Though JSLAB2004 is capable of performing the analysis for six different foundations systems, a default Winker foundation is selected by IntPave. Appendix A presents the windows shown by IntPave to input the necessary information for analyzing a rigid pavement, and the windows showing the results of available distress models.

CHAPTER FOUR - DISTRESS MODELS

INTRODUCTION

Distress models were integrated into the Integrated Pavement Damage Analyzer program (IntPave) to calculate the damage in terms of these models. In the case of flexible pavements rutting and fatigue cracking were taken into consideration. Rigid pavements on the other hand incorporated fatigue cracking and faulting models based on the JSLAB2004 capabilities for calculating stresses and deformations. Pumping is included as a third damage model for rigid pavements; however, this is only a tool that allows calculation of pumping indexes used to calculate damage factors but it does not utilize any information generated by JSLAB2004.

FLEXIBLE PAVEMENTS

The Integrated Pavement Damage Analyzer program included two models, rutting and fatigue cracking for evaluating pavement damage in terms of load repetitions, and also included a comparative model based on the AASHTO formulation in terms of load equivalency factors. IntPave provides the user a mean to compare damage caused by a truck in relation to the one caused by a standard truck defined by the user.

In a comparative analysis a damage factor is obtained based on rutting obtained for each truck and compensated by the payload carried by each truck in order to take into consideration the number of trips a truck would need to carry a given cargo in comparison to the other truck. A similar approach is considered when a fatigue cracking analysis is carried out. When a large number of load repetitions are taken into consideration, the program displays a graph depicting the damage factor in terms of rut depth. The damage factor is calculated from the ratio of the number of load repetitions of a truck to achieve a given amount of rutting and the number necessary for the standard truck to reach that given amount of rutting. Such value is later on adjusted based on the truck payloads as mentioned before. On the other hand, if a superheavy truck is considered and its damage is to be compared to the one of a standard truck, the user has the choice of viewing a graph where the damage ratio is obtained based on the rut depth for the first truck passes and compared directly to the standard truck pass. In the case of fatigue cracking, the damage ratio is obtained based on the fatigue cracked area instead of rut depth. The user still has available the rutting and fatigue cracking curves based on repetitions for each truck.

Rutting

To estimate the progress of rutting with load repetition using elastic layer theory, all layers are modeled using a constitutive model in the form,

$$\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha} \quad (4.1)$$

where ε_p is the accumulated permanent strain, ε_r is the resilient elastic strain, N is the load cycle number and α and μ are material parameters measured in the laboratory: the rate of increase in permanent deformation against the number of load applications and the permanent deformation, respectively. The total elastic strain within a pavement layer is simply the total compression of that layer, given by the difference in deflections of the top and bottom of the layer (Zhou and Scullion 2002); therefore, for any layers this difference is written as:

$$R_D(N) = \frac{\mu}{1-\alpha} \cdot (W^+ - W^-) \cdot N^{1-\alpha} \quad (4.2)$$

where R_D is the permanent deformation (rutting) level at N load repetitions and W^+ and W^- are the elastic deflection amplitudes of the top and bottom surfaces of the layer.

Modeling Multiple Axle Groups

Modeling permanent deformations for an axle group has already been described; however, if it is desired to calculate rutting based on a number of truck passes, then the effect of all axle groups must be considered. The process aims on obtaining the rut depth after a single truck pass, a value that can be easily implemented into the constitutive model shown on Equation 4.1. The first step consists on determining the rut depth generated by a single repetition for the first axle group. To add the contribution to rut of the second axle group, the number of load repetitions of the second axle group to achieve the rut depth already accumulated by the first axle group is backcalculated, and a new rut depth is calculated based on the obtained number of load repetitions plus one. The process repeats until all axle groups are considered, obtaining a final rut depth for a single pass of the whole truck, from which the final static deformation is backcalculated. From the static deformation determined for the truck, rutting can be obtained for any load repetitions in terms of truck passes.

Fatigue Cracking

In addition to rutting, fatigue cracking is another major distress type occurring on flexible pavement systems; consequently it was included into IntPave to evaluate pavement performance. For that reason, the Asphalt Institute MS-1 model was implemented into the program. Such model is suggested by the new Mechanistic-Empirical Pavement Design Guide (NCHRP, 2004). Alligator fatigue cracking is assumed to be generated from tensile strains ε_t occurring at the bottom of the asphalt layers (bottom-up cracking). Tensile strains at the bottom of AC layers are provided to the fatigue cracking model from the finite element analysis. Failure criteria are defined as follows:

$$N_f = k_1 \varepsilon_i^{-k_2} E_{ACP}^{-k_3} \quad (4.3)$$

where N_f is the number of load applications to failure, $k_1 = 0.0796$, $k_2 = 3.291$, and $k_3 = 0.854$ are regression parameters based on a 20% failure area criteria and standard mix asphalt. Fatigue cracking calculations are based on Miner's law for cumulative damage D ,

$$D = \sum_{i=1}^T \frac{n_i}{N_{fi}} \quad (4.4)$$

where n_i = traffic for period i . This is later used for calculating the fatigued cracking area

$$F.C. = \left(\frac{6000}{1 + e^{C'_1 + C'_2 \log_{10}(100D)}} \right) \cdot \left(\frac{1}{60} \right) \quad (4.5)$$

where $C'_2 = -2.40874 - 39.748 (1 + h_{ac})^{-2.856}$, $C'_1 = -2 C'_2$, and h_{ac} is the total thickness of the asphalt layers (NCHRP, 2004). Though regression parameters shown before are defined as default values, the user has the option of selecting any desired value.

RIGID PAVEMENTS

Various distress models were incorporated into IntPave to analyze rigid pavements. The models included the AASHTO, fatigue cracking, pumping and faulting.

Fatigue Cracking

The model implemented for obtaining the damage generated by a truck based on fatigue cracking is defined by the allowable number of repetitions, expressed as follows

$$\log N_f = f_1 - f_2 \left(\frac{\sigma}{S_c} \right) \quad (4.6)$$

in which N_f is the allowable number of repetitions, σ is the flexural stress in slab, and S_c is the modulus of rupture of concrete. Constants f_1 and f_2 values are set to 17.61 as explained by Huang (2004) based on 50% probability of failure of several tests. The program also lets the user consider zero-maintenance pavements whose formula is the same differing only by f_1 being reduced to 16.61. Finally, the user has the option of selecting the PCA formulation which involves the following formulas according to different stress-rupture modulus ratio,

$$\text{for } \frac{\sigma}{S_c} \geq 0.55, \quad \log N_f = 11.737 - 12.077 \left(\frac{\sigma}{S_c} \right) \quad (4.7)$$

$$\text{for } 0.45 < \frac{\sigma}{S_c} < 0.55, \quad \log N_f = \left(\frac{4.2577}{\frac{\sigma}{S_c} - 0.4325} \right)^{3.268} \quad (4.8)$$

$$\text{for } \frac{\sigma}{S_c} \leq 0.45, \quad N_f = \text{unlimited} \quad (4.9)$$

Fatigue cracking model may be applied based on two different scenarios which the user has the option to select. The first one consists on selecting a specific point along the slab on which the user wants to compare damage based on fatigue cracking. The second option is based on the point where the maximum stress occurs on the slab determined by JSLAB2004. In both cases a dynamic analysis is performed consisting on analyzing the slab at different loading conditions defined by the moving truck. The slab response is calculated at different intervals as the truck enters to, passes through, and leaves the slab. The maximum stress is selected for both cases and taken as worst case scenario to perform the comparison based on the fatigue cracking models. Based on these stresses, the allowable number of repetitions for each truck are calculated and compared to obtain a damage factor. The damage factor obtained directly from the model are multiplied by a ratio of the payloads in order to take into consideration the number of trips required to carry a similar cargo.

Faulting

Another type of distress typical of jointed concrete pavements is faulting, occurring mainly in transverse joints. JSLAB2004 allows the calculation of faulting by providing the maximum deformation of concrete under the dowel, which along with a modulus of dowel support of 1,500,000 pci, the maximum bearing stress can be calculated. Faulting for a doweled pavement is obtained then using the formulation expressed on Equation 4.10 (Huang, 2004),

$$F = N_{18}^{0.5377} \left[2.2073 + 0.002171S^{0.4918} - 0.0003292JS^{1.0793} - 2.1397k^{0.01305} \right] \quad (4.10)$$

where N_{18} is the number of equivalent 18-kip single-axle loads, in millions, S is the subgrade soil type, JS is the transverse joint spacing, in ft, and k is the estimated modulus of subgrade reaction on top of the subbase, in pci. The maximum faulting is therefore selected and compared directly to the one developed by the user-selected standard truck based on a damage ratio.

If an undoweled jointed concrete pavement is selected, a different formulation is used (Huang, 2004):

$$F = N_{18}^{0.3157} \left[0.4531 + 0.3367z^{0.3322} - 0.5376(100w)^{-0.008437} + 0.0009092FI^{0.5998} + 0.004654B \right. \\ \left. - 0.03608ES - 0.0187S - 0.009467D \right] \quad (4.11)$$

where N_{18} is the number of equivalent 18-kip single-axle loads, in millions, FI is the mean air freezing index in degree-days, B is the erodibility factor for subbase materials, ES is the edge support condition, S is the subgrade soil type, D is the drainage index, w is the corner deflection

based on a 9,000 lb load with a contact pressure of 90 psi applied at a free corner, and z is the joint opening determined by the size of slab. Joint opening is determined from Equation 4.12 (Huang, 2004),

$$\Delta L = CL(\alpha_t \Delta T + \varepsilon) \quad (4.12)$$

in which ΔL is the joint opening caused by temperature change and drying shrinkage of concrete, α_t is the coefficient of thermal expansion of concrete, ε is the drying shrinkage coefficient of concrete, L is the slab length, ΔT is the temperature range, and C is the adjustment factor due to slab-subbase friction, which may be 0.65 for stabilized bases or 0.8 for granular bases. The erodibility factor for subbase material may take the following values: 0.5 for a lean concrete subbase, 1.0 for cement-treated granular subbase, 1.5 for cement-treated nongranular subbase, 2.0 for asphalt-treated subbase and, 2.5 for untreated granular subbase. Edge support condition can take the value of 0 for no edge support, or 1 for tied edge beam or tied concrete shoulder. Subgrade soil type may be 0 for fine-grained soils (A-4 to A-7), or 1 for coarse-grained soils (A-1 to A-3).

For both cases, the damage factor obtained directly from the ratio of the case truck faulting by the standard truck faults is multiplied by a ratio of the payloads.

Pumping

In addition to fatigue cracking, a pumping model was incorporated into the program. This model calculates the pumping index based on Equation 4.13,

$$PI = N_{18}^{0.443} \left[-1.479 + 0.255(1 - S) + 0.0605P^{0.5} + 52.65H^{-1.747} + 0.0002269FI^{1.205} \right] \quad (4.13)$$

where N_{18} is the number of equivalent 18-kip single-axle loads, in millions, FI is the mean air freezing index in degree-days, P is the annual precipitation, in cm, H is the slab thickness in inches, and S is the subgrade soil type taking the value of 0 for coarse-grained soils (A-1 to A-3) and 1 for fine-grained soils (A-4 to A-7). As it may be seen from this formula, this model does not make use of any output value of JSLAB2004 but was included into IntPave as an important mode of distress.

EQUIVALENT AXLE LOAD FACTORS

Another method used to compare the damage caused by a truck is based on the AASHTO equivalent factor, which is included into IntPave for both flexible and rigid pavements. The equivalent axle load factor (EALF) defines the damage per pass to a pavement by the axle in question relative to the damage per pass of a standard axle load of 18-kip (80-kN) single-axle load (Huang, 2004). This value depends on the type of pavements, thickness or structural capacity and the terminal conditions at which the pavement is considered failed.

Flexible Pavements

The following regression equations describe the process for determining the equivalent axle load factor for flexible pavements,

$$\log\left(\frac{1}{EALF}\right) = \log\left(\frac{W_{tx}}{W_{18}}\right) = 4.79 \log(18+1) - 4.79 \log(L_x + L_2) + 4.33 \log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad (4.14)$$

$$G_t = \log\left(\frac{4.2 - p_t}{4.2 - 1.5}\right), \quad (4.15)$$

$$\beta_x = 0.40 + \frac{0.081(L_x + L_2)^{3.23}}{(SN + 1)^{5.19} L_2^{3.23}}, \quad (4.16)$$

where W_{tx} is the number of x -axle load applications, W_{18} is the number of 18-kip single-axle load applications, L_x is the load in kip on one single axle, one set of tandem or tridem axles; L_2 is the axle code (1 for single axle, 2 for tandem axles, and 3 for tridem axles); SN is the structural number; p_t is the terminal serviceability; G_t is a function of p_t as shown in Equation 4.15; and β_{18} is the value of β_x when L_x is equal to 18 and L_2 is equal to 1 (Huang, 2004).

Rigid Pavements

The following regression equations describe the process for determining the equivalent axle load factor for rigid pavements,

$$\log\left(\frac{1}{EALF}\right) = \log\left(\frac{W_{tx}}{W_{18}}\right) = 4.62 \log(18+1) - 4.62 \log(L_x + L_2) + 3.28 \log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad (4.17)$$

$$G_t = \log\left(\frac{4.5 - p_t}{4.5 - 1.5}\right), \quad (4.18)$$

$$\beta_x = 1.00 + \frac{3.63(L_x + L_2)^{5.20}}{(D + 1)^{8.46} L_2^{3.52}}, \quad (4.19)$$

where variables W_{tx} , W_{18} , L_x , L_2 , p_t , β_{18} , and β_x have the same definitions as for flexible pavements, and D is the slab thickness in inches (Huang, 2004).

The equivalent axle load factor is calculated for each single axle group. However, both formulations do not take into consideration when an axle group is larger than a tridem axle. When an axle group consists of four axles or more, the EALF is obtained for sets of tridem axles adding to the number the one corresponding to an extra EALF calculated for either a single or tandem axle, until all axles are totaled. Besides considering the number of axles within an axle group for determining the equivalent axle load factor, the axle spacing is also taken into consideration. The equivalent load factors are calculated for a standard axle spacing of 48 in. On the other hand, if the axle spacing exceeds 72 in. then the EALF for that given axle must be calculated as a single axle. Whenever the axle spacing is within 48 in. and 72 in. then the EALF

must be calculated for these two distances, and finally an intermediate value must be obtained by linearly interpolated from these values. In order to compute the load factor for a truck, then all axles' EALFs must be added together. If a damage factor is desired from a comparative analysis, then a ratio of EALFs is obtained from a case truck by a standard truck and multiplied by a ratio of carrying cargos of each truck.

INFLUENCE OF AXLE SPACING ON LOAD EQUIVALENCY FACTORS

The AASHTO Pavement Design Guide distinguishes between the damaging effects of dual and triple axle combinations, but assumes that these combinations have similar damaging effects regardless of the axle spacing within the combination. In spite of this assumption, axle spacing has a significant effect on pavement damage. Hajek and Agarwal (1990) studied the influence of axle spacing on pavement damage on flexible pavements concluding that load equivalency factors were significantly influenced by pavement response parameters (deflection, strains) on which they are based. Gillmann (1999) further developed an adjustment method to estimate load equivalency factors for both flexible and rigid pavements. However, in this project the obtained load equivalency factors presented in the previous sections were adjusted linearly by taking a standard axle spacing of 48 in and setting a 72 in limit where the axle can be considered as independent single axles. The procedure consists on calculating the load equivalency factors from the AASHTO formulae for the given axle group and for a single axle and setting these values for the 48 and 72-in spacing, respectively. An adjustment factor is then obtained from the contribution of these factors when the axle spacing is between these limits. The effect of axle spacing on pavement damage is presented and discussed as an example of the comparative analysis capability of IntPave in the next section.

COMPARATIVE ANALYSIS

Besides calculating rutting and fatigue cracking for a given truck, IntPave also has the capability of obtaining damage factors based on a comparative analysis. Damage factors are obtained for different types of distress caused by a truck compared to the same caused by a user defined standard truck. Similarly, damage factors may be obtained for axles or single tires. The available types of distresses were already previously.

To illustrate the capability of IntPave for calculating the damage factor for different types of distresses a sample case is presented next. A comparative analysis is performed to analyze the effect of axle spacing on tandem, tridem and quad axles. An axle spacing of 48 in. is used as the basis for a standard axle. Flexible pavement properties consist of a 6-in. asphalt-concrete layer with a modulus of 500 ksi, followed by a 12-in. base with a modulus of 50 ksi and a 25-ksi subgrade.

Figures 5.4 through 5.6 present the effect of the axle spacing on damage for flexible pavements for 34-kip tandem, 48-kip tridem and 60-kip quad axles. Damage factors are obtained using the rutting and fatigue cracking formulations. These figures show the influence of axle spacing on damage for both rutting and fatigue cracking for these axles. The ratios of both types of distresses tend to decrease as the axle spacing increases, as confirmed by the results previously obtained by Hajek and Agarwal (1990).

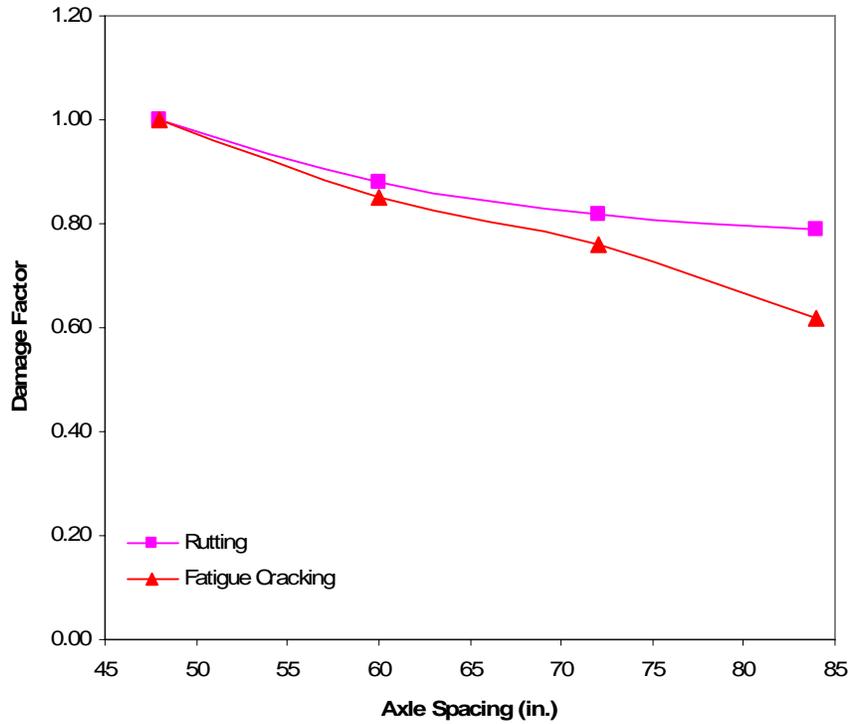


Figure 4.1 – Effect of axle spacing on damage for 34-kip tandem axles on flexible pavement.

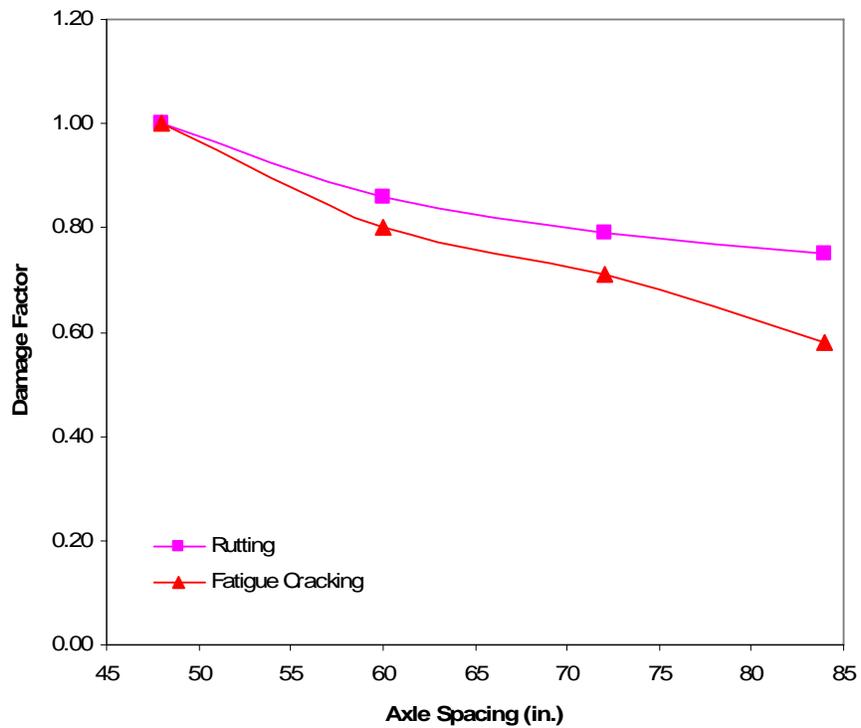


Figure 4.2 – Effect of axle spacing on damage for 48-kip tridem axles on flexible pavement.

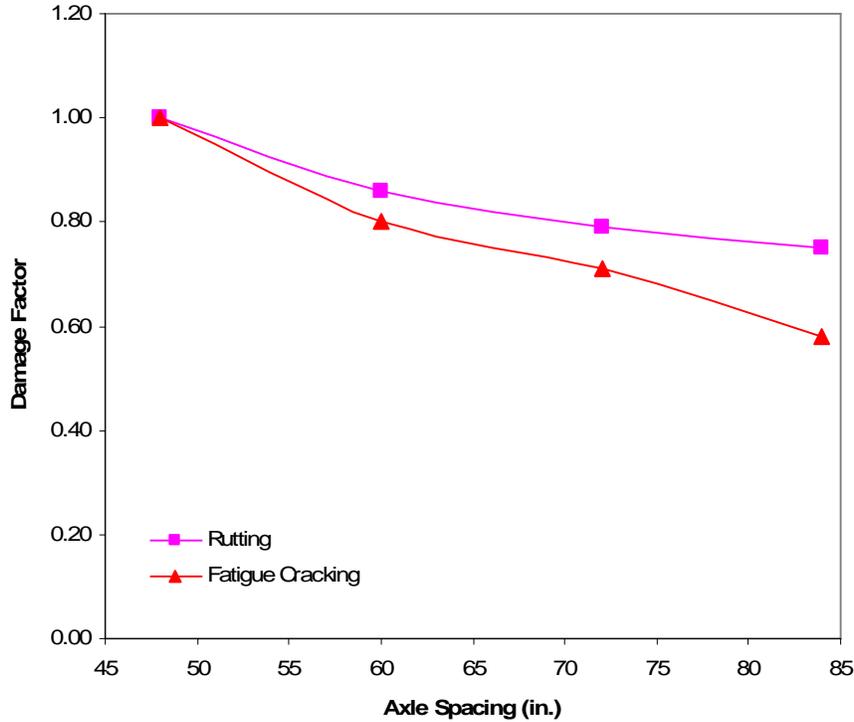


Figure 4.3 – Effect of axle spacing on damage for 60-kip quad axles on flexible pavement.

Following an identical procedure for rigid pavements, the effect of axle spacing on the same 34-kip tandem, 48-kip tridem and 60-kip quad axles is now considered. The rigid pavement properties consist of a 10-in. thick concrete slab with 1.25-in. dowels with 9-in. in length spaced at 12 in. and 0.75-in. tiebars spaced at 18 in with 9-in. in length and a 180×168 in. slab size.

Figures 5.7 through 5.8 present the effect of the axle spacing on damage for rigid pavements for 34-kip tandem, 48-kip tridem and 60-kip quad axles. Damage factors are obtained based on fatigue cracking, pumping and faulting. Once again, a 48-in. axle spacing is selected as default and is used as the basis of comparison. The models are based on the maximum observed stresses along the slab as the truck passed through the analyzed slab. As observed from these figures, damage factors tend to decrease as the axle spacing increases, following the trend previously obtained by Gillmann (1999) for load equivalency factors on rigid pavements.

The procedure to perform a comparative analysis is described in Appendix A. IntPave can perform this analysis for single tires, axles and trucks alike.

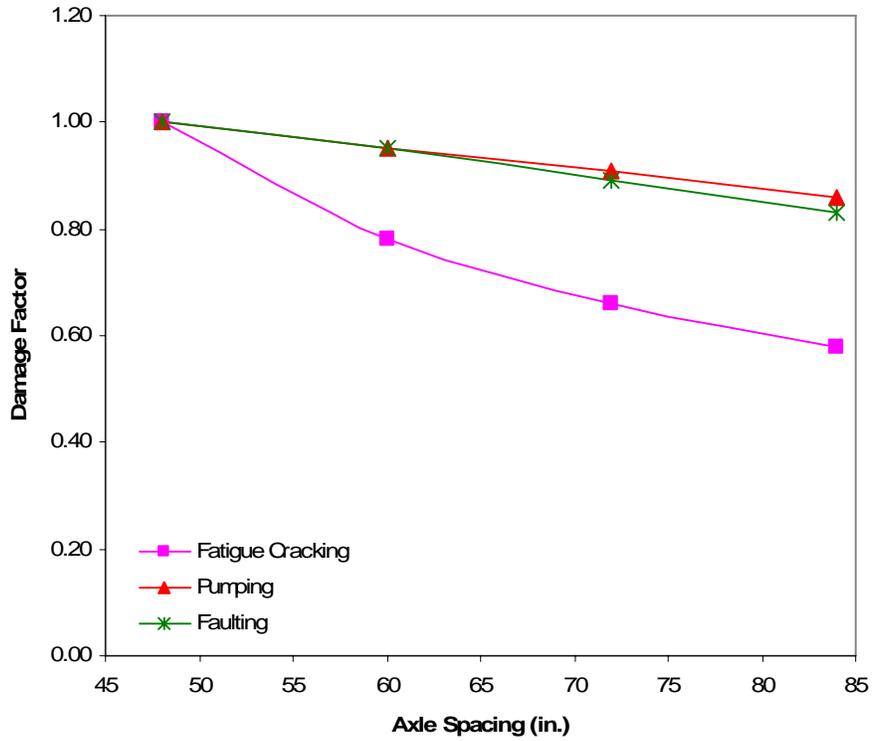


Figure 4.4 – Effect of axle spacing on damage for 34-kip tandem axles on rigid pavement.

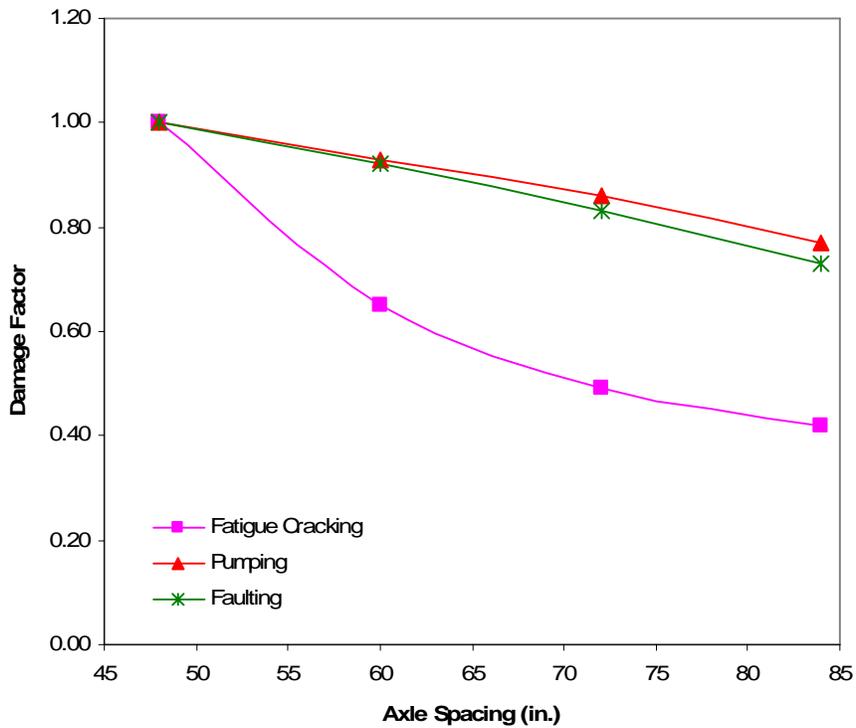


Figure 4.5 – Effect of axle spacing on damage for 48-kip tridem axles on rigid pavement.

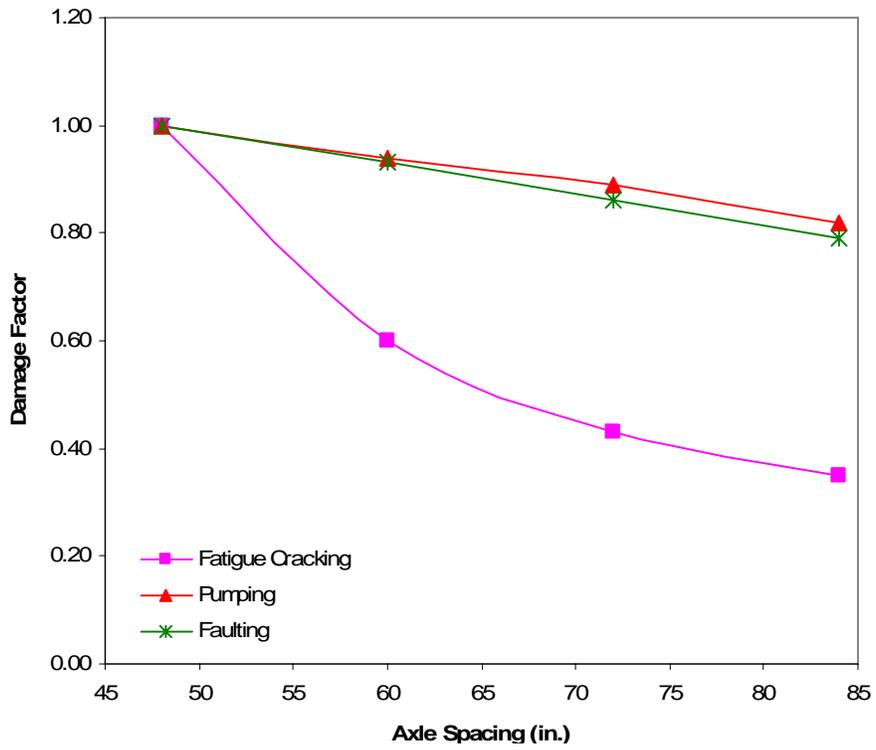


Figure 4.6 – Effect of axle spacing on damage for 60-kip quad axles on rigid pavement.

CHAPTER FIVE - SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

SUMMARY AND CONCLUSIONS

Different models have been developed over the years to evaluate pavement distresses. A program titled Integrated Pavement Distress Analyzer (IntPave) was developed for calculating pavement distresses for both flexible and rigid pavements relying on the codes of two finite element analysis programs.

For flexible pavements, models developed based on the elastic layer theory have proven efficient for calculating rutting under daily traffic and different climatic seasons. However, these models fail to consider nonlinear behavior of the materials. In order to consider nonlinear properties of pavement structure, finite element models are needed. For that reason, a finite element program was developed to analyze the response of a flexible pavement system. The developed program has the advantage of rapid execution time due to optimizations performed on the programming code. The finite element model provides the pavement primary response used to determine both rutting and fatigue cracking.

On the other hand, to assess pavement damage on rigid pavements, JSLAB, a finite element analysis program created for jointed concrete pavements was utilized for predicting pavement response. The processor of JSLAB was incorporated into IntPave, which send to and receives from the information necessary analyzing damage.

The developed program has the capability of calculating pavement distress under any type of traffic load, and to make a comparison of the level of distress caused by a standard and a non-standard truck for both flexible and rigid pavements.

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APPENDIX A

INTEGRATED PAVEMENT DAMAGE ANALYZER (INTPAVE) GRAPHICAL USER INTERFACE MANUAL

INTEGRATED PAVEMENT DAMAGE ANALYZER (INTPAVE) GRAPHICAL USER INTERFACES MANUAL

The software to analyze pavement damage was developed into a stand alone executable program which has the following characteristics:

- Easy-to-use interface.
- Convenient data input.
- Integrated FEA model that calculates rutting and stresses for flexible pavements, developed in Matlab[®].
- Newer and simpler graphical user interface that sends to and receives data from an external concrete pavement analysis program (JSLAB-2004).
- Graphical display of results.

The software may be used for the following purposes:

- Rutting calculation for a given flexible pavement structure and traffic loading scenario by means of finite element analysis.
- Fatigue cracking determination for a given pavement structure by means of Asphalt Institute procedure as described by the Guide for Mechanistic-Empirical Design (2004).
- Damage factor determination based on comparison of a truck against a standard truck defined by user based on equivalent axle load factors, rutting and fatigue cracking for flexible pavements, and equivalent axle load factors, fatigue cracking, faulting, and pumping index for rigid pavements.

MAIN WINDOW OVERVIEW

Executing the software prompts a main window that displays the main menu with a list of options, as shown in Figure 1. Below the main menu lies a set of buttons that correspond to basic items linked to actions that are also within the main menu. Putting the mouse over the action buttons will display a message showing the function of the button. The action of these buttons is as follows: New File, Open File, Save File, Analysis Type, Run FEA Analysis for a Single Truck, and Exit. Figure 2 presents the list of each button and the corresponding action.



Figure A.1 – Main window.

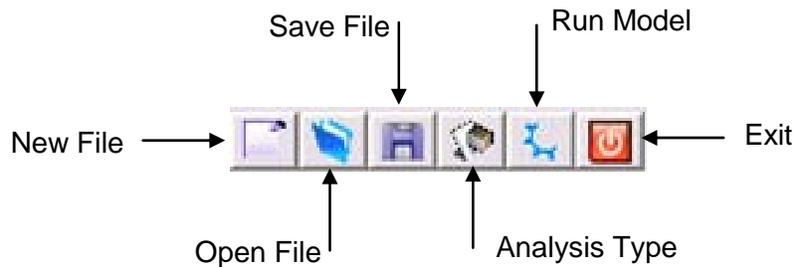


Figure A.2 – Button activities.

The selection of any of the main menu options will open another list below them displaying related actions to their corresponding title. As an example, selecting the **File** menu will display a list consisting of **New**, **Open**, **Save** and **Exit** options. Creating a new file will automatically send the user to the next menu, **Input**, specifically to **Pavement Type**. The user will have to continue through the rest of the steps by filling the empty forms displayed. On the other hand, opening a file will load a previously saved file with information regarding the pavement structure, loading conditions and traffic rate. Such data may be edited by the user and saved into another file at any moment.

FLEXIBLE PAVEMENTS

Selecting the Input option from the main window will display a menu with options related to the pavement properties of the program. Such list is shown on Figure 3.

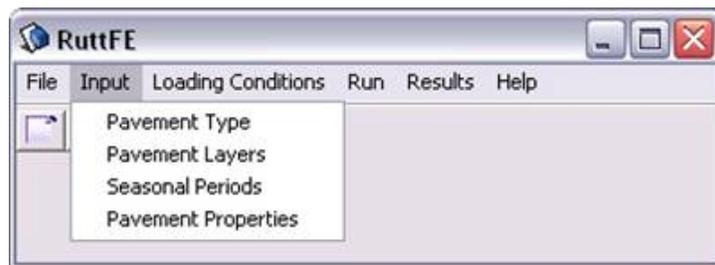


Figure A.3 – Input menu for pavement structural properties.

The first item on the list is the **Pavement Type**. This item lets the user decide what kind of pavement to analyze, which can be either a flexible or a rigid pavement. A screenshot of the displayed window is shown in Figure 4.



Figure A.4 – Pavement type selection.

As it may be seen, each window has the option of going to the next screen, that is the next item on the menu, or closing the current active window letting the user skip menu items to select whatever item the user wants to edit if a file was previously loaded into the program. If the user selects a “Flexible Pavement” and clicks on the “Next” button, a new window titled **Pavement Layers** is displayed asking the user to enter the number of layers the pavement has in its structure, and the thickness and Poisson ratio of each layer. Figure 5 shows the displayed window.

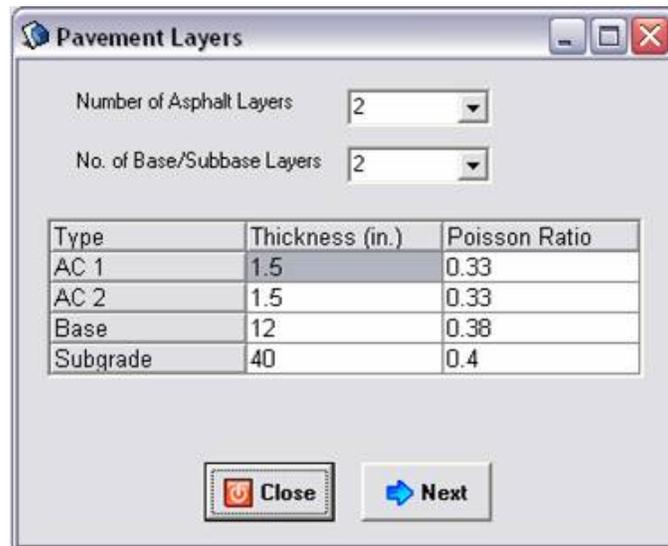


Figure A.5 – Number of pavement layers and structural properties.

Other pavement properties have seasonal variation, and these were differentiated from the previous properties, as they vary according to the number of seasons specified by the user. The window prompted by the **Seasonal Periods** option allows the user to indicate the number of seasons within the analysis period and the season duration in days, as shown in Fig. 6.



Figure A.6 – Seasonal period analysis.

The last item within the pavement structural properties input menu, **Pavement Properties**, lets the user enter into the program time dependent properties, such as the modulus of elasticity, α , μ , and nonlinear parameters k_2 and k_3 . The window on Figure 7 shows sample properties on a selected layer.



Figure A.7 – Seasonal pavement properties

LOADING CONDITIONS

Selecting the **Loading Conditions** option from the main menu will display a submenu with options related to the traffic loading conditions. The first displayed item in the submenu is the Traffic option that prompts a window as shown on Figure 8.

The prompted window asks the user the required traffic information in terms of daily number of repetitions. Furthermore, it asks the user to specify if the analysis has to be done for a specific truck or if a comparative analysis is required in order to compare damage generated by a truck relative to the one generated by a standard truck. From this point, the analysis may follow two different paths and results are displayed in a different manner.

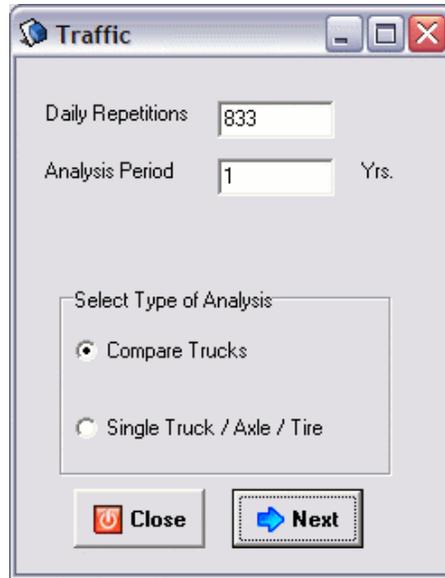


Figure A.8 – Seasonal pavement properties.

SINGLE TRUCK, AXLE OR TIRE

The option **Single Truck** sends the user to the window shown in Figure 9. This window asks the user for information regarding the axle loading and other properties such as tire radius, pressure, axle spacing and tire spacing depending on the number of axles within the axle group.

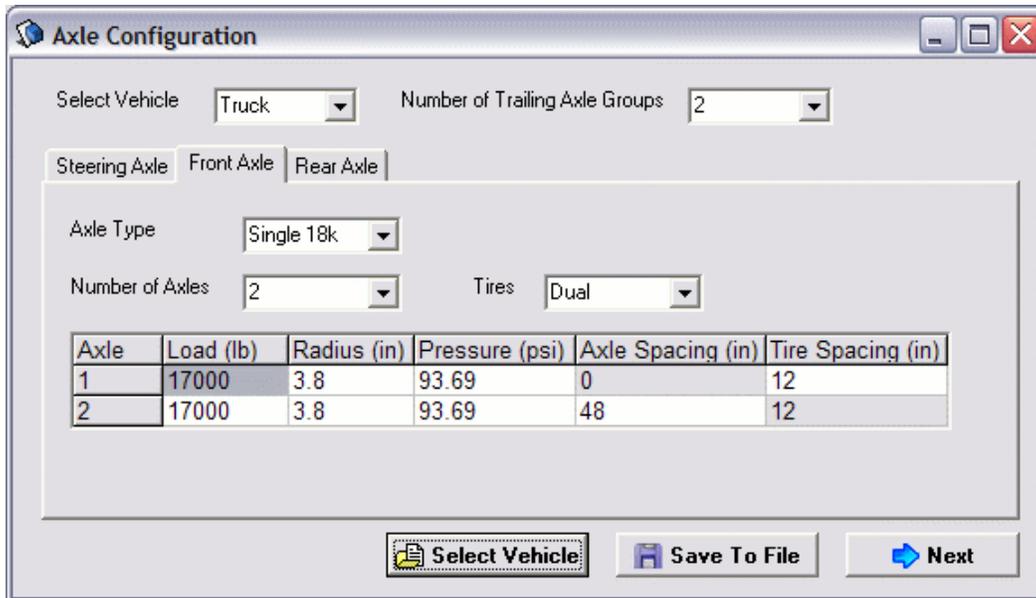


Figure A.9 – Axle loading and properties

Furthermore, the user may analyze a single tire if that option is selected. The following window, shown on Figure 10, prompts the user to select an **Analysis Type** which can either be a linear or nonlinear analysis and each can be two- or three-dimensional. Two-dimensional modeling is

only available for single tires; if an axle or truck is analyzed, the 2D option is hidden. If the 3D option is selected, the user will get the option of saving the mesh and stresses for further reference.

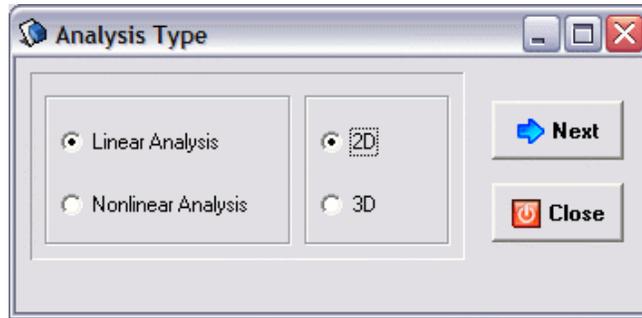


Figure A.10 – Analysis type, selecting a 2D model.

2-D Model

Selecting a 2D model analysis, as shown in Figure 10, will lead to an axisymmetric finite element analysis, for this reason two-dimensional modeling is only available for single tires. Though the mesh may be viewable using Gmsh by opening Geometry2D.msh file, the analysis will not produce an output file with the stresses obtained from the analysis. Clicking on the **Next** button leads the user to the same steps that will be explained for the 3-D Model.

Gmsh is a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. This GNU General Public License program is used as a meshing tool called from the finite element analysis program and is used as a post-processor for viewing stress contours as well as the resulting mesh for multiple axles for three dimensional modeling.

3-D Model

Selecting a 3-D model analysis from the **Analysis Type** window, as shown in Figure 11, will lead to a three-dimensional finite element analysis. Though Figure 11 presents all options, the 2D option will not be available if an axle or a truck was selected when the configuration was defined.

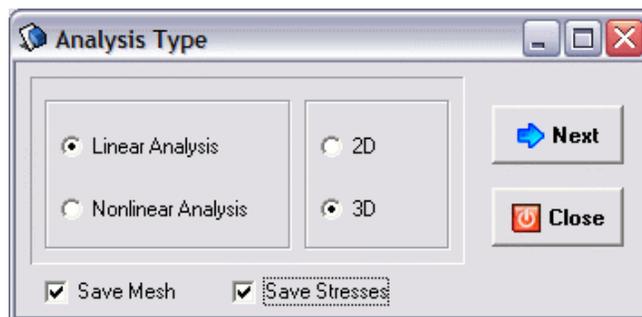


Figure A.11 – Analysis type, selecting a 3D model.

Once an analysis type has been selected, another form titled **Summary of Input** prior to the analysis execution is displayed presenting a summary of all input information, as shown in Figure 12. All information previously input will be displayed containing the pavement seasonal properties, traffic information, as well as the axle configuration. In Figure 12, the information for a truck having a steering axle carrying 12,000 lbs, and two tandem axles with 17,000 lbs are displayed, similar to the information displayed on Figure 9.

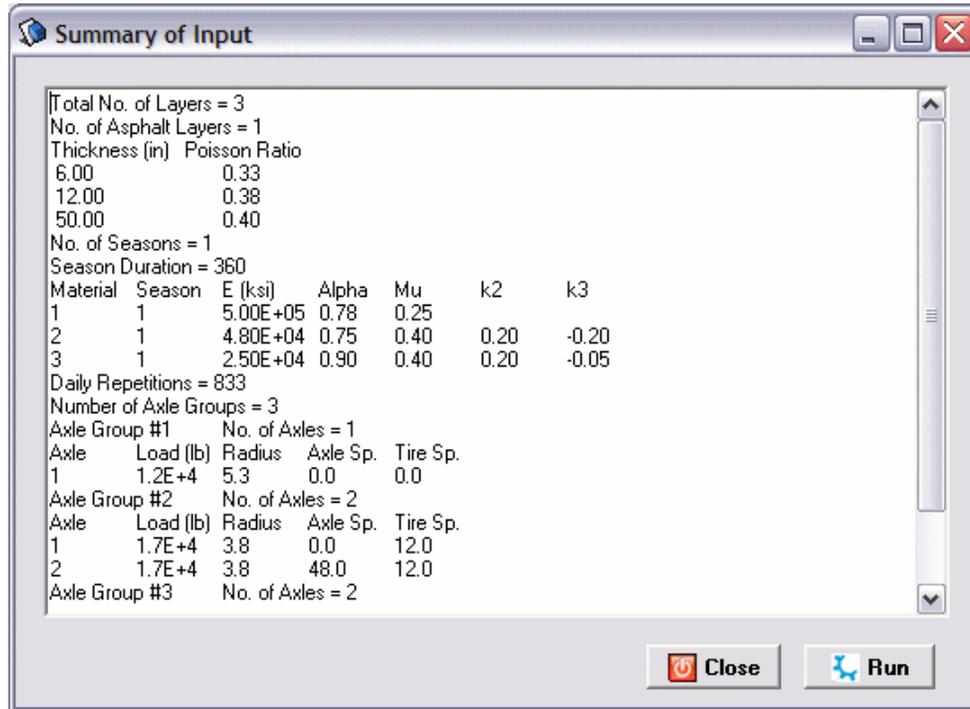


Figure A.12 – Summary of input

Clicking the **Run** button will execute the finite element program based on the decision taken on the analysis type. The analysis will generate a mesh and stresses files for each axle and stored at the *Mesh* and *PosGen* folders created within the root folder, respectively. Files will be numbered with respect to the axle number accordingly, overwriting files from previous executions.

As soon as the execution process is finished, the results will be available to the user. Automatically, the **Rutting** window will be presented to the user; a sample rutting graph obtained from the results is depicted on Figure 13, which displays a graph with the total rutting as well as the contribution of each layer compared to the number of load repetitions. The number of repetitions available is the one the user selected for the analysis period.

By selecting **Fatigue Cracking** button a new window is displayed as shown in Figure 14 which displays a graph of fatigue cracking area with respect to load repetitions. The default method of calculating fatigue cracking is based on the Asphalt Institute formulation; however, constant parameters *k* may be changed to any value the user defines and a new graph will be displayed after the user clicks on the **Calculate** button. Similar to the rutting form, the fatigue cracking form has a summary button that displays the summary of results.

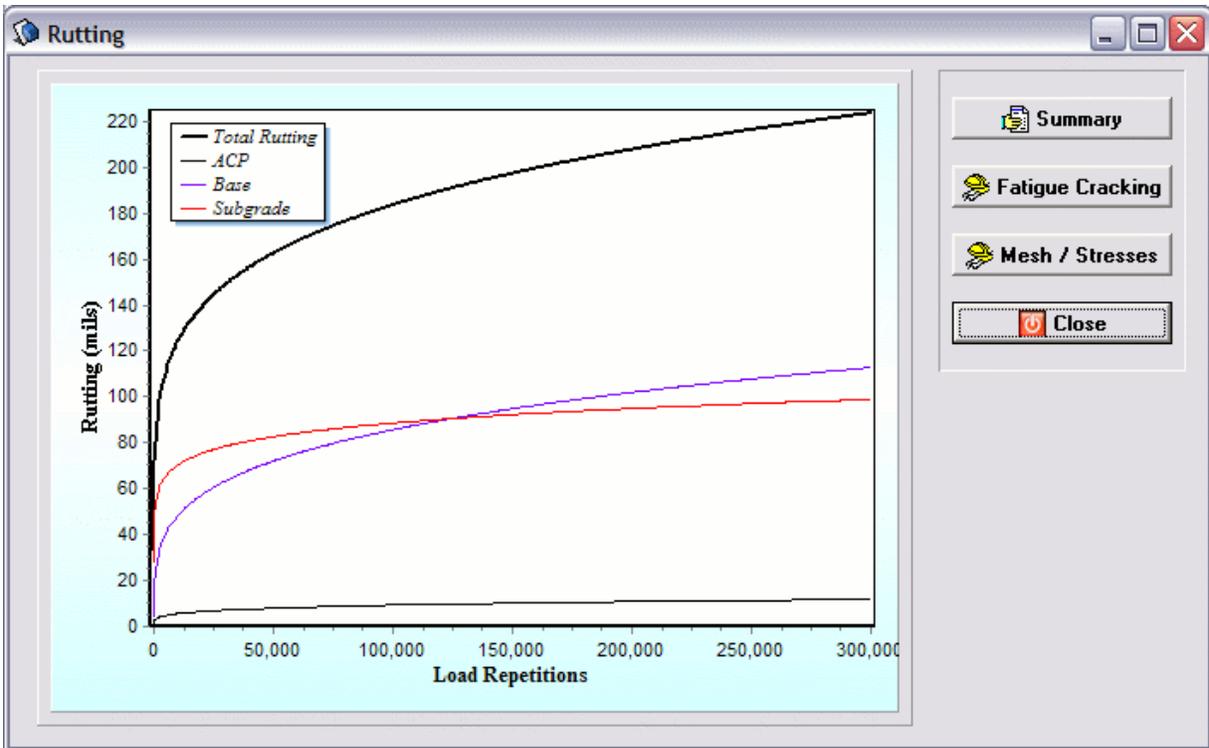


Figure A.13 – Rutting vs. load repetitions.

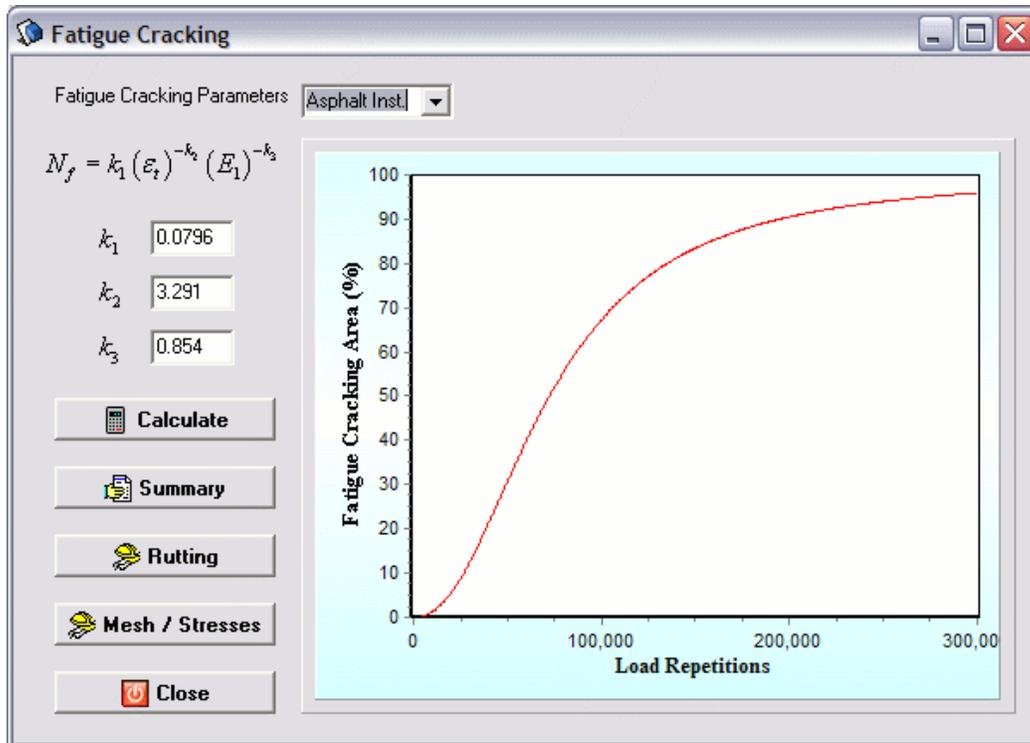


Figure A.14 – Fatigue cracking results.

The user will have other information readily available that may be displayed by selecting the options shown in the **Rutting** or the **Fatigue Cracking** windows. The user has further access to view rutting or fatigue cracking results, mesh and stresses' contours or view a summary of the information obtained and displayed by just clicking on the buttons located next to the graph.

By selecting the **Summary** button a new window is opened that displays a field with a summary of the total rutting at the end of each season, as well as the contribution of each layer at the end of the total analysis period in terms of percentage, as shown in Figure 15. This information may be saved into an ASCII text file.

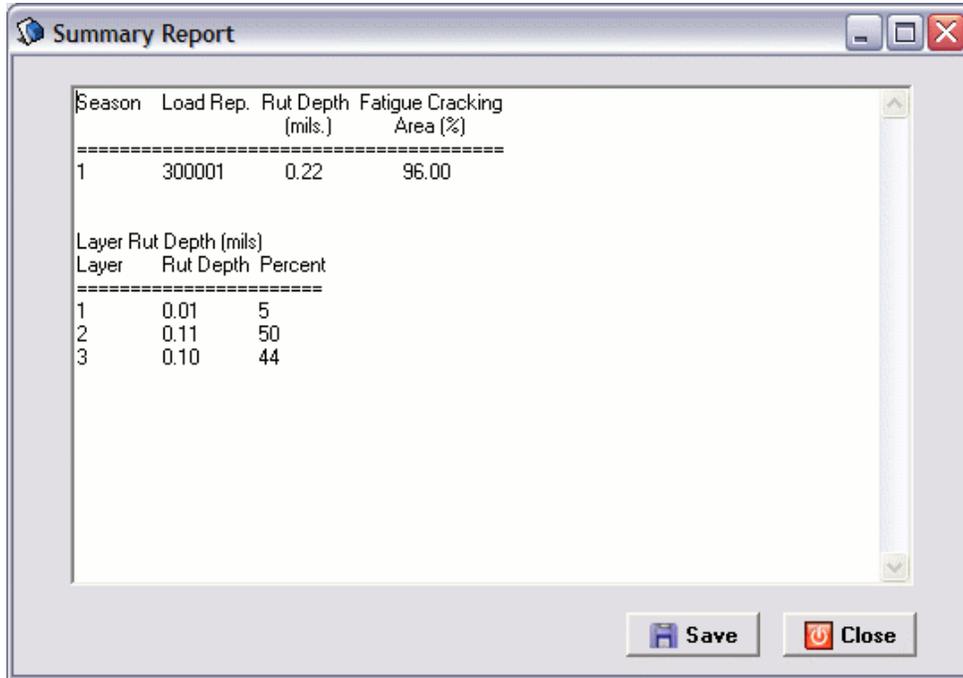


Figure A.15 – Summary of results.

Clicking on the **Mesh / Stresses** button displays another window form that allows the user view the mesh of all axle groups by launching Gmsh that automatically open the axle group selected by the user from the drop-down menu, as shown in Figure 16. Similarly, the stress contours are available for all axle groups in the vertical, longitudinal and transversal directions by just selecting the desired options from the drop-down menus. Values of stresses are expressed in the same units as they were input into the pavement damage program, that unit consists of lbs/in² (psi). If the user did not selected to view this information using the check boxes in the **Analysis Type** window (see Figure 11), then the drop-down menus will display *Not Selected* and won't call these results.

Clicking on the Mesh and Stress **View** buttons will open windows as the ones that were shown in Figure 17(a) and (b), respectively.



Figure A.16 –View mesh and stresses.

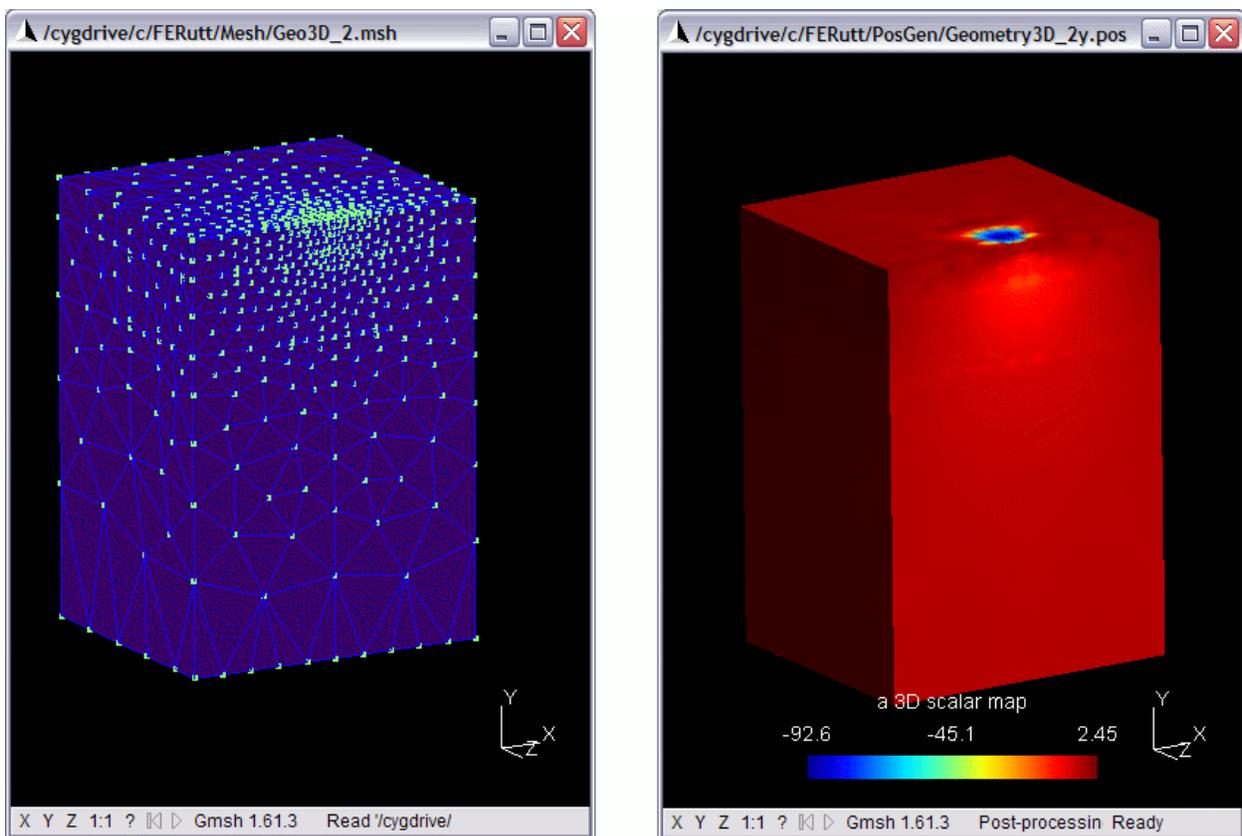


Figure A.17 –View mesh (a) and stress contours (b).

COMPARE TRUCKS

The above description applies for the case where the user selects the analysis of a single truck, axle or tire. Now it is explained the other analysis type option, which consists on comparing damage caused by a truck based on the damage caused by a standard truck, both of them user defined by the user. The selection of comparing trucks is done at the traffic form (see Figure 8), clicking on **Compare Trucks** radio button sends the user to a different form titled **Truck Vehicle Selection** where a new and standard vehicle must be defined or selected from previously stored information, as shown in Figure 18. The form allows the user select saved vehicle information, or create and/or edit vehicle information for both trucks. Moreover, it asks the user to enter information regarding the empty vehicle weight of each of the vehicles, and automatically displays the gross vehicle weight (GVW) once the vehicle axle configuration has been created.

Figure A.18 – Truck vehicle selection.

Selecting on the **Create/Modify Vehicle** button opens another window, titled **Truck Characteristics**, Figure 19, where the user can enter the number of axle groups besides the steering axle, the axle type of each group (i.e. single, tandem, tridem, etc.), the number of tires (single or dual), and the corresponding tire properties and distances for each configuration. The user will be able to save new or modified axle groups configurations at any time for later use, once all blank fields are filled. This window form is similar to the **Axle Configuration** form shown for the single truck analysis.

Axle	Load (lb)	Radius (in)	Pressure (psi)	Axle Spacing (in)	Tire Spacing (in)
1	17000	3.8	93.69	0	12
2	17000	3.8	93.69	48	12

Figure A.19 – Truck characteristics.

Once both vehicles are selected, the procedure requires the user to select an analysis type to compare vehicles, as shown in Figure 20. There are three analyses available, the first one consisting on a comparison based on the equivalent axle load factor for each truck (AASHTO), the second one based on rutting and the third one based on fatigue cracking. Each selection provides a relative damage based on the standard truck. In the case of rutting, it is necessary to provide what type of analysis the finite element code must perform, either a linear or nonlinear analysis.

Figure A.20 – Compare vehicles form.

If the comparison based on the equivalent axle load factor for each truck is selected by clicking in the **AASHTO** button, a new window will be displayed as shown in Figure 21. This window

will provide the ratio between the equivalent axle load factors of the analyzed case truck divided by the selected standard truck.



Figure A.21 – Damage factor based on AASHTO formulation.

On the other hand, a finite element analysis will be executed if a **Rutting** or **Fatigue Cracking** analysis is selected. For both cases, a three-dimensional model will be implemented. The window selecting the analysis type appears before the finite element code execution, as shown in Figure 22. In this comparison analysis, the user won't have the save mesh and stresses options.

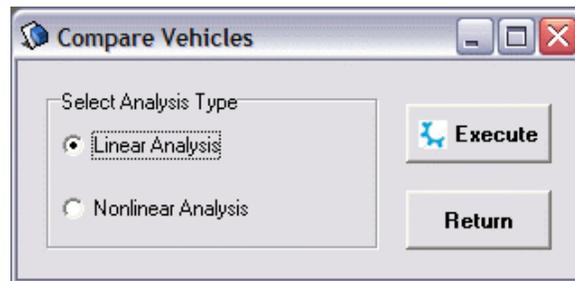


Figure A.22 – Analysis type for comparison.

Selection of the rutting comparison will open a new graph displaying a tab control generating a graph depending on the selected tab. The first of the four displayed tabs offers the results of damage factors obtained from a ratio of load repetitions for both trucks required to attain a given amount of rutting, taking also into consideration the payload carried by the trucks too. The damage factor obtained is shown in a graph as the one in Figure 23.

The next two tabs display the rutting generated by the case truck and the selected standard truck based on the number of repetitions, as shown in Figure 24. This information is similar to the one obtained from a single truck analysis (see Figure 13).

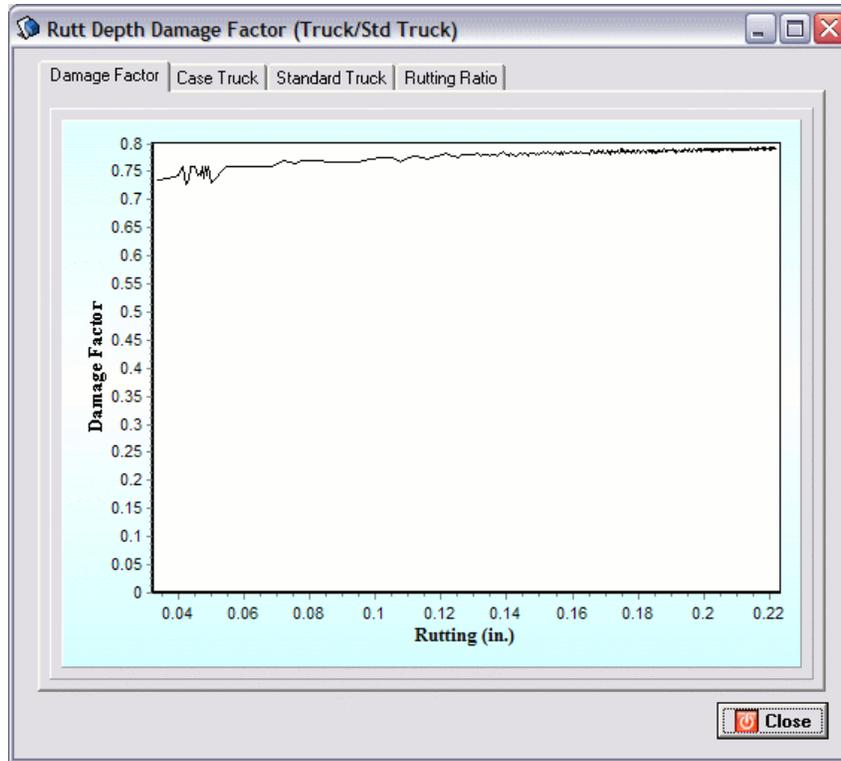


Figure A.23 – Damage ratio based on rutting.

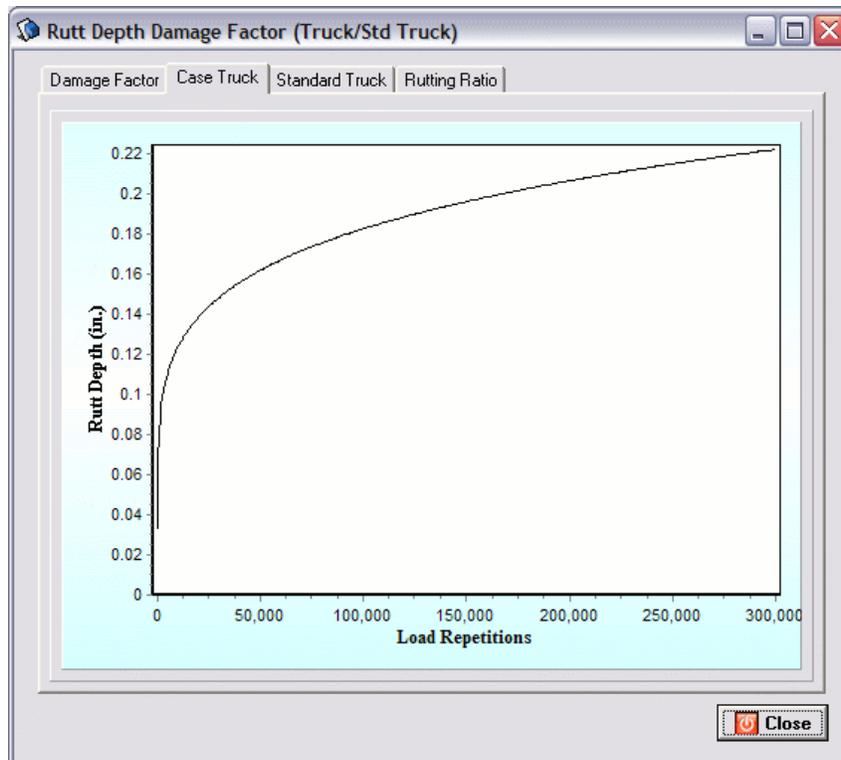


Figure A.24 – Rutting vs. load repetitions for each truck.

Finally, the ratio of damage factor based on rutting of the new truck to the standard truck obtained for the first repetitions is displayed if the fourth tab is selected. This information directly compares the rutting generated for each truck pass, which is more suitable for a superheavy truck pass. A sample graph is shown in Figure 25.

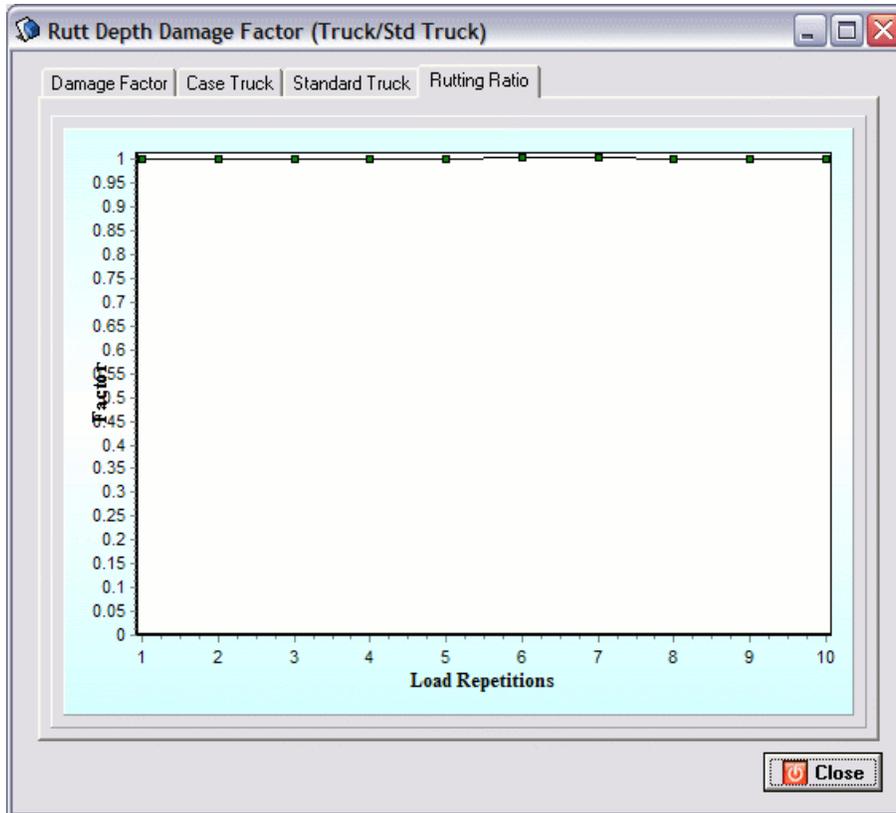


Figure A.25 – Ratio based on rutting for the first truck passes.

Similarly, fatigue cracking comparison displays similar charts, with the same tab control options from the rutting window. Figure 26 presents a sample graph of the rutting comparison. Again, the first of the four displayed tabs offers the results of damage factors obtained from a ratio of load repetitions for both trucks required to attain a given amount of fatigued cracked area, the payload carried by the trucks is again considered. The damage factor based on fatigue cracking is shown in a graph as the one in Figure 26. Changing the *k* parameters and clicking on the **Calculate** button will generate a new graph.

Similarly to the rutting results, the fatigue cracking curves are available for each truck as shown in Figure 27. A direct ratio of case to standard truck based on fatigue cracking for the first load repetitions is also available.

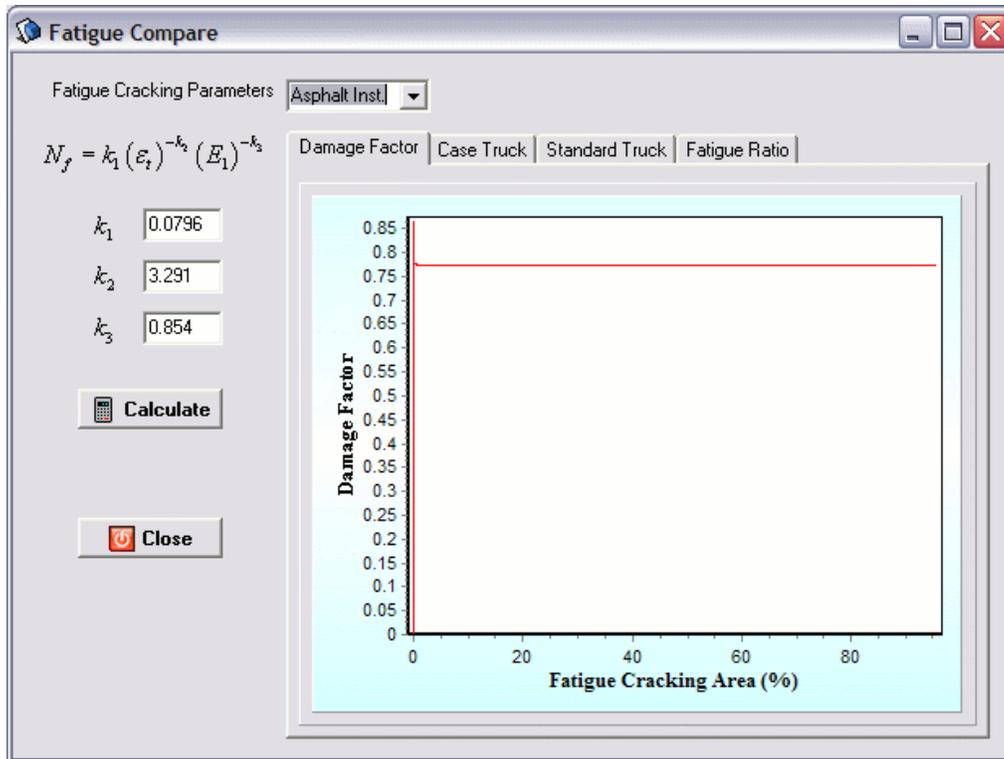


Figure A.26 – Damage ratio based on fatigue cracking.

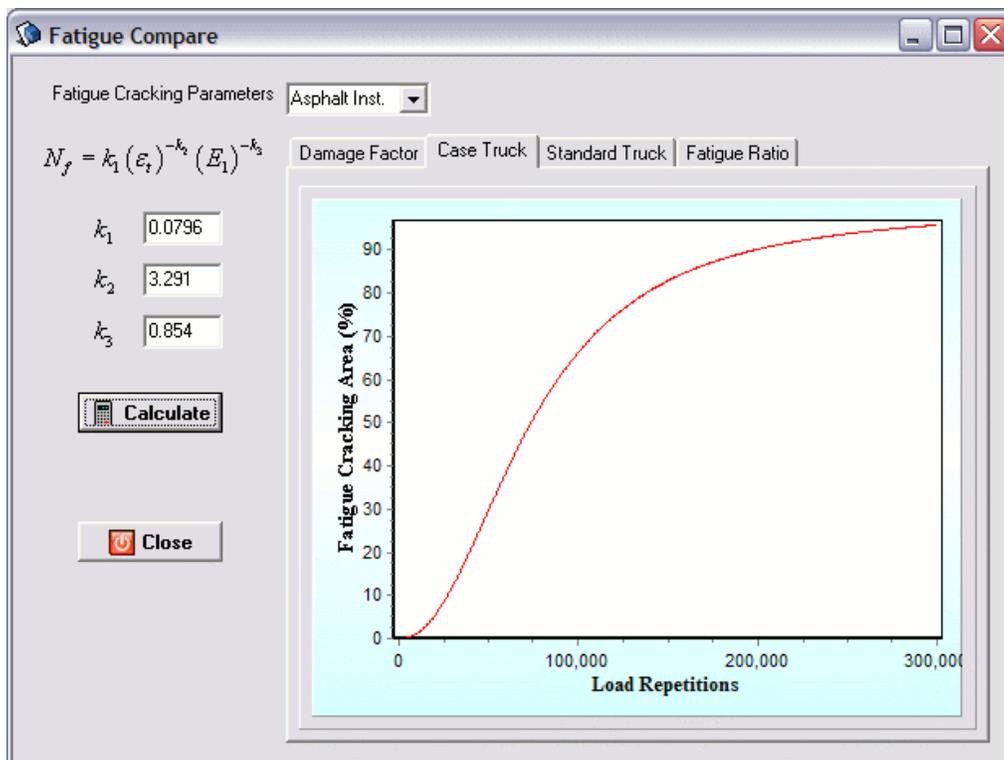


Figure A.27 – Fatigue cracking based on load repetitions results per truck.

RIGID PAVEMENTS

The Integrated Pavement Damage Analyzer (IntPave) includes a section for distress analysis of rigid pavements. A graphical user interface was created to send pavement structure and traffic information to an external concrete pavement analysis program called JSLAB-2004, this program is capable of analyzing jointed pavement responses under a moving load from one end of a multiple-slab pavement to the other. The pavement damage analyzer incorporates distress models that make use of the resulting stresses obtained by JSLAB-2004 which are read by the pavement damage analyzer program to assess damage.

Selection of **Rigid Pavement** from the **Pavement Type** window (see Figure 4) leads the user through different windows. Starting with the **Rigid Pavement Properties** window, the user needs to input information related to the slab material (i.e. concrete's elastic modulus, Poisson's ratio, unit weight, equivalent temperature gradient and coefficient of thermal expansion), its thickness, and subgrade modulus. Default values are already displayed for the user to modify, as shown in Figure 28.

Property	Value
Thickness (in.)	10
Elastic Modulus (psi)	4000000
Poisson's Ratio	0.15
Unit Weight (lb./in. ³)	0.0868
Equivalent Temperature Gradient (°F/in.)	d
Coefficient of Thermal Expansion	5E-6
Subgrade Modulus (psi/in)	200

Figure A.28 – Rigid pavement properties.

Next, slab properties must be input such as slab dimensions; this information is input into a window form as shown in Figure 29. It further requires to input desired wheel path distance to edge of slab. The program locates a second wheel path 6 ft above the selected wheel path. Moreover, a point within the slab must be defined; this point will be used if stresses want to be found at that specific point. Its location is based on the distance from the edge of slab

(perpendicular to wheel path direction) and the distance from the edge of slab where a joint is located, that is parallel the wheel path (see Figure 30).

The screenshot shows a software dialog box titled "Slab Properties". It is organized into three main sections:

- Slab Size:** Contains two input fields: "Slab Length (in.)" with the value 180 and "Slab Width (in.)" with the value 168.
- Wheel Path:** Contains one input field: "Distance to Edge (in.)" with the value 48.
- Data Collected @:** Contains two input fields: "Distance to Joint (in.)" with the value 0 and "Distance to Edge (in.)" with the value 48.

At the bottom of the dialog, there are two buttons: "Next" (with a blue arrow icon) and "Close" (with a red power icon).

Figure A.29 – Rigid pavement properties.

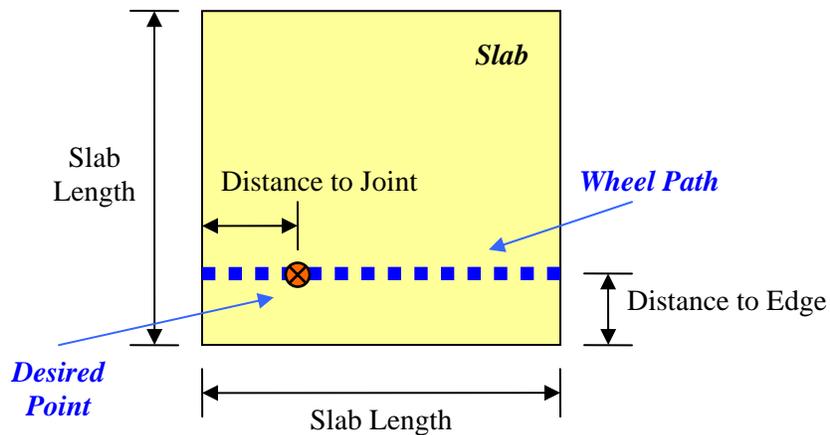


Figure A.30 – Wheel path and selected point location within slab.

The following form titled **Joints** asks the user to enter information about the joints on the rigid pavement. Information about dowels and tiebars should be provided if required, as shown in Figure 31. Input fields activate depending if dowels exist or do not.

After this information is input, the form titled **Truck Vehicle Selection** is displayed in order to perform a comparative analysis. As in the case of the flexible pavement, a new and standard vehicle must be selected, as it was shown previously in Figure 18.

Figure A.31 – Joints.

Again the user will have to edit the truck characteristics if necessary, opening a window as shown in Figure 32, which happens to be similar to the one displayed from the flexible pavement; however, a new field activates on the bottom part of window that asks the user to enter the distance between axle groups. This information is necessary in order to dimension the truck.

Once the necessary information is provided, the next window asks the user to select the type of analysis desired, shown in Figure 33. Among the options it is possible to compare damage of the new to the standard truck based on the equivalent axle load factor for each truck (AASHTO), or based on the stresses generated by each truck based on a dynamic analysis of the truck moving through the slab.

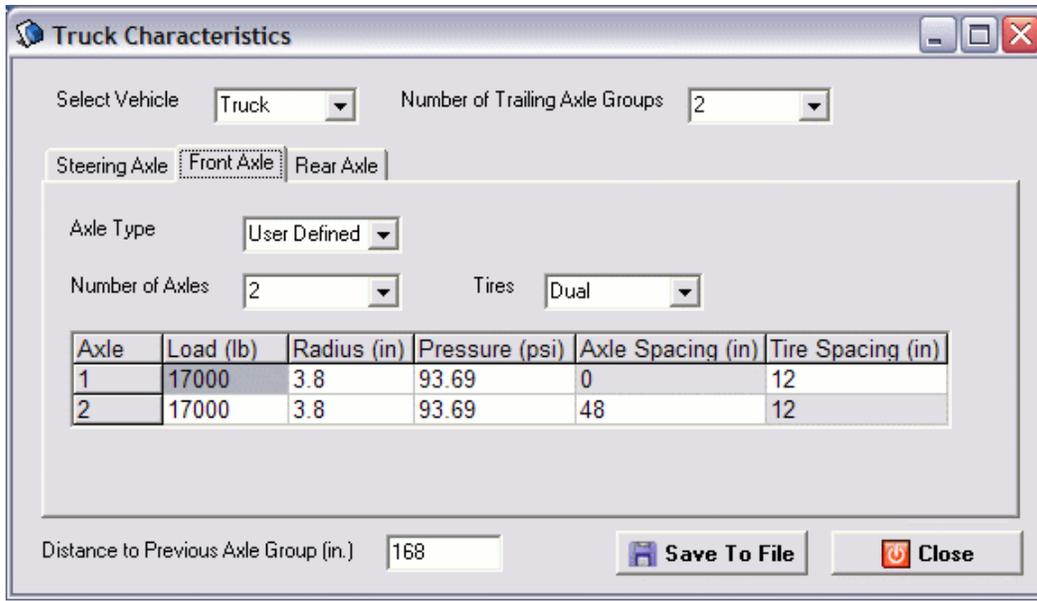


Figure A.32 – Truck characteristics.



Figure A.33 – Analysis type.

The first option, similarly to the flexible pavement, obtains the damage factor based on the equivalent axle load factor for each truck. By clicking in the **AASHTO** button, a new window will be displayed as shown in Figure 34. This window will provide the ratio between the equivalent axle load factors of the analyzed case truck divided by the selected standard truck.



Figure A.34 – Damage factor based on AASHTO formulation.

Selection of the **Fatigue Cracking @ Point** button makes the program to perform a dynamic analysis to obtain the stresses in order to find fatigue cracking at the point that was previously specified by the user on the Slab Properties window (Figure 29). This will provide the damage factor based on fatigue cracking at a unique point as shown in Figure 35.

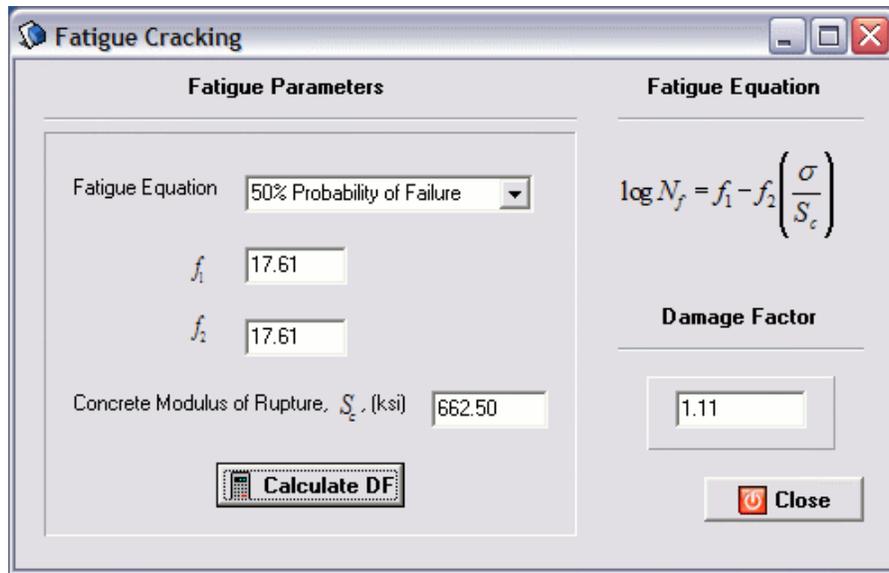


Figure A.35 – Damage factor based on fatigue cracking at user defined point.

The user has the option of changing the fatigue equation as well as the f constants in order to obtain a new damage factor after pressing the **Calculate DF** button, as shown in Figure 36.

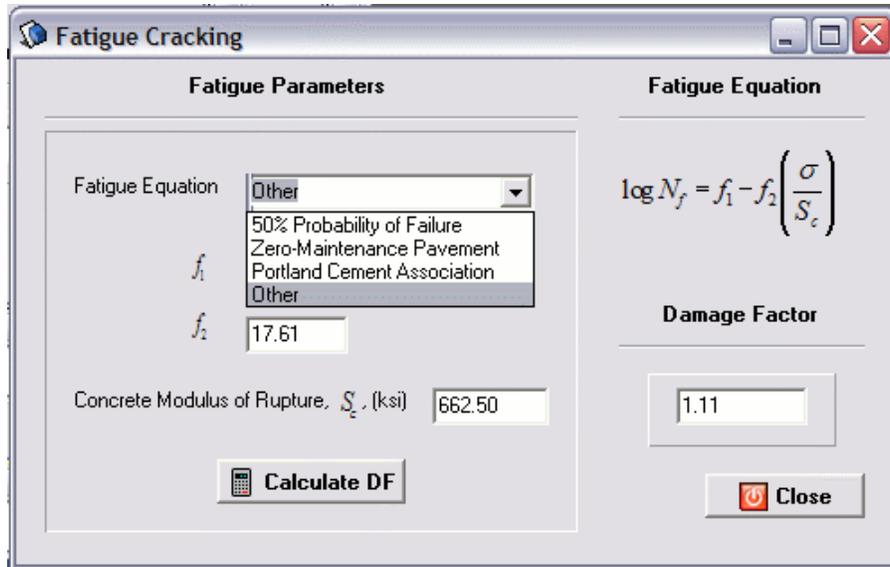


Figure A.36 – Available fatigue equations.

On the other hand, it is possible to obtain the damage factor based on fatigue cracking at the point where maximum stress occurred in the slab by selecting the **Fatigue Cracking @ Slab** option. The maximum stress is obtained after each iteration as the truck passes through the slab, and a comparison is made based on the maximum of them. The same form is presented but a slightly different damage factor is obtained from the maximum stresses (Figure 37).

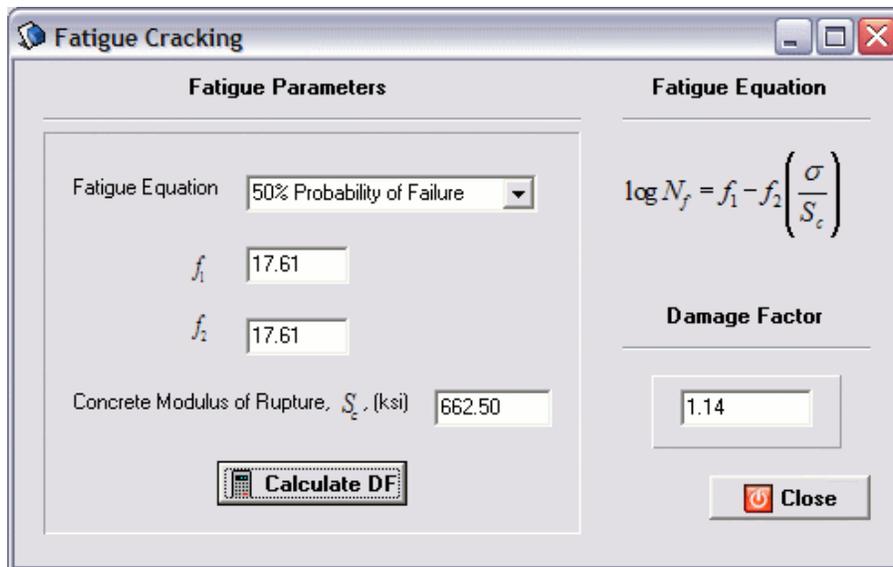


Figure A.37 – Available fatigue equations.

Selecting the **Pumping** option presents the user another window that finds the damage factor based on a ratio of pumping indexes. The user is asked to provide the soil type from a drop-down menu, as well as the annual precipitation and freezing index in order to compute the pumping indexes, as shown in Figure 38.

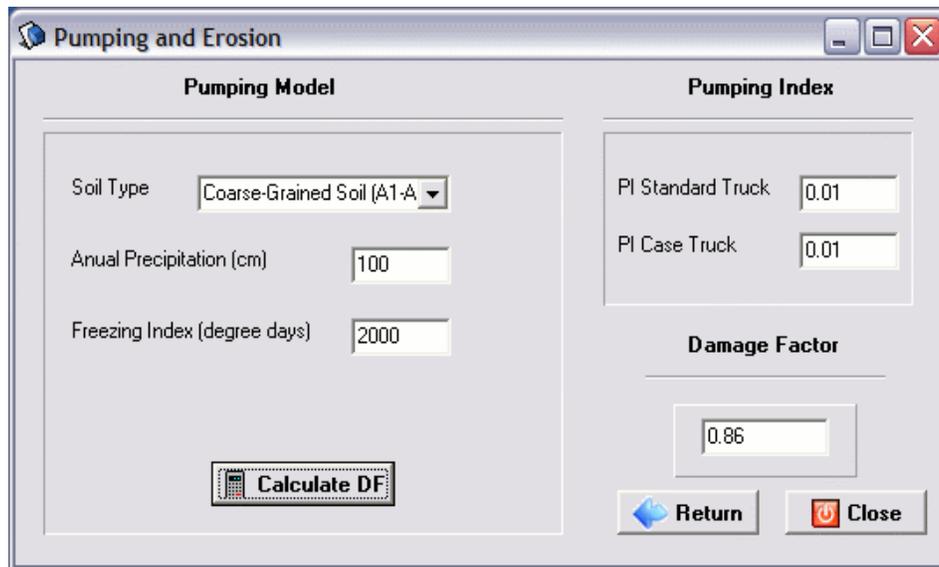


Figure A.38 – Pumping model.

Finally, the last available option consists on the **Faulting** model shown in Figure 39. The damage factor is obtained based on the ratio of maximum faulting of the case truck by the standard truck observed for all dowels as the truck moves through the slab. If the pavement joints lacked dowels then the damage ratio is obtained from a faulting model that utilizes the maximum stresses found through the slab from the dynamic analysis of each truck; however, the user still needs to enter more information needed by the faulting model such as the soil type, subbase erodibility factor, edge support, drainage index and freezing index.

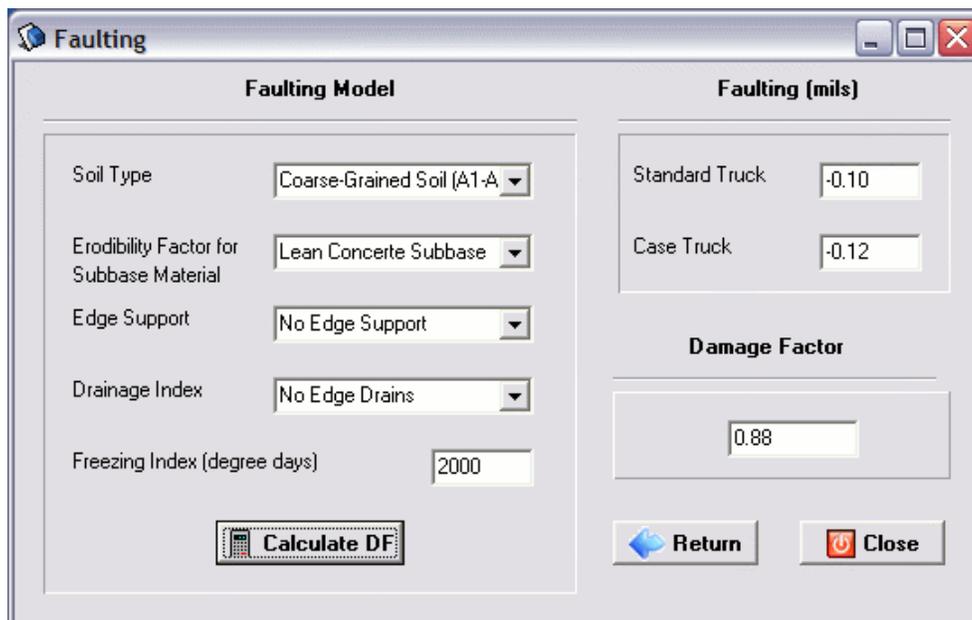


Figure A.39 – Faulting model.

