A MECHANISTIC METHODOLOGY FOR ESTIMATING PERMIT COSTS FOR OVERWEIGHT TRUCKS

Conducted for:

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

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

October 2007

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-05/9-1502-01-9	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Mechanistic Methodology for Estimating Permit Costs for Overweight Trucks		**5. Report Date** October 2007
		6. Performing Organization Code
7. Authors C. Tirado, J.M. Mares, C. Carrasco, N. Gharaibeh and S. Nazarian		**8. Performing Organization Report No.** 9-1502-01-9
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 9/06– 8/07
		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

16. 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 tools to address these issues.

A software package with the capacity to calculate the pavement distress for flexible and 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, a cost module to estimate the cost of permit for heavy trucks based on the mechanistic analysis is added.

17. Key Words Pavement Response, Rutting, Finite Element Analysis, Superheavy Vehicles, Permit Cost.	**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** 79	**22. Price**

Form DOT F 1700.7 (8-69)

DISCLAIMERS

Cesar Tirado, MSCE
Jose Maria Mares, MSIE
Cesar Carrasco, Ph.D.
Nasir Gharaibeh, Ph.D., P.E. (OH 68391)
Soheil Nazarian, Ph.D., P.E. (TX 69263)

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Cesar Tirado, MSCE
Jose Maria Mares, MSIE
Cesar Carrasco, Ph.D.
Nasir Gharaibeh, Ph.D., P.E.
Soheil Nazarian, Ph.D., P.E.

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The Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, TX 79968-0516

ACKNOWLEDGEMENT

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.

The truck size and weight has been an issue of concern to federal and state agencies, and for the general public for many years. Different agencies view the issue of truck dimensions and loads from different perspectives a primary concern is how much more do heavy trucks should pay in comparison to standard trucks since they cause more damage to the pavement. In order to address these issues a methodology was developed. This methodology implemented allows us to calculate the permit fee according to the truck configuration.

A software package with the capacity to calculate pavement distress for 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, a cost module to estimate the cost of permit for heavy trucks based on the mechanistic analysis is added.

IMPLEMENTATION STATEMENT

This study was aimed to develop a methodology to estimate a fee that accounts for the extra damages that heavy or super-heavy trucks may cause to a pavement section.

The outcome of this study is a new software module that calculates the permit fee depending on the truck configuration and pavement structure. The outcomes of the model developed here can be used to more accurately account for the economic impact of the damage caused by the heavy and super-heavy trucks.

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 highway agencies 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 heavy and super-heavy loads on the existing roads, a software package based on finite element models and several well-known damage models has developed as reported in Tirado et al. (2007). To determine the permit fee that a heavy truck should pay, a methodology discussed in this report was developed.

OBJECTIVE AND APPROACHES

The main objective of this research was to develop a methodology to estimate the permit fee for heavy and super-heavy trucks, depending on their axle configuration and pavement structure. A tool was developed to aid in the calculation of the permit fee.

Based on the pavement distress models developed in the previous versions of the software, the potential excess damage due to one pass of a heavy truck is estimated. Based on the pavement structure the number of repetitions to reach a threshold damage considered for rehabilitation is then determined. Through an economic analysis module, the cost of the repair associated with the pass of the heavy truck is estimated. This cost is then assigned as the permit fee.

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 as well as the different performance models incorporated into the graphical user interface program. Chapter 4 discusses the methodology developed to estimate permit fees. In chapter 5 a series of parametric studies are presented to show how the permit fee model behaves under different traffic and pavement section properties. Finally, chapter 6 includes the summary of the work accomplished and the status of the project.

CHAPTER TWO - BACKGROUND

INTRODUCTION

The methodology presented here for estimating the permit fee for super-heavy trucks consists of two major components: 1) a set of mechanistic-empirical pavement performance prediction models, and 2) a cost allocation algorithm. Prediction models are used for forecasting future pavement condition; from which future maintenance and rehabilitation needs and costs are determined. The cost allocation algorithm is then used for estimating the permit fee for super-heavy trucks based on the predicted long-term damage caused by these trucks and estimated cost for repairing the deteriorated pavement.

A review of the state of pavement performance prediction modeling and highway cost allocation methods as they relate to the developed permit fee estimation methodology is presented in the remaining sections of this chapter.

PAVEMENT PERFORMANCE PREDICTION MODELING

Accurate predictions of pavement performance (i.e., distresses) are critical for the results of the developed permit fee estimation methodology to be meaningful. However, the inputs to these models need to be readily available and their computational speed needs to be acceptable. Generally, mechanistic-empirical (M-E) models tend to meet these criteria. In these models, mechanical responses (e.g., stress or strain) are computed using methods such as finite-element analysis based on engineering and material properties (e.g., modulus of elasticity), loading, climatic effects, and pavement structure. The mechanical responses are correlated to field distresses through empirical models. Several M-E models have been developed in the past decade for both asphalt and concrete pavements. The most recent set of M-E models for asphalt and concrete pavements has been developed under the NCHRP 1-37A project and calibrated using national field data obtained from the Long-Term Pavement Performance (LTPP) program. While these models appear to be promising, they are still being evaluated by the pavement community. Thus, several models were considered and a set of well-established models (including some from the NCHRP 1-37A project) were selected for this study. The mathematical details of these models are discussed in Chapters 3 and 4.

HIGHWAY COST ALLOCATION

The fact that the highway system accommodates a vast variety of vehicles serving a multiplicity of uses has led to the development of highway cost allocation studies that seek to distribute highway costs equitably among all groups (e.g., vehicle classes) of users. The theoretical foundation of the proposed methodology for assessing super-heavy permit fees stems from the principles of these studies.

Highway Cost Allocation Studies (HCASs) have been conducted at the Federal and State levels to compare the expenses that various groups of highway users necessitate to provide and maintain the highway infrastructure to the revenues that each group generates.

All Federal and most State HCASs use the cost-occasioned approach for the allocation of highway development, maintenance, and operation costs. Under this approach, each user pays the highway costs that it creates or "occasions." Although the philosophy of this approach appears logical, it is controversial in terms of what costs to consider. The cost-occasioned approach is widely used because it promotes an economically efficient allocation of scarce resources (ECONorthwest 2007). The principal alternative to the cost-occasioned approach is the benefits approach. Under the benefits approach, the greater the benefits, the greater the share of user fees a vehicle class pays, regardless of its contribution to highway costs (Boilé et al. 2001).

Within the cost occasioned approach, the most common method for allocating costs to different vehicle classes is the incremental method. Under this method, the minimum design (considered adequate for light vehicles only) is considered a common responsibility of all highway users and shared by all vehicle classes based on common measures such as vehicle miles traveled (VMT). The costs of the pavement's extra thickness required to carry heavy vehicles and the cost of load-related repairs are allocated based on standard 18-kip single axle load (ESAL) or VMT-weighted ESAL.

In 1982, the Federal Highway Administration (FHWA) conducted the first comprehensive HCAS, under which mechanistic-empirical distress prediction models were developed to estimate the amount of damage that different vehicle classes and the environment cause to the pavement (FHWA 1997). The 1982 HCAS was refined in 1997 and new mechanistic-empirical distress prediction models were developed and used in the current nationwide pavement cost model (NAPCOM) for allocating highway costs (FHWA 1997). In 2000, an addendum to the 1997 HCAS was completed to include estimates of air pollution-related costs attributable to highway use by motor vehicles.

At the State level, several State Departments of Transportation (DOTs) have conducted highway cost allocation studies to address their local highway systems and conditions. Examples of these studies include the 1999 Arizona Simplified Model for Highway Cost Allocation Studies (Arizona SMHCAS) (Carey 1999), the 1998 and 2007 Oregon cost-responsibility study (Stower et al. 1999; ECONorthwest 2007), the Indiana 1983 and 1988 highway cost allocation studies (Sinha and Fwa 1987; Fwa et al. 1990), the Georgia 1979 and 1981 highway cost allocation

studies (GDOT 1979; GDOT 1981), and the Minnesota 1990 highway cost allocation study (MnDOT 1990). The Oregon, Georgia and Minnesota studies use the Federal HCAS procedures, and the Indiana and Arizona studies use a simplified version of the Federal HCAS procedures. The details of these State studies can be found in the cited references and a summary of all of them can be found in Boilé et al. (2001).

Generally, highway cost allocation studies have been devised to resolve the complicated distribution of revenues and expenses among different groups of highway users and assess the equity of highway user tax structures (Boilé et al. 2001). These studies provide an opportunity for assessing the cost of permit fees for super-heavy loads based on a sound theory. The proposed methodology applies HCAS principles, in conjunction with new models, to generate realistic estimates of permit fees for super-heavy loads that is based on the allocation of pavement damage and cost of repair for any given pavement segments. This methodology is described in Chapter 4 of this report.

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 materials (especially granular bases and subgrades) under actual traffic loads.

For this reason 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. In addition, the analysis of rigid pavements distress is done using JSLAB2004 processor, a finite element program developed by others for jointed concrete pavements.

A graphical user interface (GUI) called "Integrated Pavement Damage Analyzer" (IntPave) was developed to facilitate the input of pavement section properties and traffic load. This software integrates the finite element programs to calculate both flexible and rigid pavement response. The graphical user interface was developed on Visual C++ code. See Appendix A for a thorough description of the 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 calculate pavement distress. The finite element program has the capability of performing an analysis in both two- and three-dimensions. Using an open source pre/post processor called GMSH, it was possible to create a 2-D mesh with triangular elements for an axisymmetric model, and a 3-D mesh using four-node tetrahedral elements, as shown in Figure 3.1. In both cases the mesh becomes more refined in the proximity of load application points, namely the tire contact areas.
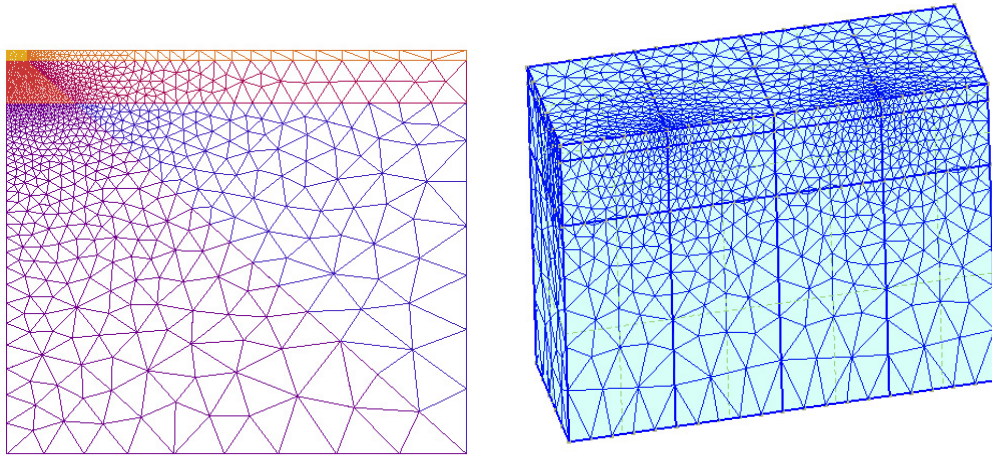
Figure 3.1 – 2-D and 3-D mesh with element refinement transition.

CONSTITUTIVE MODELS

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 type of analysis, the nonlinear constitutive model used in the FEA program considers a stress dependent modulus. This constitutive model developed by Barksdale, *et al.* (1994) has shown good correlation with experimental data for both fine and coarse grained base and subgrade materials,

$$E = k_1 \sigma_c^{k_2} \sigma_d^{k_3} \tag{3.1}$$

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. Since the state of stress can only be known if the material properties are known, an iterative process is necessary to implement the 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, 2004). JSLAB is a 2-D structural finite element rigid pavement analysis program that uses a mesh of four-node, 12 degrees-of-freedom elements.

Integrating the finite element processor of JSLAB2004 (Galaxy Scientific Corporation, 2004) into IntPave's 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 leaving several of the modeling parameters as default. 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 3.2. 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.
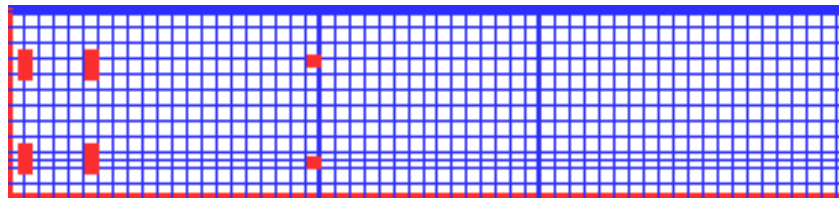
Figure 3.2 – 2-D mesh for 3-slab system for a truck consisting of a tandem dual axle and single axle single tire combination.

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.

DISTRESS MODELS

Several distress models were implemented in IntPave to calculate pavement damage. In the case of flexible pavements rutting and fatigue cracking were taken into consideration. For rigid pavements fatigue cracking and faulting models based on the JSLAB2004 capabilities for calculating stresses and deformations were also incorporated. 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 includes 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. The comparative analysis process seeks to get a damage factor based on a type of distress 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.

Calculation of rutting requires the number of load repetitions as well as α and μ material parameters measured in laboratory which are the rate of increase in permanent deformation against the number of load applications and the permanent deformation, respectively. A sample rutting response to a standard 80-k truck of a State Highway pavement consisting of a 3-in. 500 ksi asphalt concrete pavement, a 12-in. 50-ksi base, and a 10-ksi subgrade, is shown in Figure 3.3. On the other hand, fatigue cracking is obtained through the Asphalt Institute MS-1 model. Alligator fatigue cracking is assumed to be generated from tensile strains ε_t occurring at the bottom of the asphalt layers (bottom-up cracking). Both rutting and fatigue cracking models are thoroughly explained in Tirado et al. (2007).
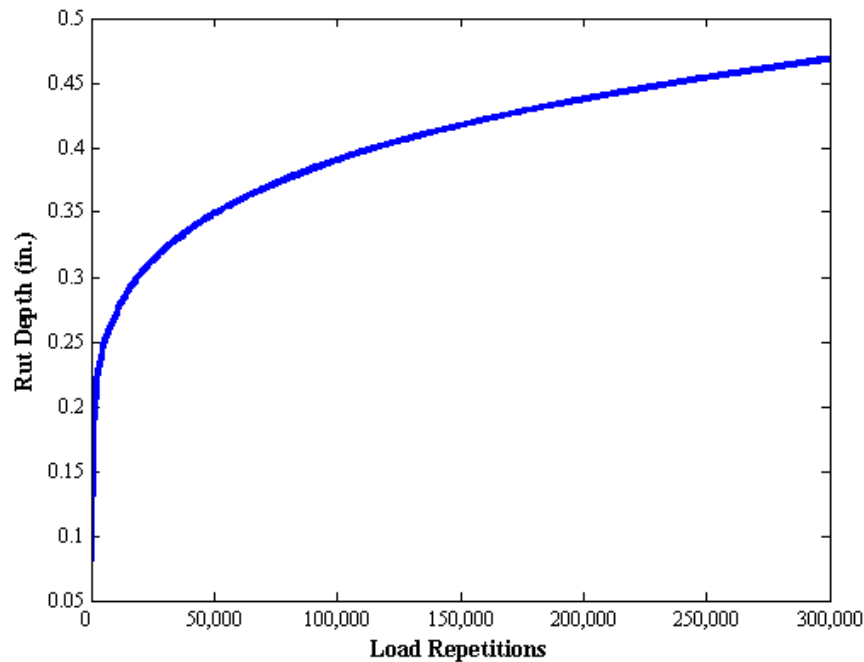
Figure 3.3 – Rutting for a typical state highway to a standard 80-k truck.

Rigid Pavements

Various distress models were incorporated into IntPave to analyze rigid pavements. The models included the AASHTO, fatigue cracking, pumping and faulting. All these models are implemented into the comparative analysis. The fatigue cracking model implemented for obtaining the damage generated by a truck based is defined by the allowable number of repetitions, expressed in terms of flexural stress and concrete's modulus of rupture. 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 while the second option is based on the point where the maximum stress occurs within the slab. In both cases, the slab are analyzed at different locations to simulate the movement of the 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 to reach are calculated and compared to obtain a damage factor. Figure 3.4 presents IntPave's window for calculating these damage factors for rigid pavements based on fatigue cracking. A similar process is involved for faulting and pumping. Thorough explanation of these models is found in Tirado et al. (2007).

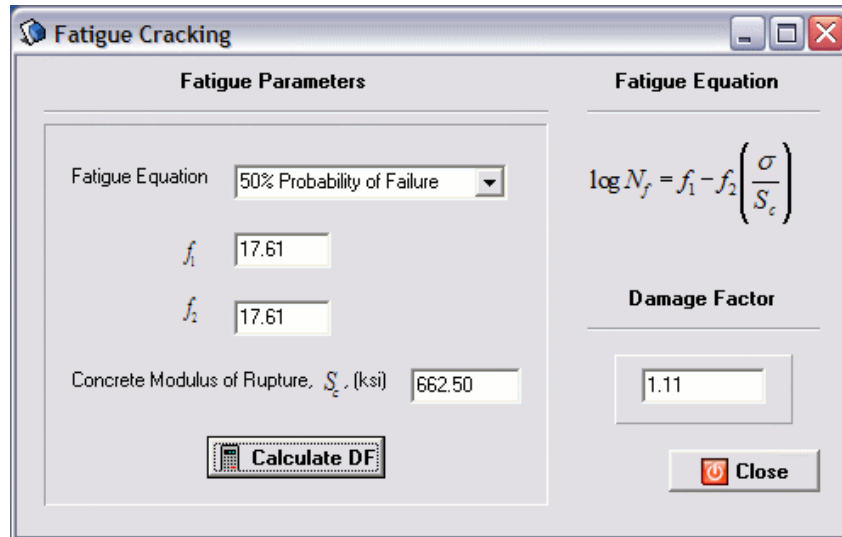**Figure 3.4 – Rigid pavement fatigue cracking evaluation in IntPave.**

CHAPTER FOUR - PERMIT FEE ESTIMATION METHODOLOGY

In the United States, trucking accounts for about 80 percent of freight transportation (TRB 2002). At the Federal level, trucks are considered "legal" provided they meet weight guidelines of the 1975 Federal Bridge Formula B. However, vehicles operating on the state and local highway system are not subject to Federal Formula B limits. Additionally, at least 30 states permit exceptions to the Interstate System axle load limits or gross weight limits either with or without special permits (Sivakumar et al. 2007). In Texas, for instance, a gross vehicle weight (GVW) that exceeds 250,000 lb (115,500 kg) is considered "super-heavy load" and requires a permit before traveling on a state-maintained roadway system (Chen et al. 2005). The number of these permits issued by any given State can be significant. For example, in 2002, TxDOT issued 364 super-heavy load permits. Typically, these permits are requested to transport loads such as transformers, generators, or combustion turbines.

Generally, the permit fee for super-heavy loads is established to recover administrative costs of issuing the permit (such as load inspection costs and permit processing fee). What is lacking is a formal, yet practical, methodology to aid highway agencies in determining permit fee for super-heavy loads considering the cost of repairing highway infrastructure due to the extra long-term damage that these loads cause. A simple engineering-economic methodology for estimating the permit fee for super-heavy trucks is presented here.

As shown in Figure 4.1, the permit fee is estimated based on the predicted long-term damage caused by super-heavy loads and estimated cost for repairing the deteriorated pavement. The cost of repair is allocated based on the extra damage caused by the passing of a super-heavy vehicle compared to the damage caused by a standard truck (e.g. an 80-kip T3S2 truck).
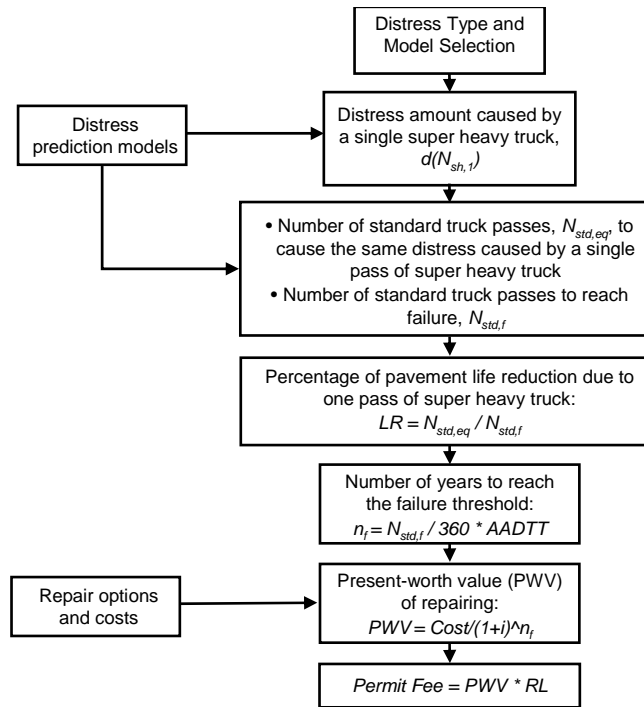
Figure 4.1 – Methodology for estimating super-heavy truck permit fees.

The steps required to calculate the permit fee are discussed as follows:

Step 1: Define key pavement distress types for long term assessment, such as rutting for flexible pavements or fatigue cracking for rigid pavements and select appropriate models for predicting these distresses.

Step 2: Using the selected distress prediction models, estimate the distress amount caused by a single super-heavy truck, $d(N_{sh,1})$.

Step 3: Using the same distress prediction models, estimate the number of standard truck passes, $N_{std,eq}$, to cause the same distress caused by a single pass of super-heavy truck, $d(N_{sh,1})$ and the number of standard truck passes to reach failure, $N_{std,f}$.

Step 4: The percentage of pavement life reduction due to one pass of super-heavy truck (LR) is then calculated as a ratio of $N_{std,eq}$ over $N_{std,f}$.

Step 5: The pavement design life is (i.e., number of years to reach the failure threshold, n_f) is calculated.

Step 6: The present-worth value (PWV) of repairing the pavement when the failure threshold is reached. Repair strategies are defined by the user based distress thresholds. For instance the user can specify a 3-in mill-and-overlay repair for asphalt pavement when rutting reaches a threshold value of 0.3 in. Example repair methods and their typical unit prices are shown in Table 1. These repair methods and average unit prices were obtained from TxDOT's Average

Low Bid Unit Price database for 2006-2007 (see http://www.dot.state.tx.us/business/Avgd.Htm); and thus may not necessarily be applicable to other agencies.

Table 4.1 - Typical pavement repair methods and unit prices.

Pavement Type	Repair Method	Unit Price
Flexible Pavement	Cold-milling (1-3 in)	2.5 $/SY
	Cold-milling (> 3 in)	5 $/SY
	HMA overlay (virgin materials)	65.88 $/ton
	HMA overlay (reclaimed materials)*	59.88 $/ton
Rigid Pavement	Diamond Grinding	4.00 $/SY
	Full-depth Repair	21.25 $/SY/in.
	HMA overlay (virgin materials)	65.88 $/ton
	HMA overlay (reclaimed materials)	59.88 $/ton

*using TxDOT's estimate of $6 saving compared to virgin material.

Step 7: The permit fee is calculated by multiplying the life reduction ratio times the PWV of pavement repair.

$$Permit\ fee = PWV \times LR$$

ILLUSTRATIVE EXAMPLE

To demonstrate the developed methodology, it was applied to determine the permit fee for a 160-kip truck, traveling on the following example pavement sections:

- Interstate Highway (IH): The pavement design consists of 10-in HMA layer, 12-in base, over subgrade.
- U.S. Highway (US): The pavement design consists of 6-in HMA layer, 12 in. of base over subgrade.
- State Highway (SH): The pavement design consists of 3-in HMA layer, 12 in. base over subgrade.
- Farm-to-Market Road (FM). The pavement design consists of 1-in HMA layer, 10-in. base over subgrade.

The modulus of the HMA was assumed to be 500 ksi for all road types except the FM road where a modulus of 300 ksi was used. Similarly, the modulus of the base was assumed to be equal to 50 ksi except for the FM road where a modulus of 30 ksi was used. Finally, a modulus of 10 ksi was assumed for the subgrade for all cases.

For all cases, the methodology was applied considering rutting only as the critical distress type. This is because these pavements are likely to fail due to rutting (i.e., the rutting threshold is likely to be reached earlier than reaching the thresholds of other distresses). The VESYS model as described in Huang (2004) was implemented in a finite element code for predicting rutting. The details of the code can be found in Tirado et al. (2007).

Table 4.2 shows the results of applying the developed methodology to each of the above pavement types. The computations performed to arrive at these results are explained on a step-by-step basis for the case of 160-kip super-heavy load traveling on an IH pavement. These computations can be performed in the same manner for any other type of pavement and super-heavy truck.

Table 4.2 - Permit fee estimation for 160-kip super-heavy truck traveling on example pavement sections.

Parameter	IH Section	US Section	SH Section	FM Section
$d(Nsh,1)$, in.	0.085	0.095	0.107	0.118
$N_{std,eq}$, passes	21	14	9	6
$N_{std,f}$, passes	2,229,325	505,300	101,504	29,025
LR	0.0009%	0.0028%	0.0089%	0.0207%
n_f, year	4.5	1	0.2	0.06
Permit Fee, $/Lane-mile	0.65	1.94	7.01	16.36

Step 1: As mentioned earlier, rutting is used as the critical failure mode and IntPave was used for predicting rutting.

Step 2: As shown in Figure 2, the rutting amount caused by a single pass of 160-kip truck is 0.085 in (i.e., $d(Nsh,1) = 0.085$ in).

Step 3: As shown in Figure 4.3, the number of standard truck passes, $N_{std,eq}$, to cause 0.0853 in. is 21 passes (i.e., $N_{std,eq} = 21$ passes). The number of standard truck passes to reach failure is 2,229,325 passes (i.e., $N_{std,f} = 2,229,325$ passes).

Step 4: The percentage of pavement life reduction due to one pass of a 160-kip super-heavy truck (LR) is then calculated as: LR = $N_{std,eq} / N_{std,f} = 21/2,229,325 = 0.0009\%$

Step 5: The pavement design life is assumed to be 4½ years (i.e., $n_f = 4.5$ years).

Step 6: In this example, a repair option of mill-and-overlay and a discount rate of 3 percent were used. The unit costs and quantities are as follows:
- Milling thickness = 2.0 in.
- HMA Overlay Thickness = 3.0 in.
- Cost of Milling = $1.5/S.Y.
- Cost of HMA Overlay = $65.88/ton
- Lane width = 12 ft

The PWV of this repair option is computed as: $PWV = C/(1+i)^{n_f} = \$69,336$ per lane-mile.

Step 7: The permit fee is calculated as follows:

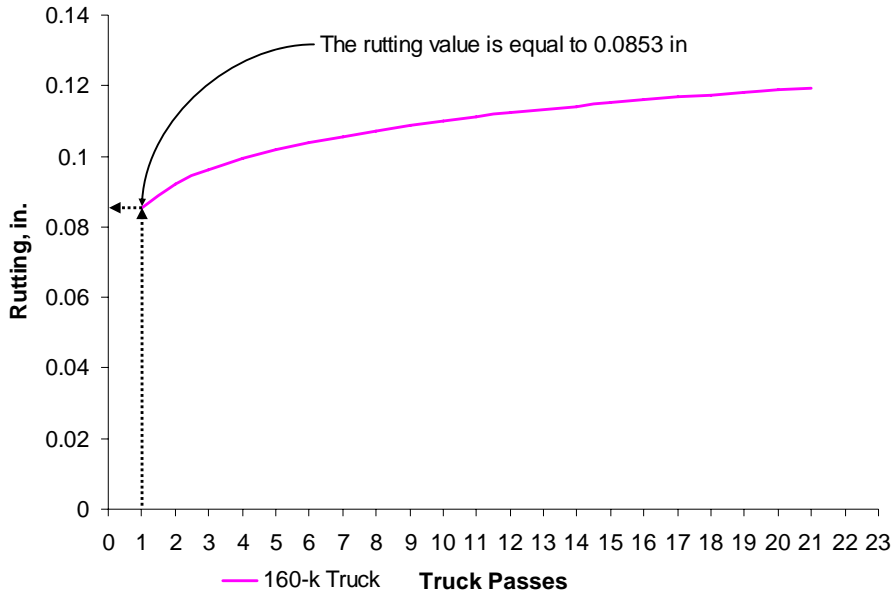$$Permit\ fee = PWV \times LR/100\% = \$0.65\ per\ lane\text{-}mile$$

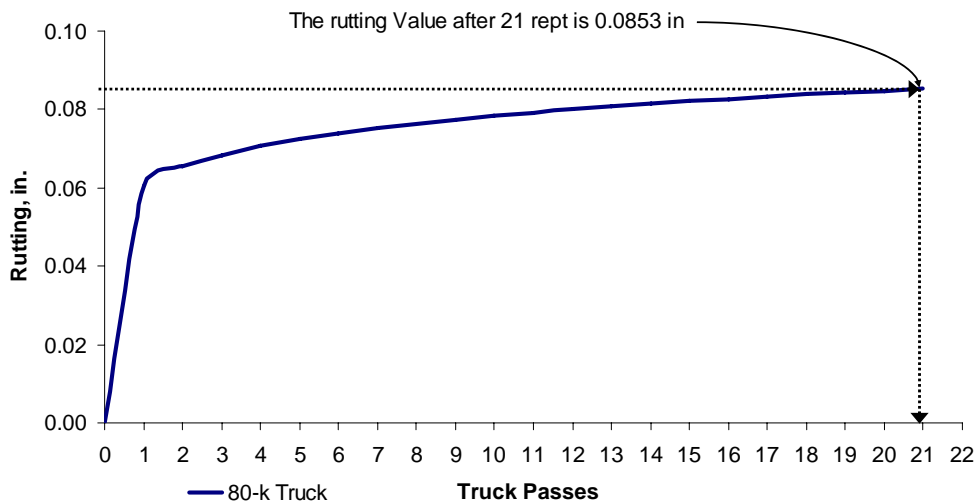**Figure 4.2 – Rutting vs. truck passes for super-heavy 160-kip truck.**

Figure 4.3 – Rutting vs. truck passes for standard 80-kip.

In Texas, fees for single-trip permits for super-heavy vehicles and loads are shown bellow.

- Permit: $125
- Maintenance: $30
- Vehicle Supervision: $100-500 (depending on required pavement analysis and if the truck crosses bridges)

Thus, the total permit fee is $255 to $655. For the above example, dividing the total fee of $255 to $655 by the unit cost of $0.65/mile results in a trip distance of 392 to 1007 miles.

CHAPTER FIVE - PARAMETRIC STUDY

This chapter contains sensitivity analyses on the model used to assess the permit cost methodology for super heavy trucks. Some of the design parameters (such as the acceptable rutting threshold for rehabilitation, the gross vehicle weight and the number of years to reach failure) and pavement structural parameters (such as the thickness and moduli of different layers) were varied to study their impact of the cost of permit.

BASIC ASSUMPTIONS

A three layer flexible pavement system, as shown in Figure 5.1, is considered in this study as the control section. The hot mix asphalt (HMA) layer is 3 in. thick, with a modulus of 500 ksi. The base layer is 12 in. thick, with a modulus of 50 ksi, and the subgrade with a modulus of 10 ksi. Other relevant properties are shown in the figure.

HMA	$E = 500$ ksi, $H = 3$ in., $\nu = 0.33$, $\alpha = 0.78$, $\mu = 0.25$
Base	$E = 50$ ksi, $H = 12$ in., $\nu = 0.33$, $\alpha = 0.75$, $\mu = 0.40$
Subgrade	$E = 10$ ksi, $\nu = 0.33$, $\alpha = 0.90$, $\mu = 0.40$

Figure 5.1 – Control pavement section.

The control truck considered was a standard 80-kip truck as shown in summarized in Table 5.1. The variation in the rut depth with the number of passes of the control truck is shown in Figure 5.2. The rehabilitation of the project should be initiated after 1.5 million passes of the control truck, considering an accumulated rut depth of 0.5 in. as the threshold for rehabilitation. Considering the average period to rehabilitation of five years, and assuming that the pavement is designed

Table 5-1 Truck configurations considered in this study.

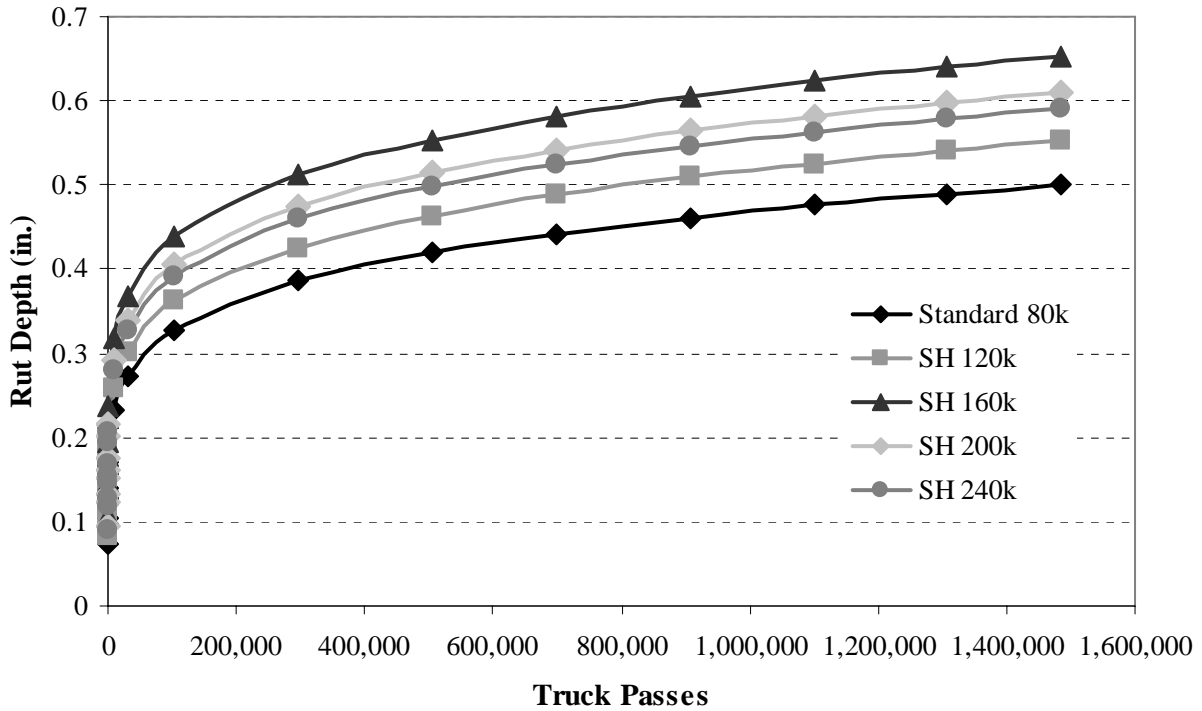| Truck	80-k (Control)	120-k	160-k	200-k	240-k
Steering Axle (lbs)	12,000	12,000	12,000	12,000	12,000
Tandem Axle (lbs)	34,000	38,000	36,000	38,000	36,000
Trailing Axle (lbs)	34,000	70,000	112,000	150,000	192,000
Trailing Axle Type	Tandem	Quad	Trunnion	Trunnion	Trunnion
Truck Configuration					
Empty Vehicle Weight (kips)	33	37	37	41	45
Cargo [Payload] (kips)	47	83	123	159	195

Figure 5.2 – Variations in rut depth with number of passes of control standard truck and heavy trucks considered for control pavement section.

properly, an average annual standard truck traffic of 300,000 was assigned as control traffic volume for this case study.

The repair strategy considered for this case study is milling 2 in. and a 3 in. overlay, with an assumed average cost of $12.25 /yd^2. A discount rate of 3% is assumed throughout this study.

Four other truck configurations are considered as heavy trucks. The gross vehicle weights of these trucks vary from 120 kip to 240 kips. The axle configurations of the trucks, as reflected in Table 5.1, were adjusted so that they were considered legal under current regulations. The details of each truck type can be found in Appendix B. The truck with a gross vehicle weight of 160 kips was used as the control heavy truck. Unless otherwise noted, this truck was used in the parametric study. The variations in the rut depth with the number of passes of the four heavy trucks are also included in Figure 5.2. Based on the algorithm described in the previous chapters, one pass of the 160-kip (control) heavy truck is equivalent to 14 passes of the standard truck.

With the assumed conditions described above, the costs of permit for the four heavy trucks are shown in Figure 5.3. For the control heavy truck the estimated cost is $1.93/mile. For the trucks with the gross vehicle weights of 200 and 240 kips, the costs of permit are lower than 160-kip truck simply because based on the current interpretation of the legal axle loads, the 160-kip truck legally can exert more pressure per tire than the other two heavier trucks.
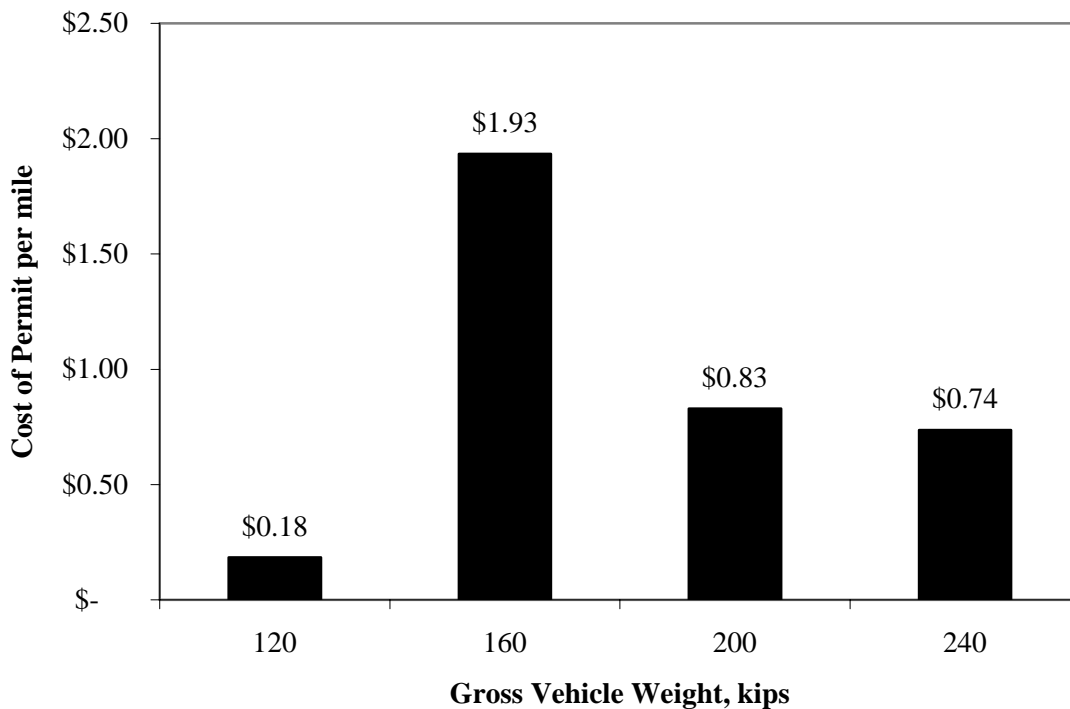

Figure 5.3 – Impact of rutting threshold to rehabilitation on permit cost.

PARAMETRIC STUDY

A number of parametric studies carried out by changing different parameters from the control condition. The results of these studies are summarized below.

Impact of Threshold to Rehabilitation

The assumed threshold to rehabilitation has an exponential impact on the cost of permit. As the rutting threshold is increase from 0.3 in. to 0.9 in., the cost of permit decreases from about $50/mile to almost zero (Figure 5.4). Therefore, the selection of a realistic threshold is necessary.

Impact of Over/Under Designing Highway

Let us assume that the estimated traffic volume on the road is more or less than the design traffic volume. For this exercise, we assumed that the actual AADT is about 30% more (time to rehabilitation of 3 yrs) or half the design AADT (time to rehabilitation of 10 years). As shown in Figure 5.5, the cost of permit somewhat decreases as the traffic volume decreases. Should the rate of increase in the cost of construction is greater than the interest rate, the trend would reverse. It seems that the assumption of 5 years for rehabilitation seems reasonable.
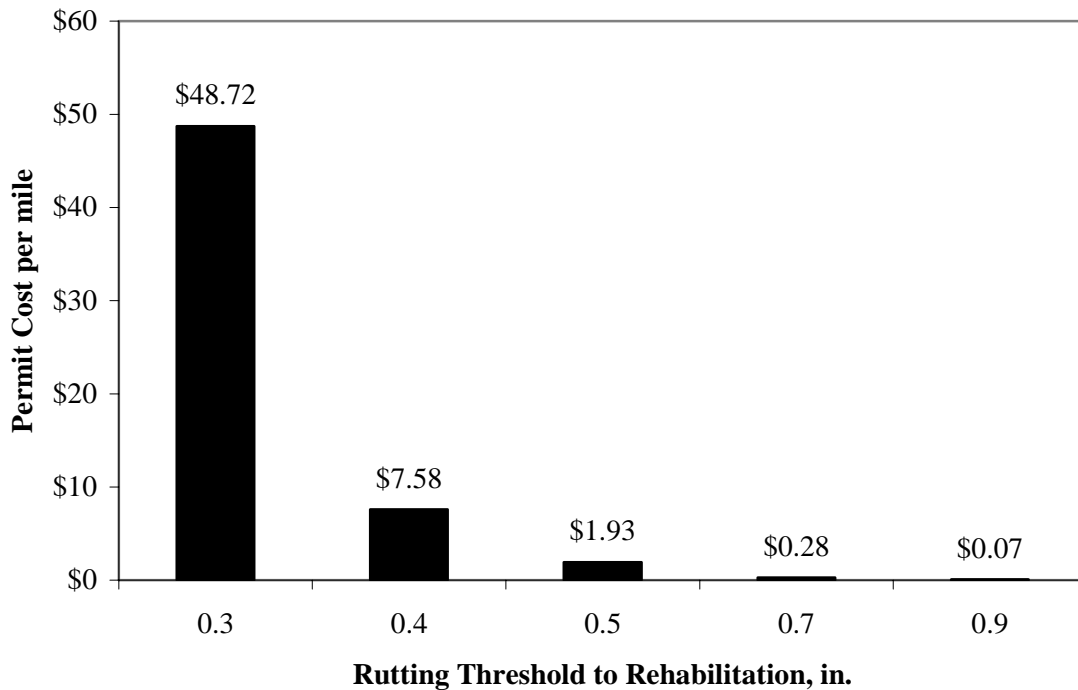

Figure 5.4 – Impact of rutting threshold to rehabilitation on permit cost.
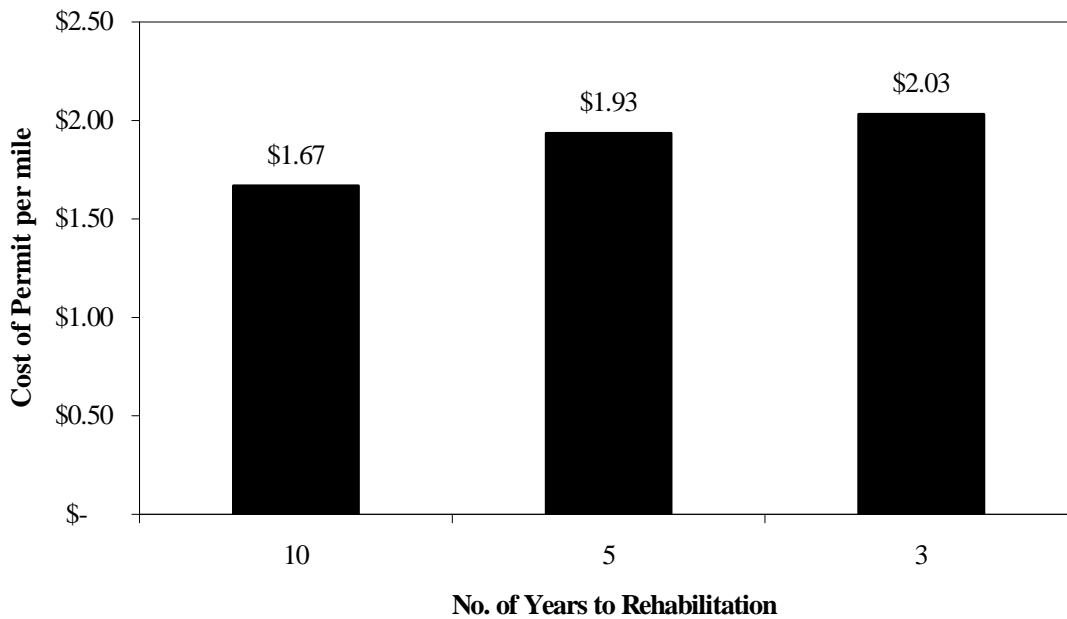
Figure 5.5 – Impact of mis-estimation of traffic volume on permit cost.

Impact of Pavement Structure

For a mechanistic permit cost analysis, the pavement structure plays an important role. For example, the impact of the thickness of the HMA layer thickness on the permit cost is demonstrated in Figure 5.6. All other structural parameters are maintained to their control values. For each HMA thickness the volume of traffic is adjusted to yield a period of five years to rehabilitation. The thicker the HMA layer is, the lower the cost of permit will be.

The impact of the base thickness on the permit cost, estimated in the same manner as for the HMA, is shown in Figure 5.7. For the control base, as the thickness of the base increases the cost of permit increases as well. This counter-intuitive trend occurs because the control base is not as high a quality as it should be. As the base becomes thicker, the rutting of the base becomes more sever, even though the rutting of subgrade becomes less (investigated but not shown). For comparison purposes, the cost of permit as a function of base thickness for a semi-rigid base (modulus of 225 ksi) is also shown in Figure 5.6. In this case, the contribution of base to total rutting is small. As such, the cost of permit decreases to about 10 cents/mile.

In the same manner, the moduli of the HMA, base and subgrade are perturbed in Figure 5.8. As the modulus of the HMA increases, the cost of permit decreases (Figure 5.8a). The increase in the modulus of the base has a drastic impact in the cost of permit as well (Figure 5.8b). As the base modulus decreases from 225 ksi (semi-rigid) to 25 ksi (very low quality) the permit cost increases from 9 cents/mile to over $6/mile. As reflected in Figure 5.8c, the modulus of subgrade is also very important. For a stiff (modulus of 30 ksi) subgrade the cost of permit is about 9 cents/mile, but on a very soft subgrade (modulus of 5 ksi) the cost is over $40/mile.
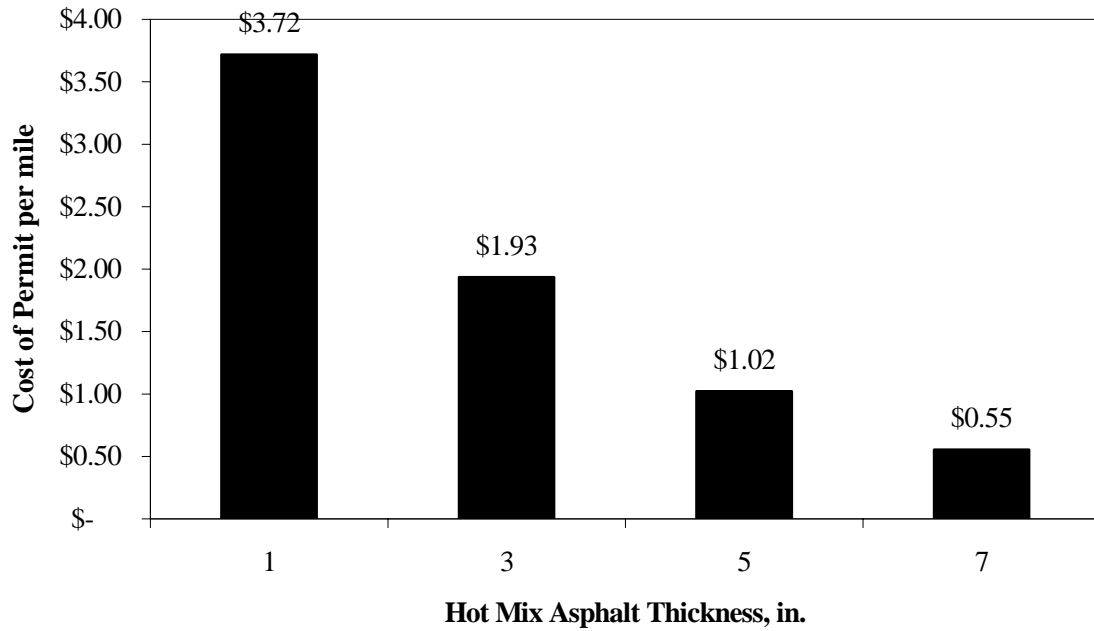
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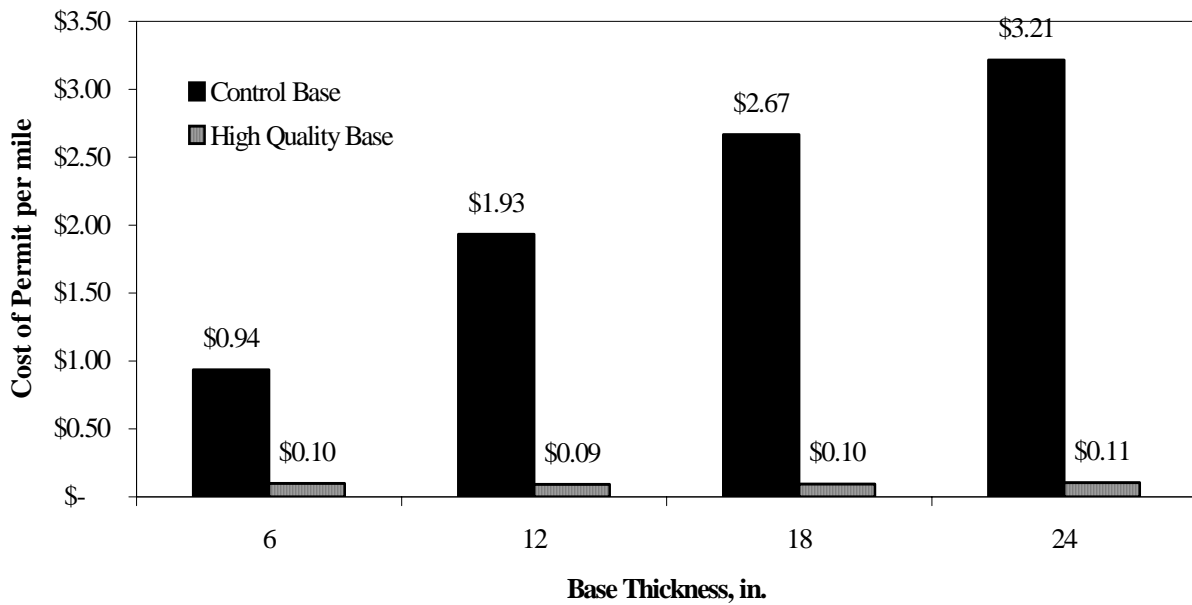**Figure** 5.6 – **Impact of hot-mix asphalt thickness on permit cost.**

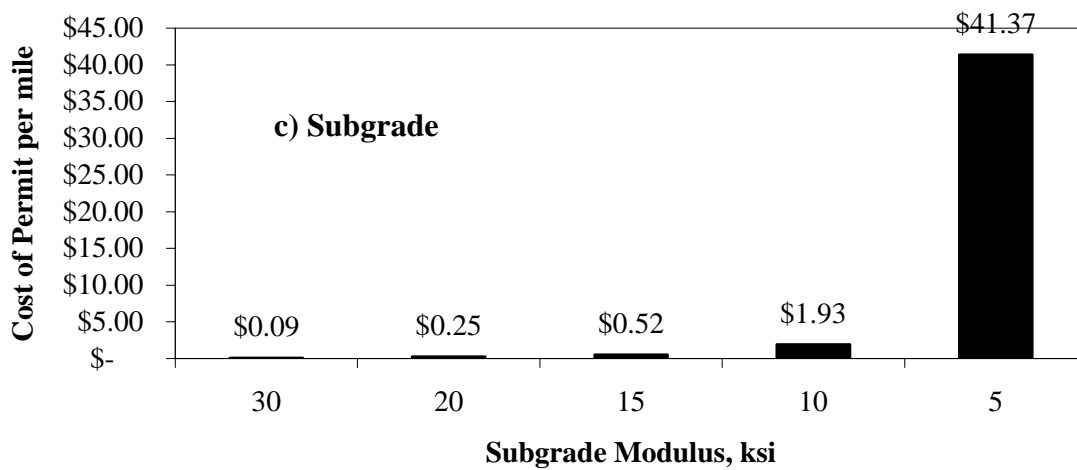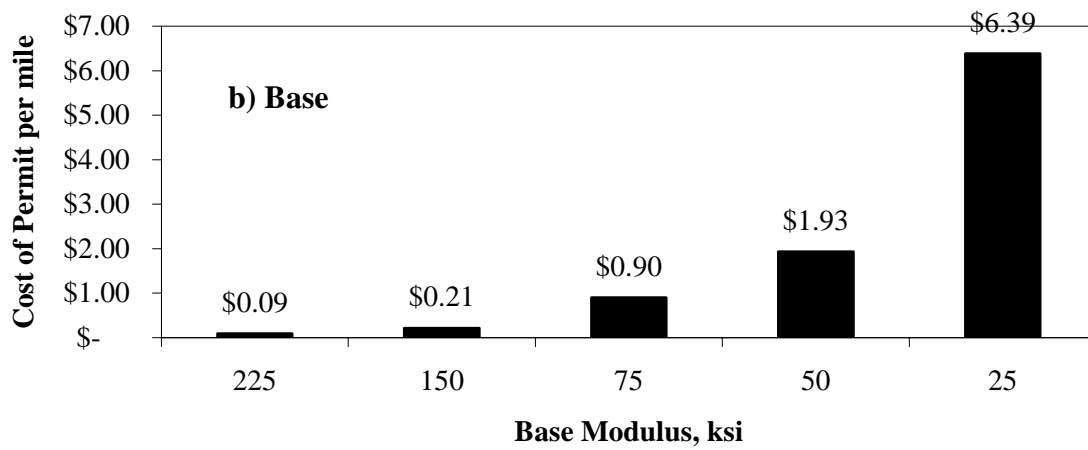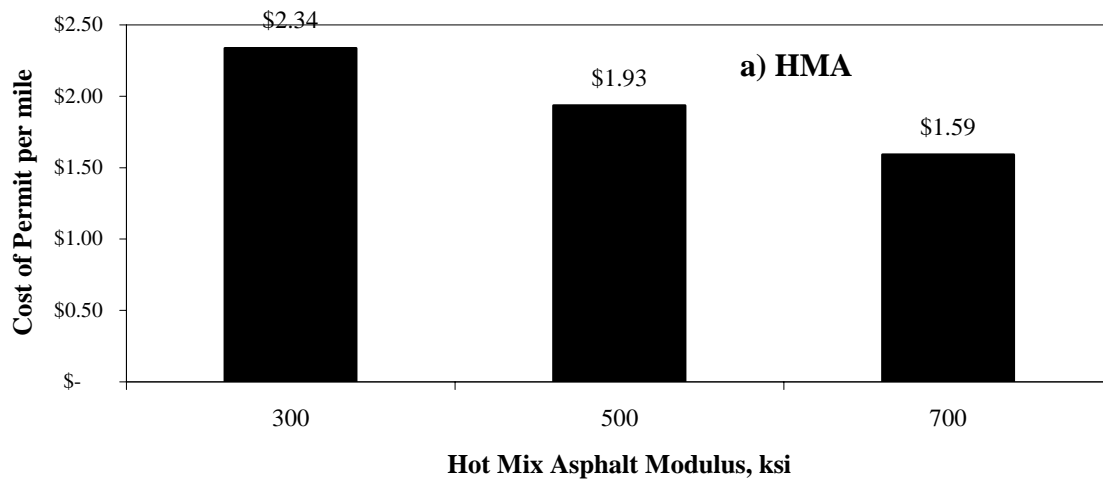**Figure 5.7 – Impact of base thickness on permit cost.**

Figure 5.8 – Impact of layer moduli on permit cost

CHAPTER SIX - SUMMARY AND CONCLUSIONS

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.

The finite element analysis program used to estimate distress on flexible pavements was developed in Matlab and is included in the IntPave software. For rigid pavements the processor of JSLAB was incorporated into IntPave, to predict pavement response.

A methodology was developed to estimate permit fees for the movement of supper heavy trucks. This methodology is based on the estimation of how pavement distress affects the remaining life of flexible and rigid pavements. This change in remaining life is transformed to a permit fee based on the present-worth value of repairing the pavement. This methodology has been implemented in IntPave with a user friendly interface.

REFERENCES

Barksdale, R.D., Alba, J., Khosla, P.N., Kim, R., Lambe, P.C., and Rahman, M.S. (1994). Laboratory Determination of Resilient Modulus for Flexible Pavement Design. Interim Report Project 1-28, FHWA, U.S. Department of Transportation, Washington, DC, 1994

Boilé, M., Ozbay, K., Naraynan, P. (2001). Infrastructure Costs Attributable to Commercial Vehicles, FHWA-NJ-2001-030, Center for Advanced Infrastructure & Transportation (CAIT), Rutgers, The State University, December 2001.

Carey J. (1999). Implementation of the Simplified Arizona Highway Cost Allocation Study Model. Arizona Department of Transportation. Phoenix, Arizona. June 1,1999

Chen, D-H, Bilyeu, J., and Chang, J-R. (2005). "A Review of the Superheavy Load Permitting Program In Texas," The International Journal of Pavement Engineering, Vol. 6, No. 1, March 2005, 47–55.

ECONorthwest (2007). Highway Cost Allocation Study 2007-2009 Biennium, Prepared for the Oregon Department of Administrative Services, Office of Economic Analysis, January 2007.

Federal Highway Administration (FHWA). (1997). 1997 Federal Highway Cost Allocation Study: Final Report. U.S. Department of Transportation, FHWA, Web Document http://fhwainter.fhwa.dot.gov/policy/hcas/final/index.htm. Accessed July 24, 2007.

Fwa T.F, Sinha, K.C., and Saha, S.K. (1990). Update Analysis of Highway Cost Allocation. *Transportation Research Record* 1990. No. 1262. p 1- 11.

Galaxy Scientific Corporation (2004). "JSLAB2004 User Manual Upgrade Supplement," Final Report, 203, FHWA National Pooled Fund Study 2. Federal Highway Administration, Washington, D.C.

Georgia Department of Transportation (GDOT). (1979). Georgia Highway Cost Allocation Study. Special Report. Research and development Bureau. Office of Materials and Research. Georgia Department of Transportation. Atlanta, Georgia.

Georgia Department of Transportation (GDOT). (1981). Update of Georgia Highway Cost Allocation Study FY 1981. Research and Development Bureau. Office of Materials and Research. Georgia Department of Transportation. Atlanta, Georgia.

Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (2004). Final Report, 1-37A, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, March.

Huang, Y.H. (2004). *Pavement Analysis and Design*. 2nd edition, Prentice Hall, Englewood Cliffs, N.J.

Minnesota Department of Transportation (MnDOT). (1990). Result of the Minnesota Highway User Coast Allocation Study. Minnesota Department of Transportation, Minnesota. October 1990.

National Cooperative Highway Research Program (NCHRP). (1979). State Resources for Financing Transportation Programs, 62 Synthesis of Highway Practice, Transportation Research Board, National Research Council, Washington, D.C.

Sinha K.C, and Fwa, T.E. (1987). "A Highway Cost Allocation Analysis at the State Level." *Transportation Quarterly*. July 1987. Vol. 41, No. 3. p 347-364

Sivakumar, B., Moses, F., Fu, G., Ghosn, M. (2007). Legal Truck Loads and AASHTO Legal Loads for Posting, Transportation Research Board, NCHRP Report 575.

Stower J.R, Reno A., Balducci P., Mingo R., Wolff H., Cohen H., and Haling D. (1999). Oregon Highway Cost Allocation Study. Department of Administrative Services. Salem, Oregon. June 1, 1999.

Tirado, C., Carrasco, C., Nazarian, S., Osegueda, R. (2007). Updates To Software for Estimating Damage due to Superheavy Loads. Report FHWA/TX-05/9-1502-01-7, Center for Transportation Infrastructure Systems, The University of Texas at El Paso, El Paso, Texas, October 2007.

Transportation Research Board (TRB). (2002). Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicle, 2002, Special Report 267.

APPENDIX A

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 as described by the Guide for Mechanistic-Empirical Design (2004).
- Damage factor determination based on comparison of a heavy 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.
- Permit fee calculation for a truck based on damage caused by a single pass of a heavy truck as compared to the damage caused by a standard truck. Distress types include rutting for flexible pavements and fatigue cracking 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 1.1. 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 A.1.2 presents the list of each button and the corresponding action.
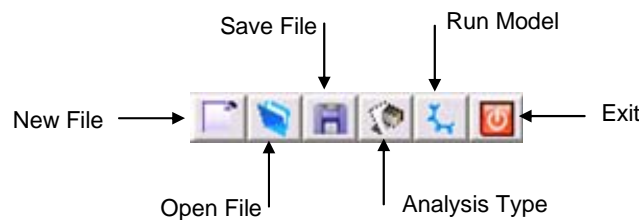

Figure A.0.1 – Main window.

Figure A.0.2 – 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

Structural Properties

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 A.2.1.
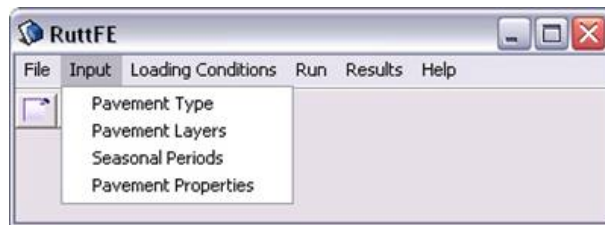

Figure A.0.1 – Input menu for pavement structural properties.

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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 A.2.2.

Figure A.0.2 – 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 A.2.3 shows the displayed window.
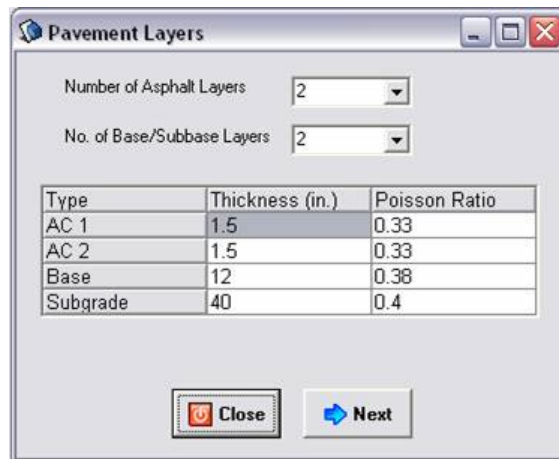

Figure A.0.3 – Number of pavement layers and structural properties.

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. 2.4.

Figure A.0.4 – 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 A.2.5 shows sample properties on a selected layer.

Figure A.0.5 – 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 A.2.6.

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.
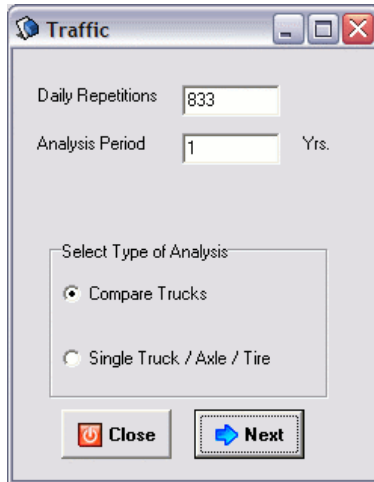
Figure A.0.6 – Seasonal pavement properties.

Single Truck, Axle or Tire

The option **Single Truck** sends the user to the window shown in Figure A.2.7. 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.
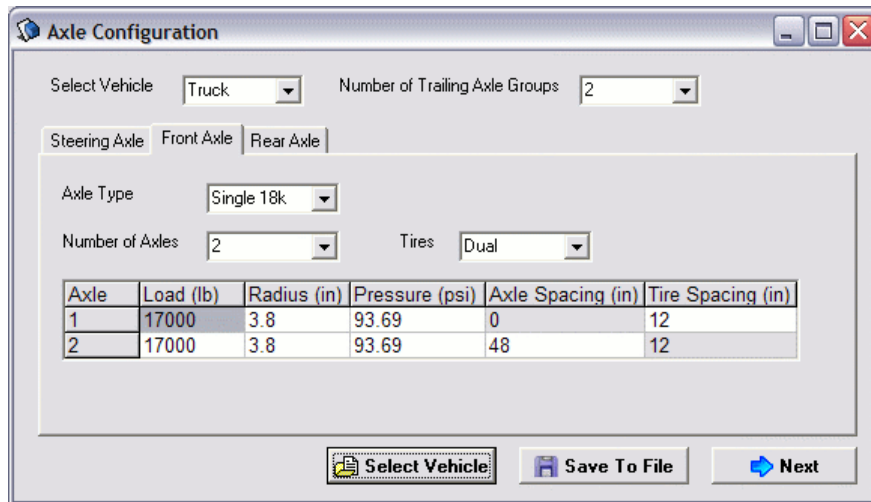

Figure A.0.7 – Axle loading and properties

Furthermore, the user may analyze a single tire if that option is selected. The following window, shown on Figure A.2.8, 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.
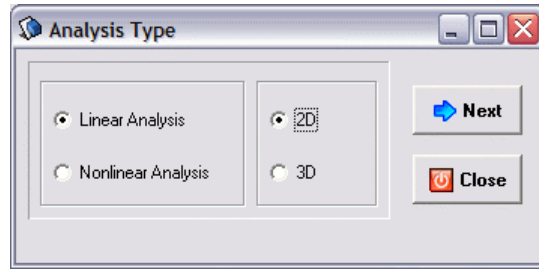
Figure A.0.8 – Analysis type, selecting a 2D model.

2-D Model

Selecting a 2D model analysis, as shown in Figure A.2.8, 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 A.2.9, will lead to a three-dimensional finite element analysis. Though Figure A.2.9 presents all options, the 2D option will not be available if an axle or a truck was selected when the configuration was defined.
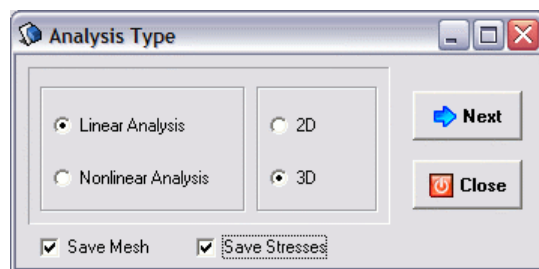

Figure A.0.9 – Analysis type, selecting a 3D model.

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 A.2.10. All information previously input will be displayed containing the pavement seasonal properties, traffic information, as well as the axle configuration. In Figure A.2.10, 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 A.2.7.
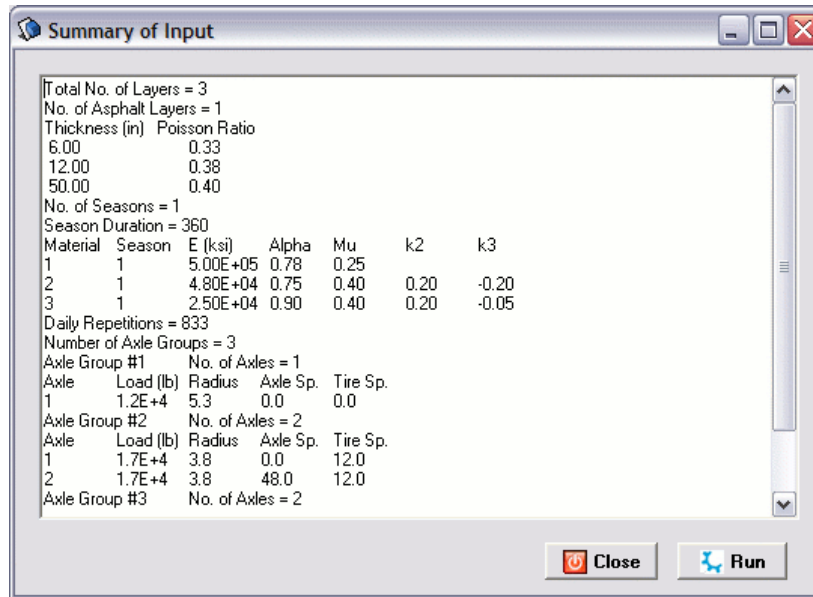
Figure A.0.10 – Summary of input

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 A.2.11, 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 A.2.12 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.

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 A.2.13. This information may be saved into an ASCII text file.
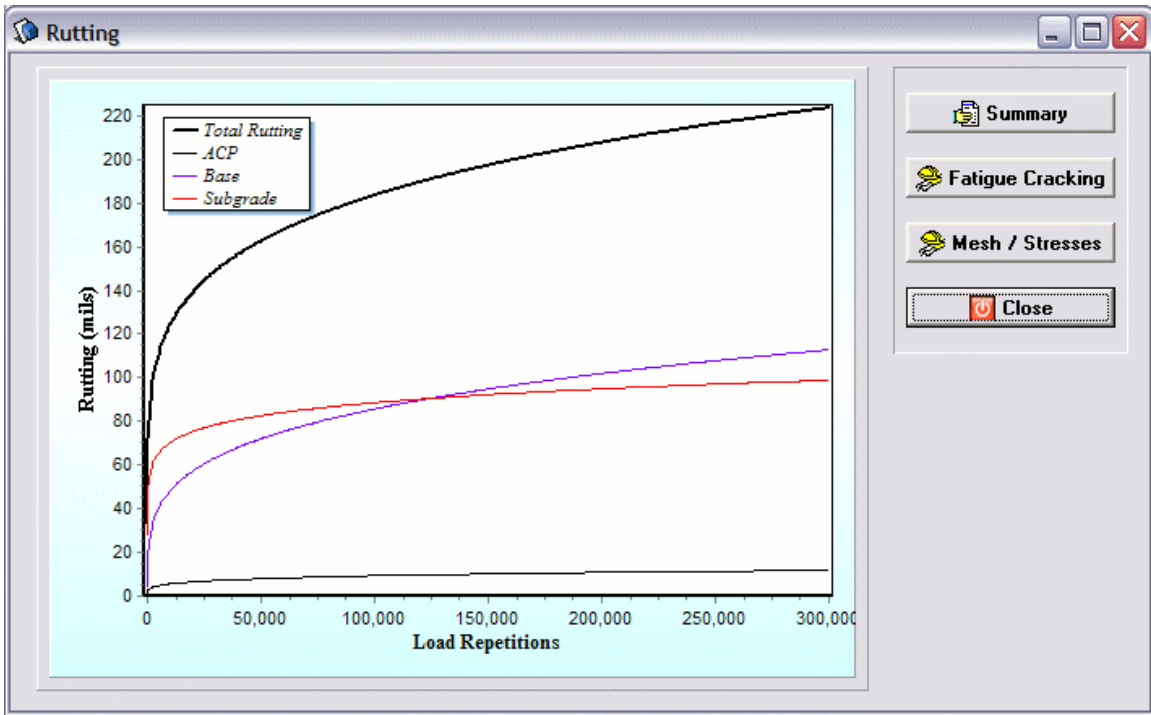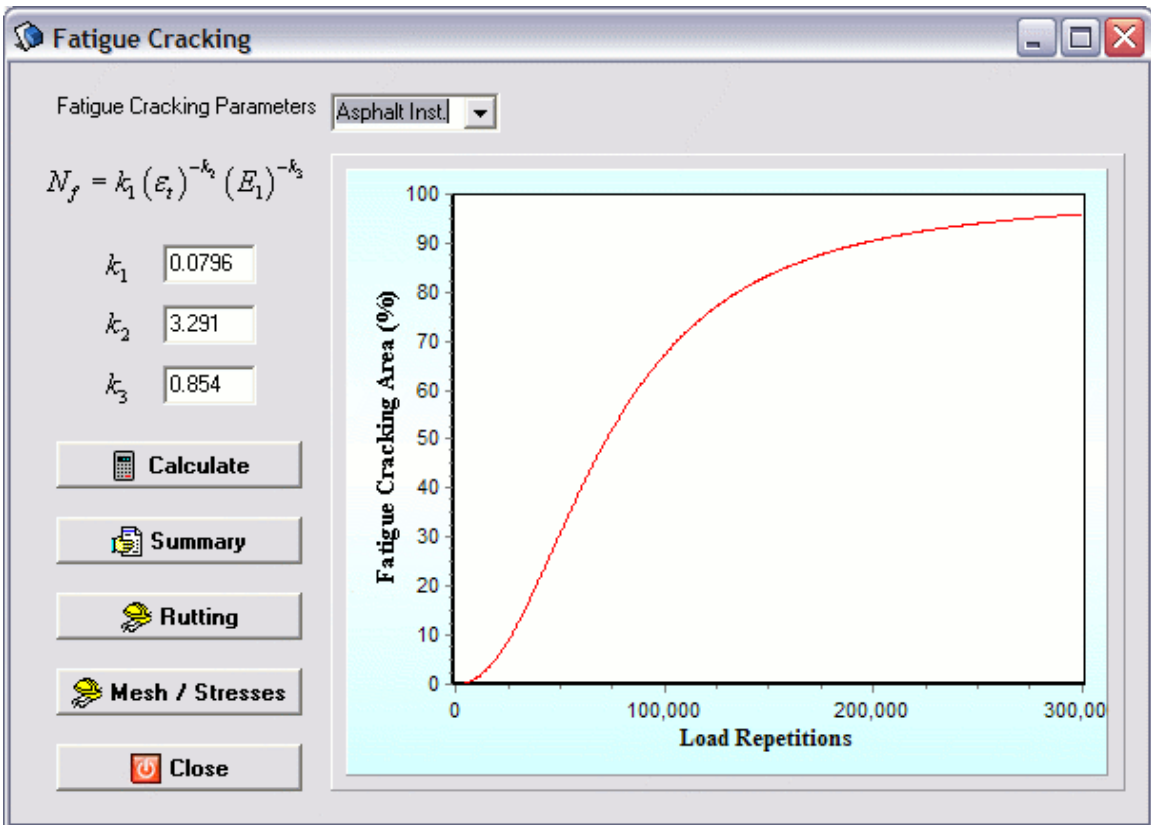
Figure A.0.11 – Rutting vs. load repetitions.

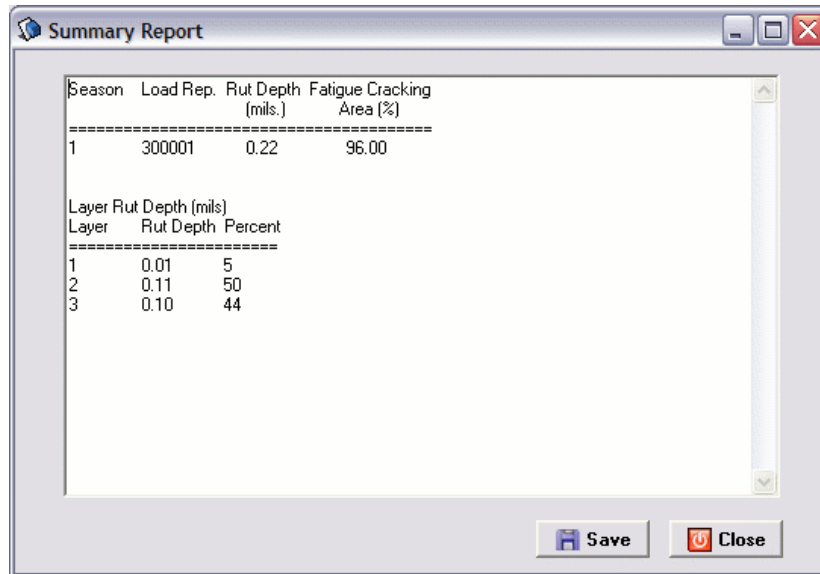**Figure A.0.12 – Fatigue cracking results.**

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Figure A.0.13 – 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 A.2.14. 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/in^2 (psi). If the user did not selected to view this information using the check boxes in the **Analysis Type** window (see Figure A.2.9), 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 A.2.15(a) and (b), respectively.
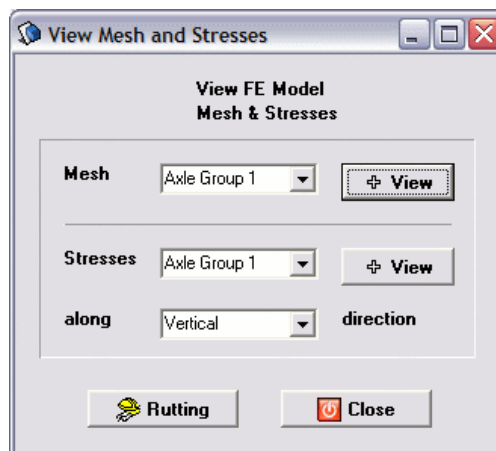

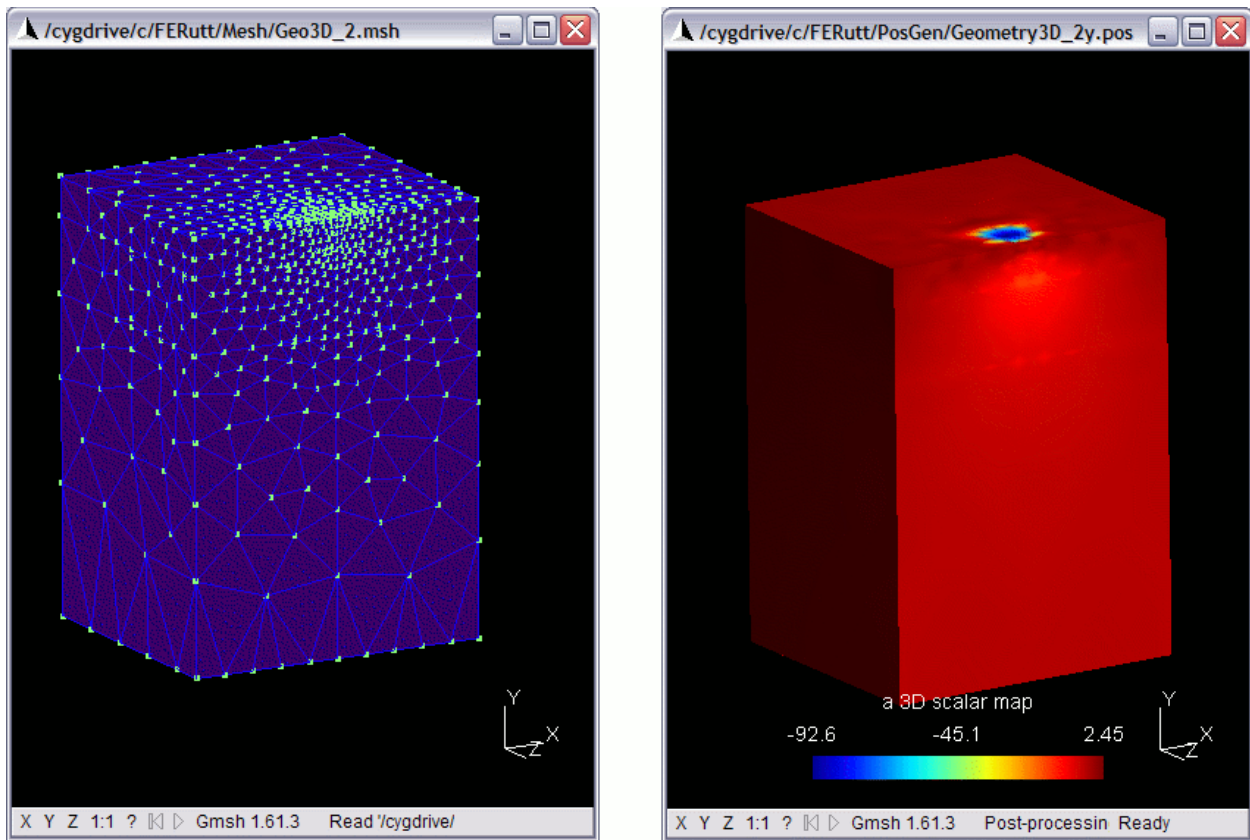**Figure A.0.14 –View mesh and stresses.**

Figure A.0.15 –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 A.2.6), 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 A.2.16. 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.

Selecting on the **Create/Modify Vehicle** button opens another window, titled **Truck Characteristics**, Figure A.2.17, 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.

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Figure A.0.16 – Truck vehicle selection.

Figure A.0.17 – Truck characteristics.

Once both vehicles are selected, the procedure requires the user to select an analysis type to compare vehicles, as shown in Figure A.2.18. There are four 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, the third one based on fatigue cracking, and a fourth one consisting on the calculation of a permit fee for the case study truck based on the rutting caused by this truck to the rutting caused by the standard truck. 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.0.18 – 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 A.2.19. This window will provide the ratio between the equivalent axle load factors of the analyzed case truck divided by the selected standard truck.
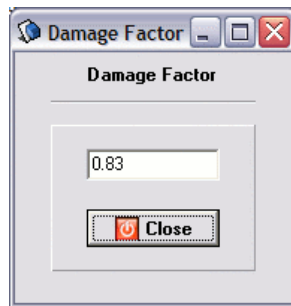

Figure A.0.19 – Damage factor based on AASHTO formulation.

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 A.2.20. In this comparison analysis, the user won't have the save mesh and stresses options.
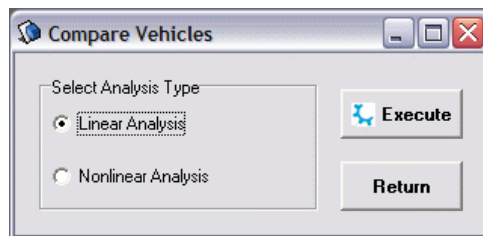

Figure A.0.20 – Analysis type for comparison.

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 A.2.21.

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 A.2.22. This information is similar to the one obtained from a single truck analysis (see Figure A.2.11).

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 heavy truck pass. A sample graph is shown in Figure A.2.23.

Similarly, fatigue cracking comparison displays similar charts, with the same tab control options from the rutting window. Figure A.2.24 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 A.2.24. Changing the *k* parameters and clicking on the **Calculate** button will generate a new graph.
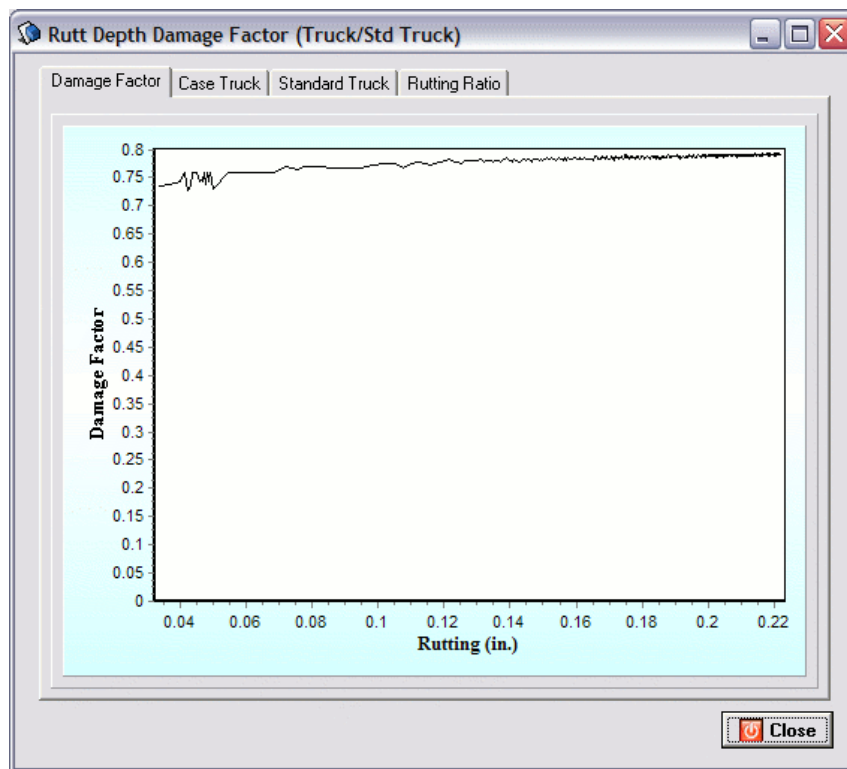

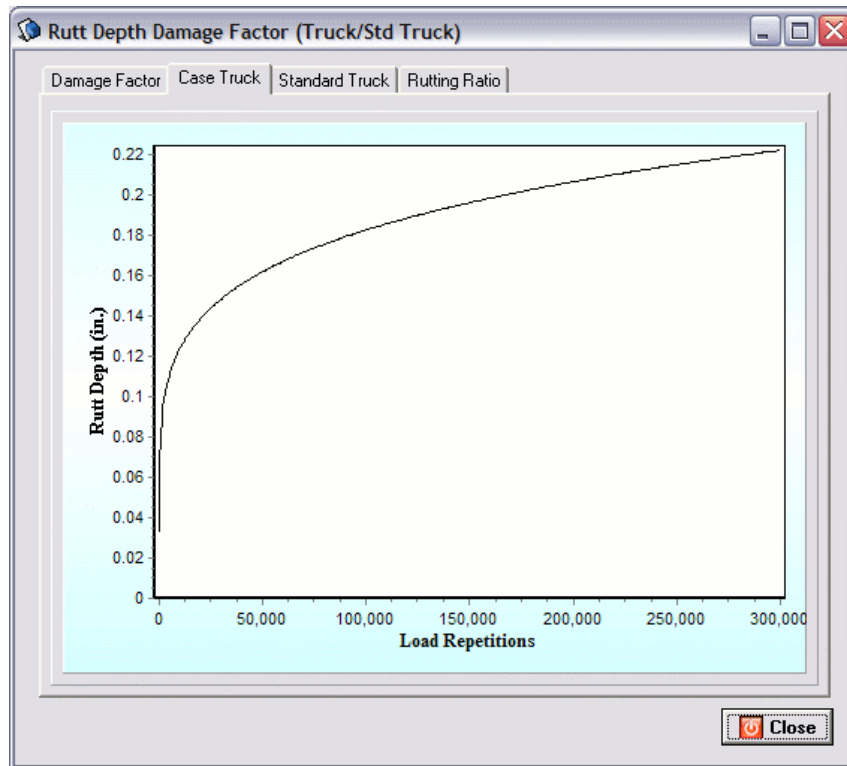**Figure A.0.21 – Damage ratio based on rutting.**

Figure A.0.22 – Rutting vs. load repetitions for each truck.
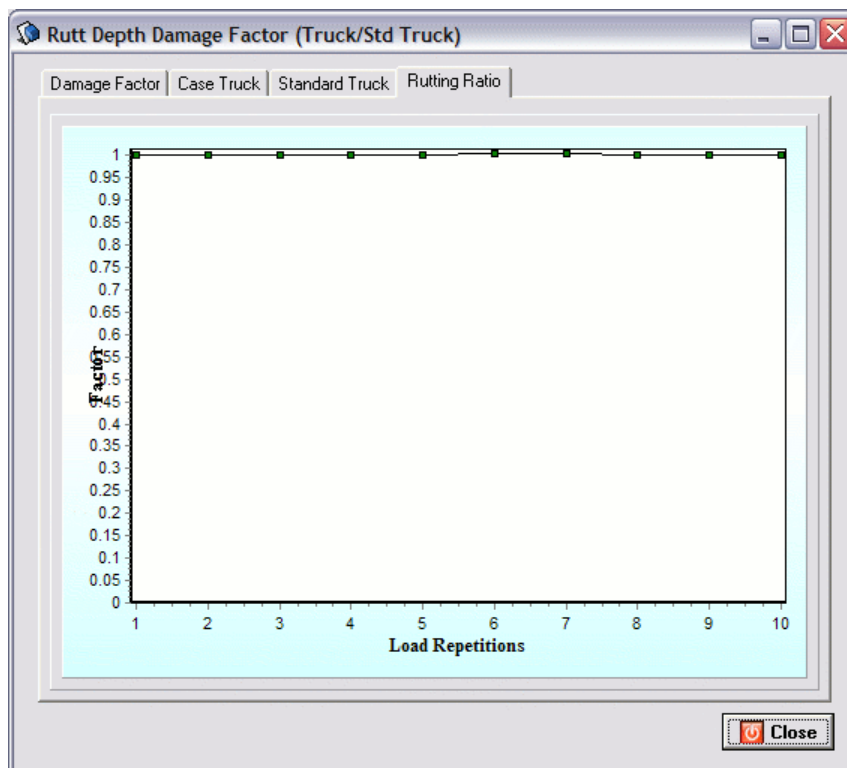

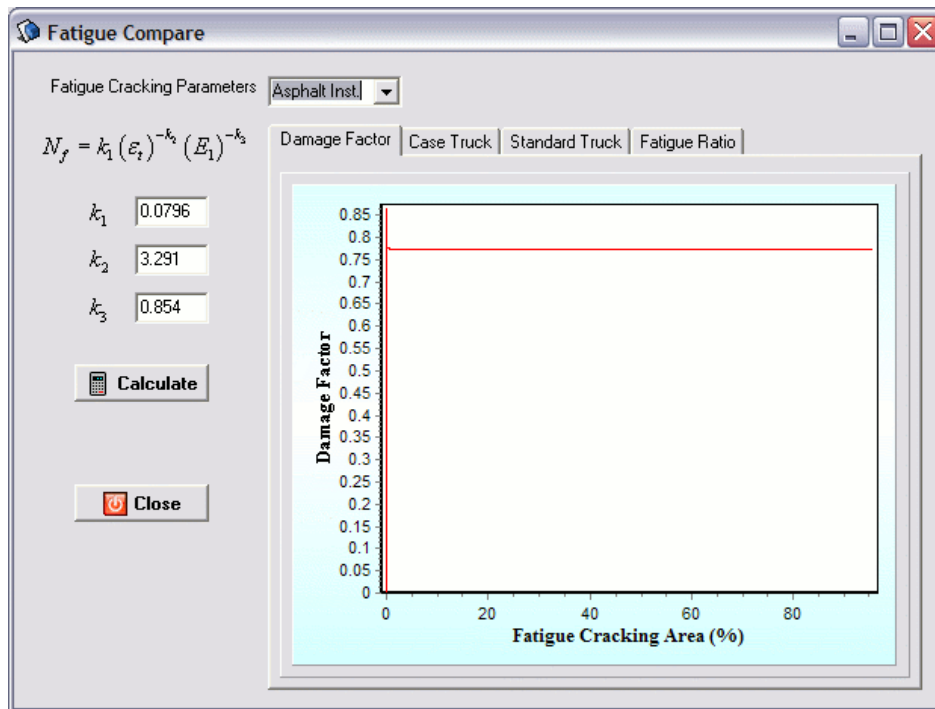**Figure A.0.23 – Ratio based on rutting for the first truck passes.**

Figure A.0.24 – Damage ratio based on fatigue cracking.

Similarly to the rutting results, the fatigue cracking curves are available for each truck as shown in Figure A.2.25. A direct ratio of case to standard trucks based on fatigue cracking for the first load repetitions is also available.

Permit Fee in Flexible Pavements

Permit fee calculation based on comparison of rutting caused by a heavy truck to the one caused by a standard truck is carried out when selecting the fourth option, titled **Permit Fee**, of the *Compare Vehicles* window, shown previously in Figure A.2.18. A new window is displayed next with a form that lets the user enter information regarding traffic such as the Average Annual Daily Truck Traffic, the threshold in rut depth to calculate the number of standard truck passes to failure in rutting, the type of repair and its related costs, as well as the discount rate for calculating present worth values, as shown in Figure A.2.26.

The options available for types of repair in the program are shown in Figure A.2.27. Each of these options has different types of input values. Furthermore, the user has the option of obtaining rutting based on a linear or nonlinear analysis. After executing and calculating the cost analysis, the permit fee is displayed along with other variables such as the repair present worth value per lane-mile. Calculation of permit fee is explained in detail in Report 9-1502-01-8.
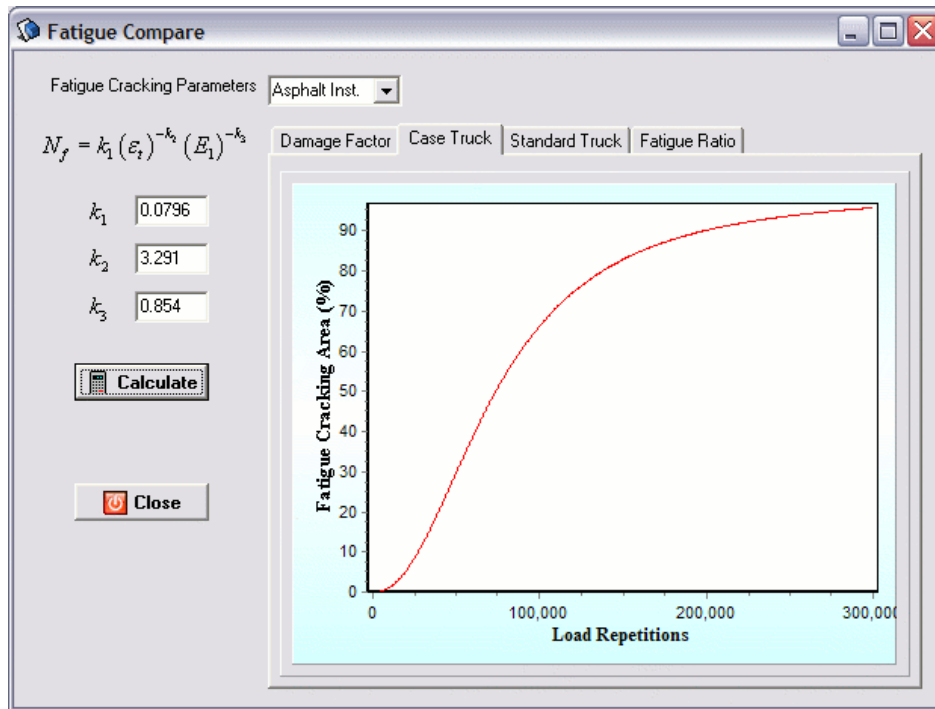
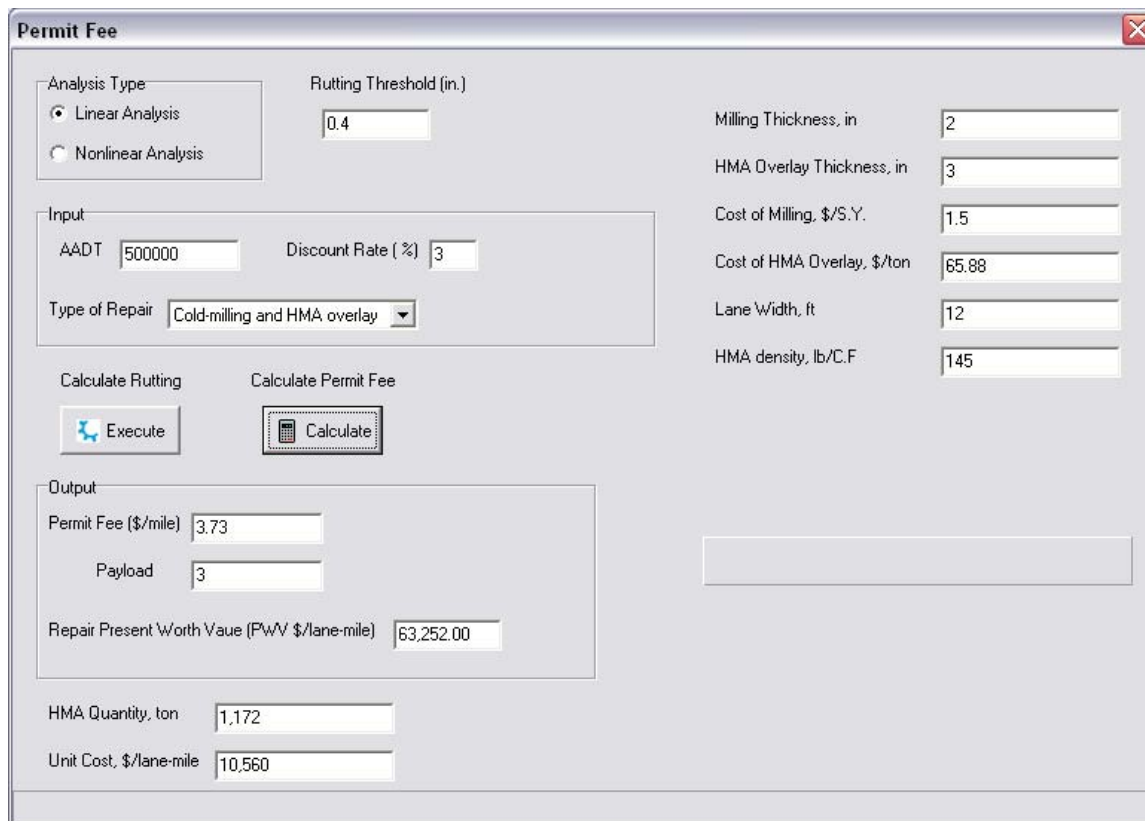**Figure A.0.25 – Fatigue cracking based on load repetitions results per truck.**

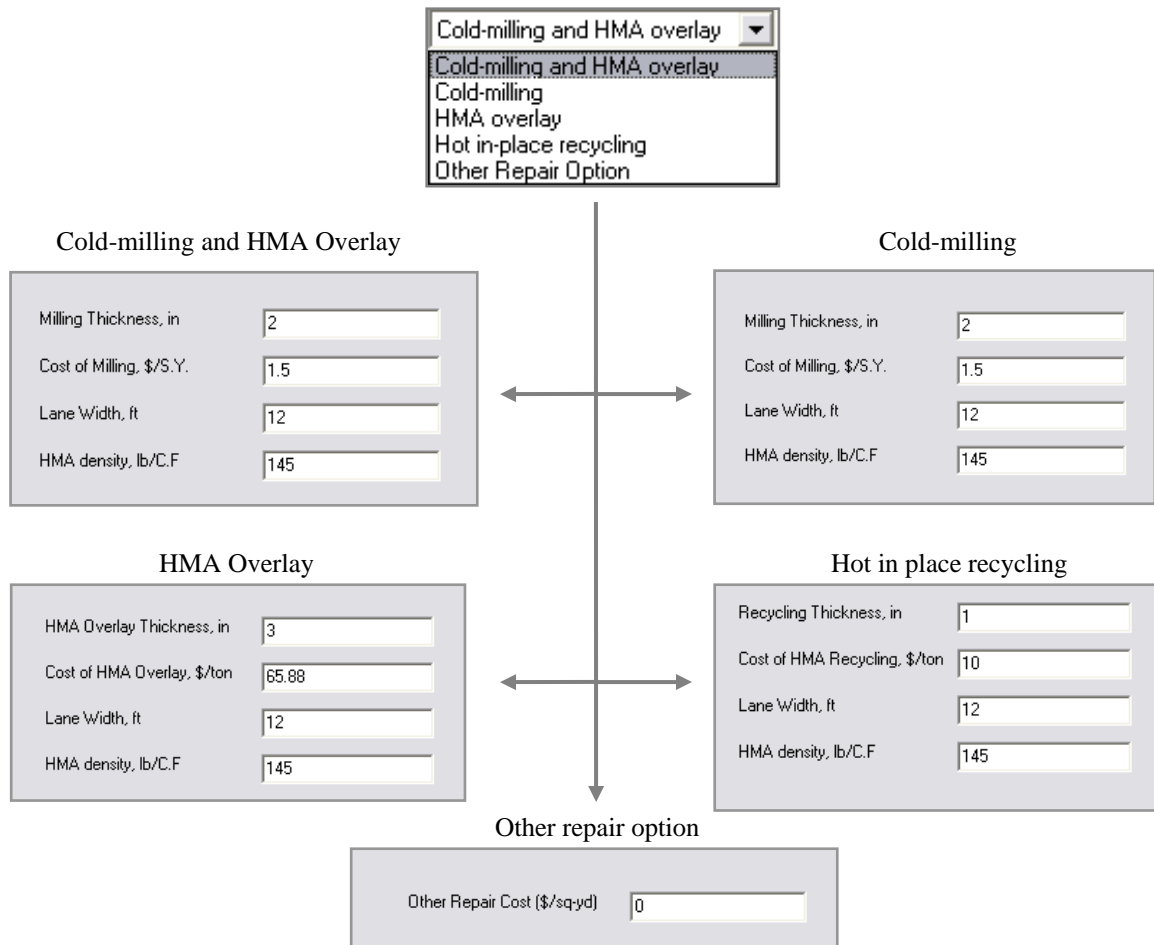
Figure A.0.26 – Permit fee calculation for flexible pavements.

Figure A.0.27 – Flexible pavement repair options.

RIGID PAVEMENTS

Pavement Properties and Truck Configuration

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 A.2.2) 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 A.3.1.

Figure A.0.1 – 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 A.3.2. It further requires inputting 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 A.3.3).

Figure A.0.2 – Rigid pavement properties.
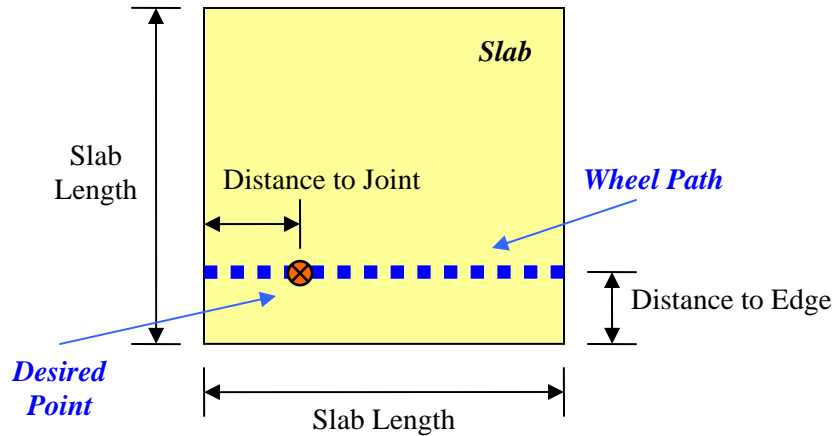
Figure A.0.3 – Wheel path and selected point location within slab.

The following form titled **Joints** asks the user to enter information about the joints on the rigid pavement. Information about dowels and tie bars should be provided if required, as shown in Figure A.3.4. Input fields activate depending if dowels exist or do not.

Figure A.0.4 – Joints.

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 A.2.16.

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Again the user will have to edit the truck characteristics if necessary, opening a window as shown in Figure A.3.5, 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.
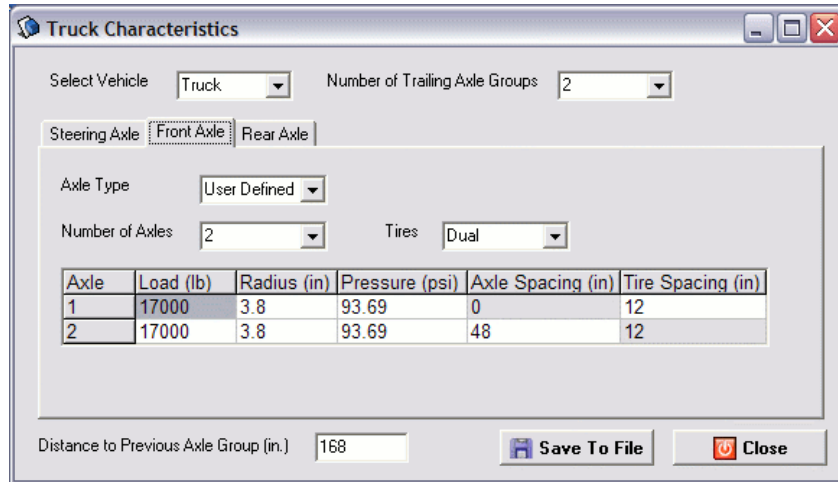
Figure A.0.5 – Truck characteristics.

Distress Models and Results

Once the necessary information is provided, the next window asks the user to select the type of analysis desired, shown in Figure A.3.6. 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, as well as calculating the permit fee for a case study truck based on fatigue cracking.

Figure A.0.6 – 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 A.3.7. This window will provide the ratio between the equivalent axle load factors of the analyzed case truck divided by the selected standard truck.
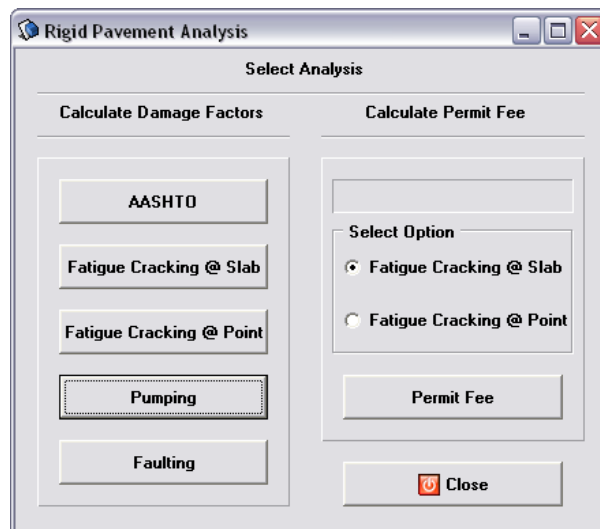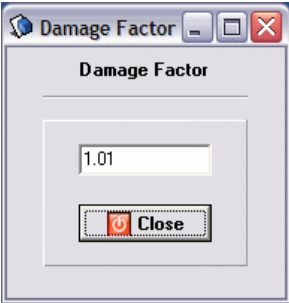

Figure A.0.7 – Damage factor based on AASHTO formulation.

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 A.3.2). This will provide the damage factor based on fatigue cracking at a unique point as shown in Figure A.3.8.
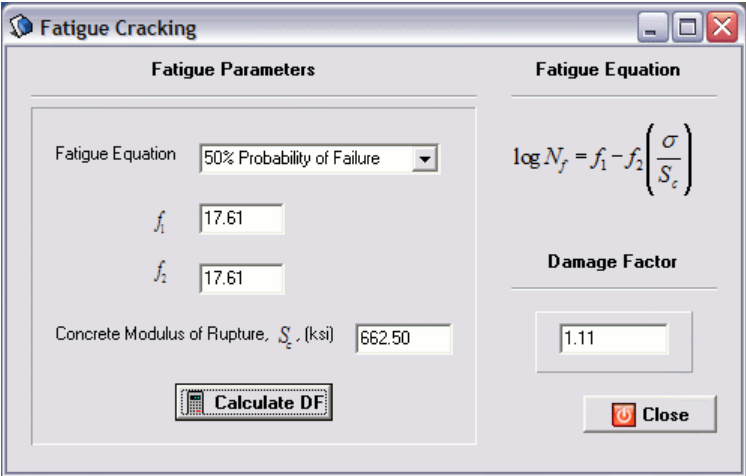
Figure A.0.8 – Damage factor based on fatigue cracking at user defined point.

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 A.3.9.

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 A.3.10).
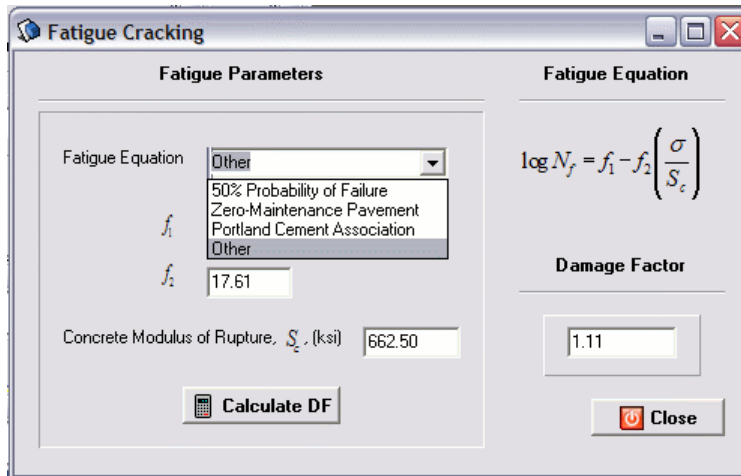
Figure A.0.9 – Available fatigue equations.
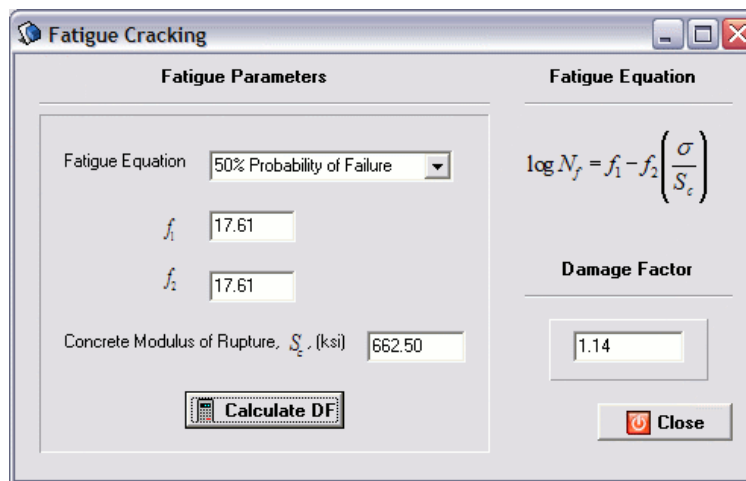
Figure A.0.10 – Available fatigue equations.

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 A.3.11.

Finally, the last available option consists on the **Faulting** model shown in Figure A.3.12. 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.0.11 – Pumping model.

Figure A.0.12 – Faulting model.

Permit Fee in Rigid Pavements

Permit fee calculation based on comparison in fatigue cracking caused by a truck to the one caused by a standard truck is carried out when selecting **Permit Fee** from the window, shown previously in Figure A.3.6. The form displayed, shown in Figure A.3.13, allows the user enter information similar to the one for the calculation of permit fees in flexible pavements, with appropriate repair type options suitable for rigid pavements, such as grinding with slab replacement and lane replacement, among others..

All analytical tools and available models used in IntPave, for both flexible and rigid pavements, are described into more detail in the Research Report FHWA/TX-05/9-1502-01-8.

Figure A.0.13 – Permit fee calculation for rigid pavements.

APPENDIX B

AXLE CONFIGURATIONS FOR TRUCKS CONSIDERED

Table B.1 – Standard truck GVW 80-k configuration.

Axle Number	Axle Weight (lbs)	Number of Tires	Sum of Tire Widths	Axle Spacing		Load per Tire (lb.)	Pressure-Tire Width	Axle Configuration
				(ft.)	(in.)			
1	12,000	2	22			6,000	545	Single Axle Single Tires
2	17,000	4	44	13	4	4,250	386	Tandem Axle Dual Tires
3	17,000	4	44	4	0	4,250	386	
4	17,000	4	44	20	0	4,250	386	Tandem Axle Dual Tires
5	17,000	4	44	4	0	4,250	386	

GVW	80,000
EVW	33,000
Payload	47,000

Table B.2 - 120-k Super-heavy Truck information.

Axle Number	Axle Weight (lbs)	Number of Tires	Sum of Tire Widths	Axle Spacing		Load per Tire (lb.)	Pressure-Tire Width	Axle Configuration
				(ft.)	(in.)			
1	12,000	2	22			6,000	545	Single Axle Single Tires
2	19,000	4	44	13	4	4,750	432	Tandem Axle Dual Tires
3	19,000	4	44	4	0	4,750	432	
4	17,500	4	44	20	0	4,375	398	Quad Axle Dual Tires
5	17,500	4	44	4	0	4,375	398	
6	17,500	4	44	4	0	4,375	398	
7	17,500	4	44	4	0	4,375	398	

GVW	120,000
EVW	37,000
Payload	83,000

Table B.3 - 160-k Super-heavy Truck information

Axle Number	Axle Weight (lbs)	Number of Tires	Sum of Tire Widths	Axle Spacing		Load per Tire (lb.)	Pressure-Tire Width	Axle Configuration
				(ft.)	(in.)			
1	12,000	2	22			6,000	545	Single Axle Single Tires
2	18,000	4	44	13	4	4,500	409	Tandem Axle Dual Tires
3	18,000	4	44	4	0	4,500	409	
4	28,000	8	80	20	0	3,500	350	Trunnion
5	28,000	8	80	4	6	3,500	350	
6	28,000	8	80	4	6	3,500	350	
7	28,000	8	80	4	6	3,500	350	

GVW	160,000
EVW	37,000
Payload	123,000

Table B.4 - 200-k Super-heavy Truck information

Axle Number	Axle Weight (lbs)	Number of Tires	Sum of Tire Widths	Axle Spacing		Load per Tire (lb.)	Pressure-Tire Width	Axle Configuration
				(ft.)	(in.)			
1	12,000	2	22			6,000	545	Single Axle Single Tires
2	19,000	4	44	13	4	4,750	432	Tandem Axle Dual Tires
3	19,000	4	44	4	0	4,750	432	
4	25,000	8	80	20	0	3,125	313	Trunnion
5	25,000	8	80	4	6	3,125	313	
6	25,000	8	80	4	6	3,125	313	
7	25,000	8	80	4	6	3,125	313	
8	25,000	8	80	4	6	3,125	313	
9	25,000	8	80	4	6	3,125	313	

GVW   200,000

EVW   41,000

Payload 159,000

Table B.5- 240-k Super-heavy Truck information

Axle Number	Axle Weight (lbs)	Number of Tires	Sum of Tire Widths	Axle Spacing		Load per Tire (lb.)	Pressure-Tire Width	Axle Configuration
				(ft.)	(in.)			
1	12,000	2	22			6,000	545	Single Axle Single Tires
2	18,000	4	44	13	4	4,500	409	Tandem Axle Dual Tires
3	18,000	4	44	4	0	4,500	409	
4	24,000	8	80	20	0	3,000	300	Trunnion
5	24,000	8	80	4	6	3,000	300	
6	24,000	8	80	4	6	3,000	300	
7	24,000	8	80	4	6	3,000	300	
8	24,000	8	80	4	6	3,000	300	
9	24,000	8	80	4	6	3,000	300	
10	24,000	8	80	4	6	3,000	300	
11	24,000	8	80	4	6	3,000	300	

GVW	240,000
EVW	45,000
Payload	195,000