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# **A GIS-BASED ALGORITHM FOR ESTIMATING DAMAGE DUE TO SUPERHEAVY LOADS**

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**Report Number 9-1502-01-6**

**Research Project TX-9-1502**

**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**

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**March 2006**

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## **EXECUTIVE SUMMARY**

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. The work-horse of this effort has been the VESYS 5 pavement damage prediction model calibrated with local materials and performance data. Despite the successes in VESYS for rutting and performance predictions in pavement systems, some limitations exist, such as difficulties in incorporating new or more advanced constitutive models into VESYS. Finite Element techniques, on the other hand, generally possess flexibility in the adoption of new emerging constitutive models and can be used in two and three dimensional configurations.

Under this research project 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 has been developed. The finite element models are then interfaced with a GIS map for the determination of the potential damage along a corridor.



## **IMPLEMENTATION STATEMENT**

This study is aimed at addressing the possible premature failure of flexible 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 finite element models are incorporated in a Geographic Information System (GIS) network with capability of routing super heavy trucks within the state New York.

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, e.g. 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.

This pooled fund study is aimed at providing these tools. The work-horse of this effort has been the VESYS 5 pavement damage prediction model calibrated with local materials and performance data. The latest version of VESYS includes the capability to include both tandem and tridem-axles and prediction of the rutting within each pavement layer. This is based upon the computed strains in each layer together with the layer material parameters of  $\alpha$  and  $\mu$ . The parameter  $\mu$  represents the proportionality between the permanent and elastic strains, and  $\alpha$  indicates the rate of increase in permanent deformation against the number of load applications. Both of these parameters can be obtained from the laboratory or backcalculated from the Accelerated Pavement Test (APT) data.

Despite the successes in VESYS for rutting and performance predictions in pavement systems, some limitations exist, such as difficulties in incorporating new or more advanced constitutive models into VESYS. Finite Element techniques, on the other hand, generally possess flexibility in the adoption of new emerging constitutive models and can be used in two and three dimensional configurations.



## **OBJECTIVE AND APPROACHES**

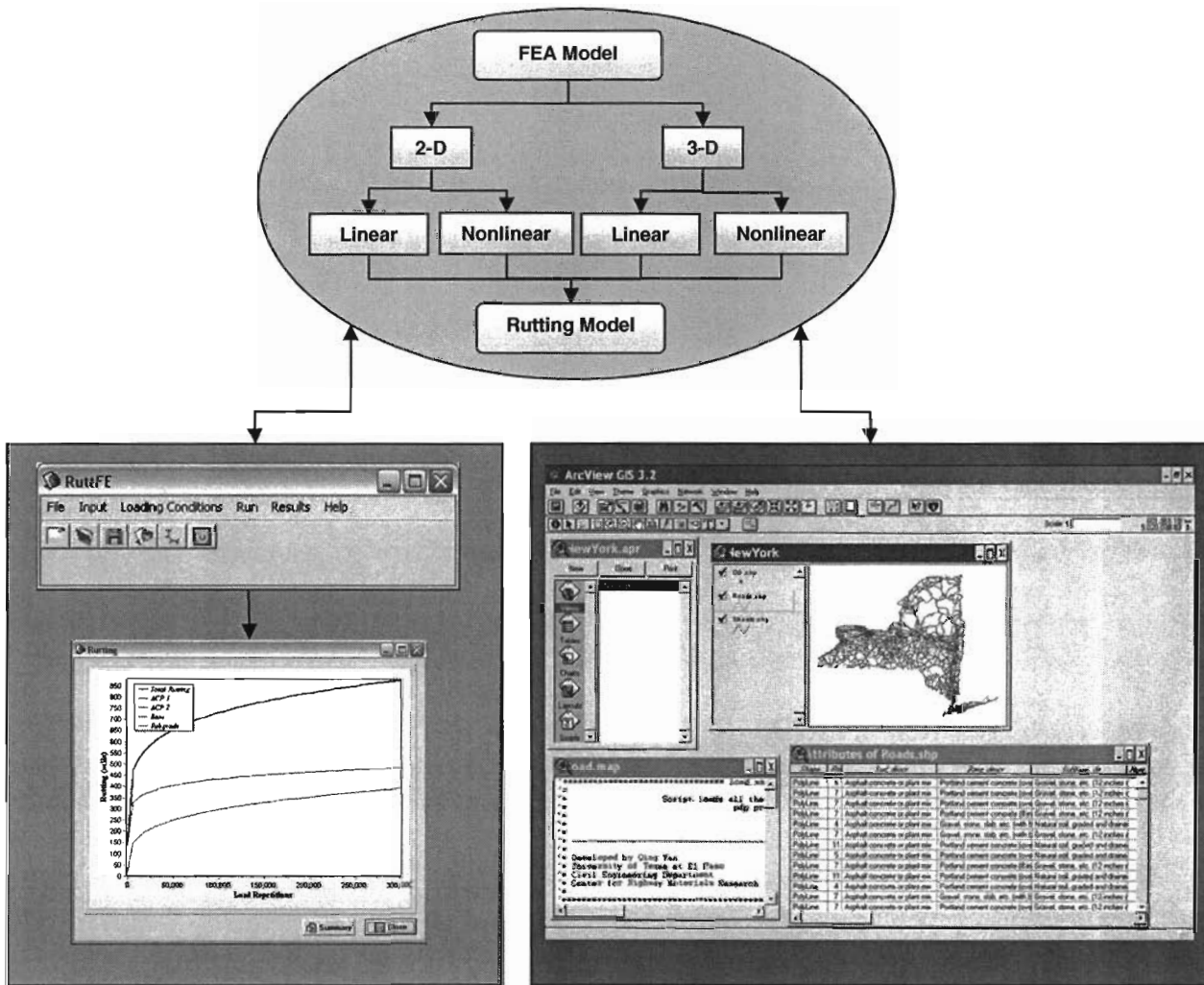
The main objective of the work conducted under this research project is to develop a tool with the capacity to calculate pavement distress under any type of traffic load and to make a comparison of the level of distress caused by a standard and a non-standard truck..

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 rutting calculations for all the pavement layers and fatigue cracking of the surface layer 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. 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.

## **ORGANIZATION OF REPORT**

Chapter 2 of this report contains a brief review of the literature. In chapter 3, the methodology followed to develop the finite element model is described, as well as the model implemented to determine the permanent deformation of pavements. Chapter 4 presents case examples for different traffic and pavement structure conditions. Chapter 5 contains a description of the GIS highway network and the implementation of the finite element model. Finally, chapter 6 includes the summary of the work accomplished, the work remaining 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 summarizes the content of the most relevant surveyed publications. Papers and reports are classified under the following categories based on their primary focus: (a) pavement performance prediction, and (b) geographic information systems to automate routing of vehicles.

### **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.

Saliba (1990) presented a brief review of the mathematical theory of visco-plasticity and the computational procedure used in a finite-element program to model tire/soil interaction.

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.

Rowe, et al. (1995) developed a method of analysis based on improved material characteristics to accurately reflect fatigue cracking and permanent deformation performance. Their work focused on the dissipated energy fatigue criterion, a visco-elastic materials characterization, and a pavement analysis using the finite-element method for determining the response to repeated wheel loading.

Kirkner, et al. (1996) addressed complexities associated with the modeling of pavement systems using the finite element method, in particular those associated with moving loads, non-linear material behavior and the unbounded domain. They discussed a methodology that is based on a steady-state assumption and the use of a moving coordinate system.

Ramsamooj, et al. (1998) presented an elasto-plastic model for predicting the stress/strain response of asphalt concrete under cyclic loading. They used multi-yield surfaces and isotropic hardening, Rowe's stress dilatancy theory to obtain the relationship between the permanent volumetric and vertical strains, and a hardening law for the changes in the sizes of the plastic moduli caused by cyclic loading.

Chen and Tsai (1999) evaluated the effects of linear visco-elastic properties of asphalt on pavement rutting and fatigue cracking. They calculated the dissipated energy per traffic cycle to directly relate the linear visco-elastic properties of asphalt binders to the pavement performance.

Seibi, et al. (2001) modeled the tendency of AC to behave elastically and visco-plastically during cold and hot seasons, respectively. The visco-plastic response was characterized by the rate dependency of the plastic response and was found to be linearly strain-hardening. The model used a yield criterion based on the loading function defined by Drucker-Prager. They calibrated their models through an optimization process that involved iterative calls between finite element results and the optimum parameters to develop a generalized elastic-visco-plastic constitutive relation for AC.

Blab and Harvey (2002) used a 3-dimensional FE model of a road pavement in which the temperature and load dependent performance of flexible pavements was characterized by a generalized Maxwell model and improved loading assumptions are used based on the required visco-elastic model parameters from dynamic shear tests. The model was evaluated using simulation calculations for a specific test structure on which rutting tests had been performed with a heavy vehicle simulator. This evaluation demonstrated good agreement between the deformations predicted by the theoretical model and the deformations actually measured.

Hossain and Wu (2002) used a three-dimensional (3-D) non-linear finite element model to simulate the initiation and propagation of rutting damage on the Superpave test sections of the Kansas Accelerated Testing Laboratory. A creep and Drucker-Prager model were chosen to

characterize the permanent deformation characteristics of the Superpave mixtures and the aggregate base and subgrade materials, respectively.

Werkmeister, et al. (2002) discuss the use of shakedown approach to characterize the deformation behavior of unbound granular materials (UGM) in pavement construction. The essence of a shakedown analysis is to determine the critical shakedown load for a given pavement. The Dresden material law was introduced for modeling the permanent and resilient deformation behavior of UGM layers in pavement constructions under consideration of the shakedown ranges. They also described a design method that uses test results from the repeated load triaxial tests to establish the risk level of permanent deformations in the UGM layers using a nonlinear resilient material law implemented into a FE Program called FENLAP.

Long, et al. (2002) discussed the development of a constitutive model that describes the permanent deformation behavior of asphalt concrete. The model was implemented in a finite element code, and simulation of laboratory and heavy vehicle simulator tests are used to validate the model.

The effect of overloads on state-maintained highways has been a subject of study in previous years. The effect of super-heavy trucks on highway networks have been previously addressed by Fernando (1997), who developed and evaluated a nonlinear layered elastic pavement response model for super-heavy load analysis that predicts the induced stress under surface wheel loads. The predicted stresses are used with the Mohr-Coulomb failure criterion to evaluate the potential for pavement damage prior to the super-heavy load move. The procedure was incorporated into a computer program called PALS. Chen et al. (1996) implemented Fernando's (1997) program to evaluate the potential pavement damage caused by a super-heavy load moved in Texas. Falling Weight Deflectometer (FWD) tests were performed on the pavement before and after the super-heavy load was moved. The FWD data and analyses show that the existing pavement structure is adequate for the planned super-heavy load move, and no significant distress due to the super-heavy load was observed after the move.

## **GEOGRAPHIC INFORMATION SYSTEMS TO AUTOMATE ROUTING OF VEHICLES**

Software tools based on Geographic Information Systems (GIS) to automate the selection of routes and evaluation of highways have already been developed. Osegueda, et al. (1998, 1999) developed a GIS to route overweight vehicles in the Houston District of Texas. The developed GIS used a network representation of highways and a relational database link to a corresponding bridge database. The system automatically finds the shortest path between an origin-destination pair and any number of intermediate points, disabling from the network road segments with insufficient clearances and load-carrying capacity. The output consists of a map with the route found highlighted and a written report that includes a description of the route and the vehicle. The network was generated from digitized maps. Laborious preprocessing was required to verify network connectivity and minimal road information completeness and an exhaustive verification of bridge locations was made. The bridges were attributed to the corresponding road segments to

create the relational database. In this project, the researches incorporated two evaluation criteria to determine the feasibility of a route: legal size and weight limits and a bridge load formulae.

In a similar manner, a software program based on GIS was developed by Melchor-Lucero (2001) to automate the evaluation of bridges and clearances along routes in the El Paso border region for vehicles exceeding legal size and weight limits, using GIS technology, to avoid inadequate structures with insufficiencies and protect them.

## **CHAPTER THREE - FINITE ELEMENT MODEL**

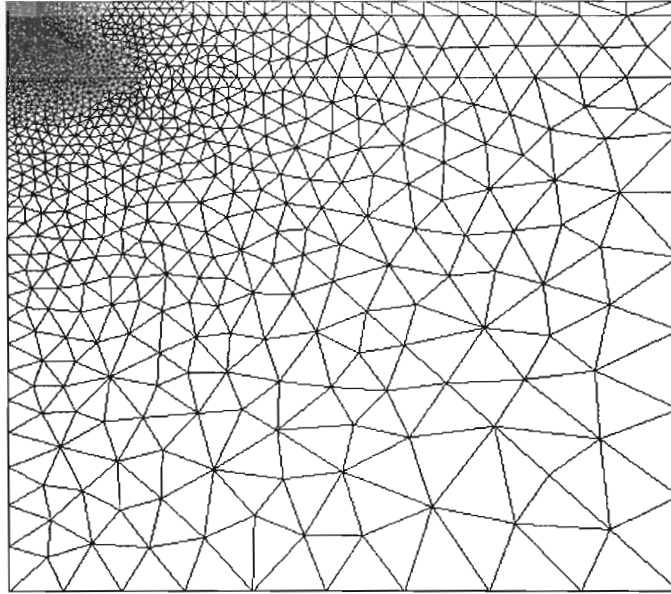
### **INTRODUCTION**

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.

The finite element program developed to calculate distress as part of the objectives of this project, has the capability of analyzing pavement sections using two- and three-dimensional models. The developed program was later incorporated into a graphical user interface that enables pavement distresses calculation, as depicted on Figure 1.1. The finite element analysis is based on a generalized Hooke's law to model the properties of pavement structure. The 2D model consists of an axisymmetric model, which is suitable for estimating the rut depth under equivalent single axial loads (ESALs). Using an open source preprocessor called GMSH, it was possible to model a 2D mesh with triangular elements. The advantage of these elements is their geometric flexibility: they allow modeling intricate geometries and facilitate transition from coarsely meshed zones of a grid to finely meshed zones. This latter feature is essential in pavement modeling, since a fine mesh is required where the load is applied, implicating a larger number of elements. Since the stresses caused by loads dissipate as they move away from the load application point, a less refined mesh is needed. Even though large meshes provide more accurate results, they require greater computation time, and having these transitions greatly reduces computation time without conceding accuracy. A sample of this type of mesh is shown in Figure 3.1. In order to improve computation time, the constant strain triangle element was used in the finite element model.

In order to evaluate the impact of super heavy loads as well as axle configurations that in many occasions may deviate from the equivalent single axle load configurations it is necessary to estimate the distress using 3D modeling. Three-dimensional models offer several advantages over two-dimensional axisymmetric ones. Actual load configurations can be readily modeled.





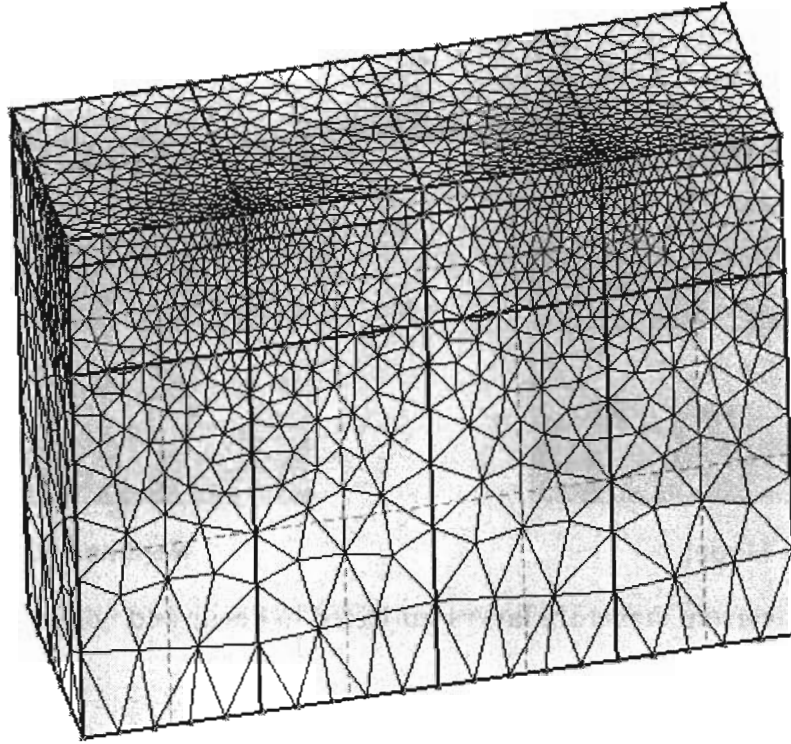
**Figure 3.1 - 2D Mesh with element refinement transition, load applied at upper left corner.**

Realistic geometric conditions such as edges, discontinuities and intricate boundary conditions can be incorporated. These advantages come at the expense of computation time and resources. Simplification of the mesh is essential to reduce computation time, and in order to accomplish this, tetrahedral elements were used for the same reasons the triangular element were used in the 2D model. Four-node tetrahedral elements were used for the analysis. A sample mesh of a 3D model is shown in Figure 3.2; the sample mesh becomes more refined as it gets closer to the load application points, namely the tire contact areas; in this case the load is that of a tandem dual axle configuration. Only two tires are shown in the model since only half of the model is needed because of plane symmetry.

### **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 2D and 3D 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 on a NCHRP project (Barksdale, et al., 1994) has endorsed a universal relationship for both fine and coarse grained base and subgrade materials in the form of,

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

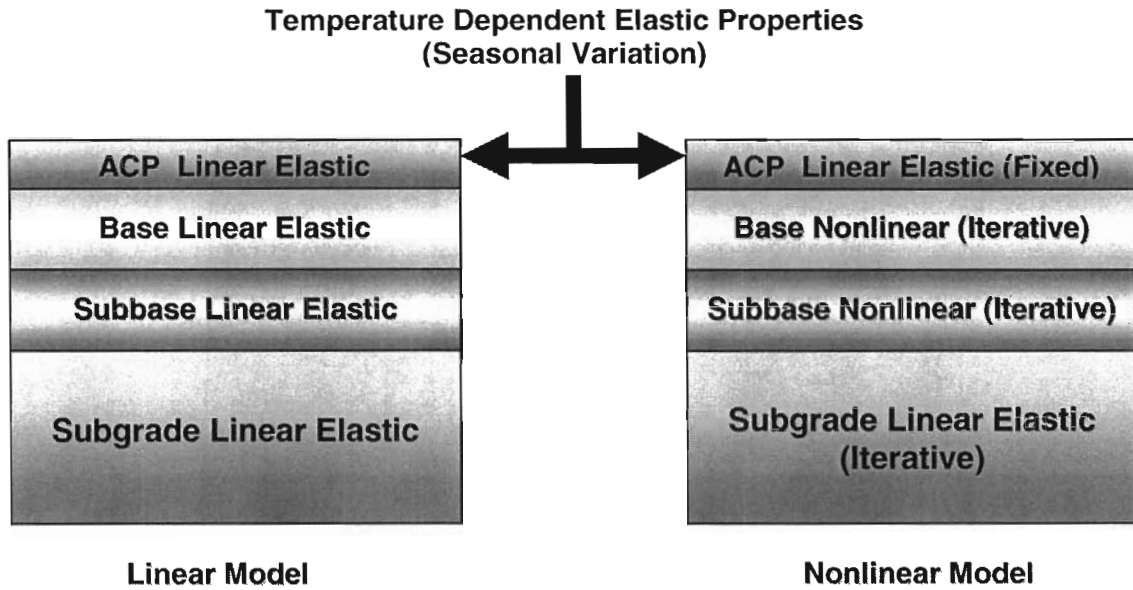


**Figure 3.2 - 3D Mesh, tandem axle, dual tire load condition.**

where  $E$  is the resilient modulus,  $\sigma_c$  and  $\sigma_d$  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 has to be used to implement this stress-modulus relationship shown in Equation 3.1.

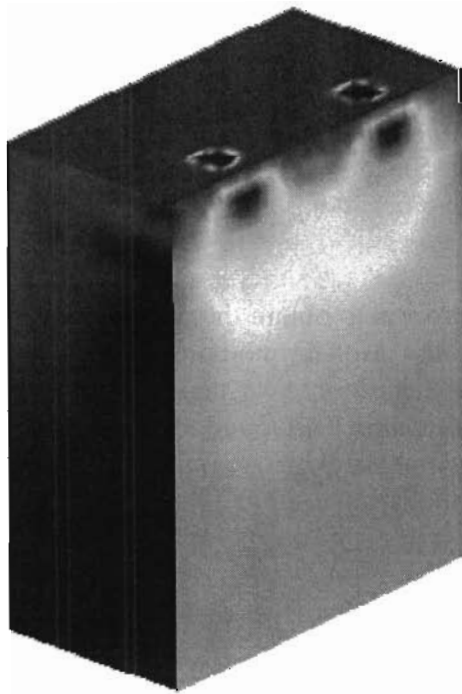
In order to implement an iterative process to obtain the non-linear resilient modulus for base and subgrade materials while keeping the asphalt modulus linear, it is required to differentiate between elements subjected to linear and nonlinear analyses. As shown in Figure 3.3, asphalt layers were not included in this nonlinear behavior and, therefore, are excluded from the iterative process. The discrimination of elements permitted the assemblage of two global stiffness matrices, one of them subjected to the iterative process while the other remains fixed. Since the mesh refines as it gets close to the surface, a considerable amount of elements, which happen to lie on the asphalt layer, are excluded from the iterative process, thus reducing the computation time. At the end of the analysis, both global stiffness matrices are integrated into a single one, as shown in Equation 3.2.

$$[GK] = [GK]_{fixed (ACP)} + [GK]_{iterated (Base+Subgrade)} \quad (3.2)$$



**Figure 3.3 - Pavement structure layers subjected to linear and nonlinear analysis.**

If the base and/or subgrade are considered linear, parameters  $k_2$  and  $k_3$  in Equation 3.1 are set to zero and the second assembly matrix (the left term of Equation 3.2) does not require iteration. The iterative process involves the calculation of stresses for those elements engaged on the iterations to obtain both confining and deviatoric stresses. Figure 3.4 presents the stress distribution for a 3D model of a tandem dual axle loading configuration.



**Figure 3.4 - Stress distribution, dual tandem configuration.**

## SEASONAL ANALYSIS ON PRIMARY RESPONSE

Pavements are subjected to different climatic conditions, for that reason, it was necessary to develop the program to perform an analysis that considers seasonal changes on the pavement structure material properties caused by temperature and moisture effects. To avoid reassembling global stiffness matrices for the asphalt material after every season, the previous assembled stiffness matrix was multiplied by the ratio of modulus of elasticity of the following to the previous season, resulting in less computation time.

## MODELING PERMANENT DEFORMATIONS

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

$$\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha} \quad (3.3)$$

where  $\varepsilon_p$  is the accumulated permanent strain,  $\varepsilon_r$  is the resilient elastic strain,  $N$  is the load cycle number and  $\alpha$  and  $\mu$  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:

$$R_D(N) = \frac{\mu}{1-\alpha} \cdot (W^+ - W^-) \cdot N^{1-\alpha} \quad (3.4)$$

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.

Figure 3.5 describes the algorithm that summarizes the entire calculation process of rutting depth. The finite element program, requires as an input the structural properties of pavement (thickness,  $E$ ,  $\nu$ , nonlinear parameters), as well as the type of truck and load (axle configuration, contact radius, axle load, axle spacing, tire spacing) to generate a mesh suitable for the analysis. Once the analysis is performed and deflections, stresses and strains are obtained, the rutting model is implemented using the required parameters  $\alpha$  and  $\mu$ , and number of load repetitions.

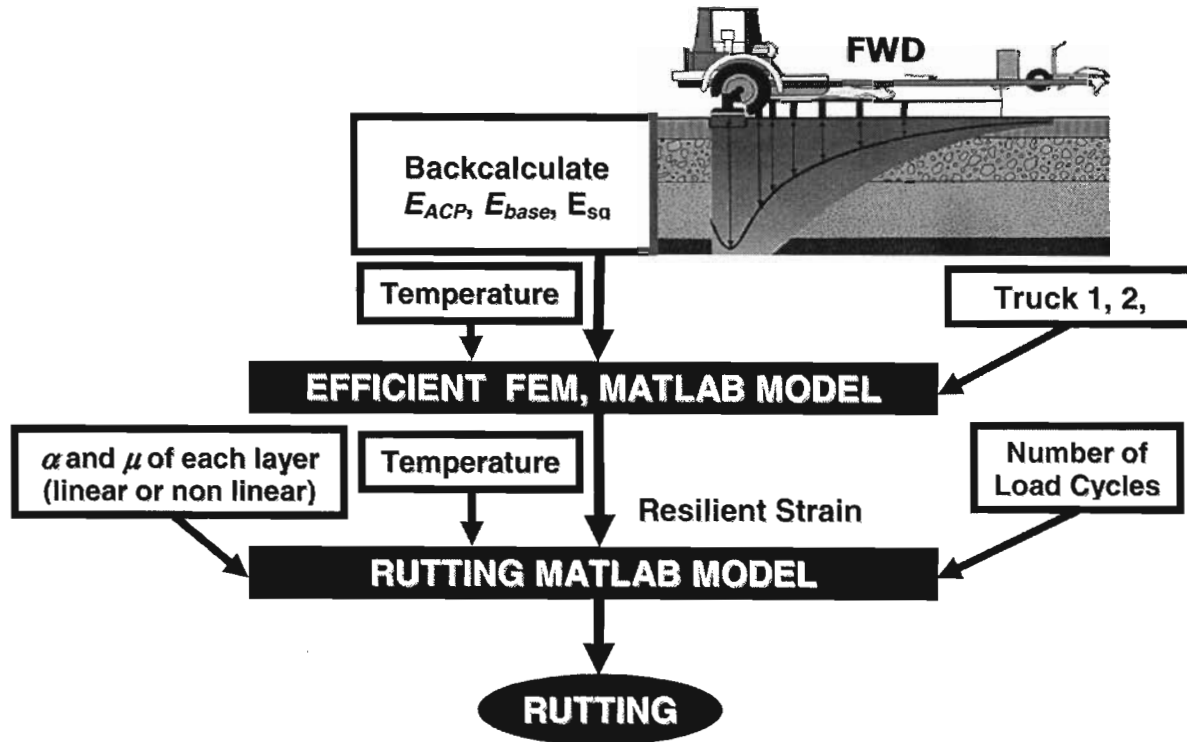


Figure 3.5 - Steps for calculating rutting.

## SEASONAL ANALYSIS ON RUTTING

Recent study by Zhou and Scullion (2002) demonstrated that  $\alpha$  and  $\mu$  are stress and temperature dependent, and as such are nonlinear. The finite element program implements these parameters to calculate rutting, as shown in Equation 3.3; nevertheless, the program code requires the user to provide such information on a seasonal basis. As mentioned before, the finite element model already performs an analysis that considers seasonal changes on the pavement structure material properties caused by temperature effects; however, the rutting model is implemented after the finite element model provides the system response to a given traffic loading. Parameters  $\alpha$  and  $\mu$  do not intervene in the process of reassembling global stiffness matrices as mentioned in the previous chapter. The rutting model is applied only after the pavement response has been determined providing a single rut depth curve with respect to load applications for each season. In order to obtain the actual rut depth with time, all seasons must be combined. In general terms, for  $n$  seasons,  $n$  variations in rut depth with load applications are obtained. Assuming that  $K_i$  ( $1 \leq i \leq n$ ) is the number of ESALs for each season, then the total number of load cycles  $T$  is given by:

$$T = \sum_{i=0}^n K_i \quad (3.6)$$

The actual rut depth as a function of ESALs from the  $n$  seasonal rut depth-ESAL curves can be obtained by combining them in the following manner: for the first  $K_1$  ESALs, corresponding to the first season, the rut depth-ESAL curve of the first season is used; for any other season, the corresponding curve of that season is shifted horizontally until the rut depth from the general

curve and the one under consideration coincide. This process is repeated for all seasons and integrated into a single rutting curve as shown in Figure 3.6.

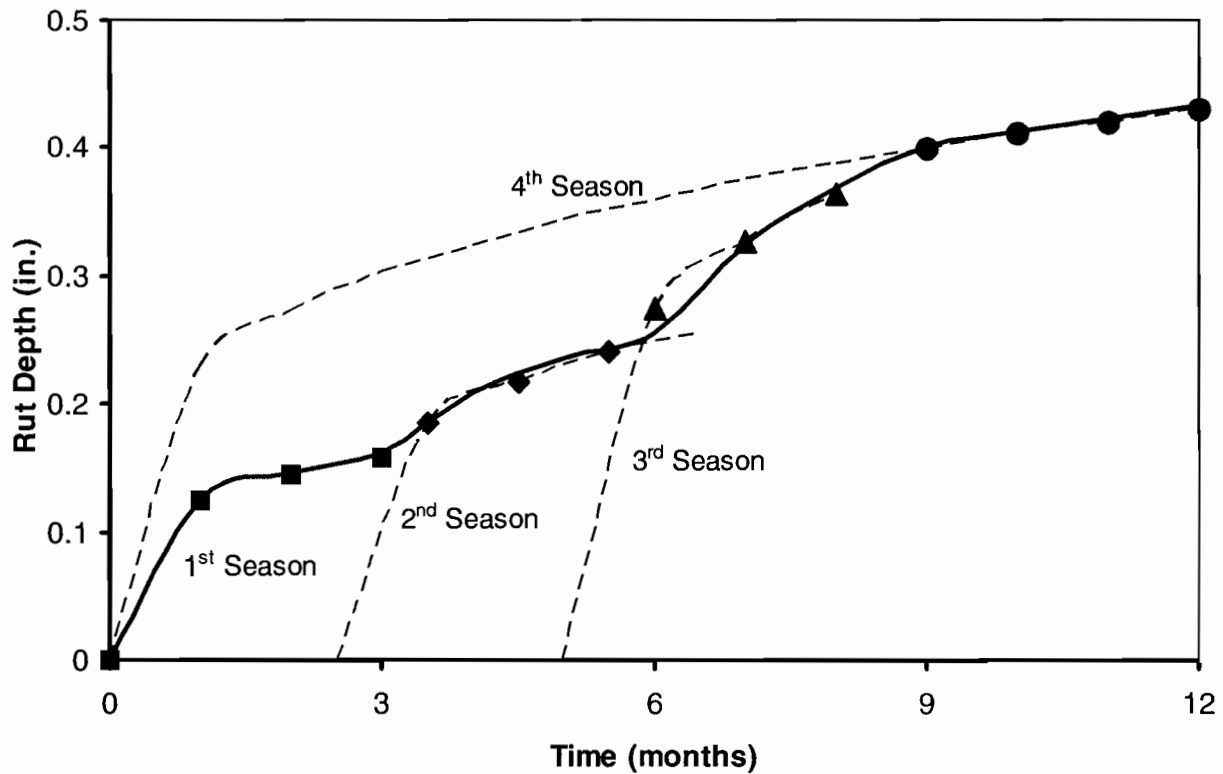


Figure 3.6 - Constructing final rut depth vs. time curve.

## PAVEMENT DISTRESS GUI

A Pavement Distress Graphical User Interface (GUI) was developed to facilitate the user the process of input of pavement section properties data. This software integrates the FE program previously described to calculate the permanent deformations caused by the user defined. The graphical user interface was developed based on Visual C++ code. On the other hand the FE program developed in Matlab<sup>®</sup> was compiled into an executable file that allows the Pavement Distress GUI to send to and retrieve data from the FE program once the user has gathered and input the necessary pavement information. See APPENDIX A for a thorough description of the Pavement Distress GUI program interface.



## CHAPTER FOUR - SAMPLE CASES

### INTRODUCTION

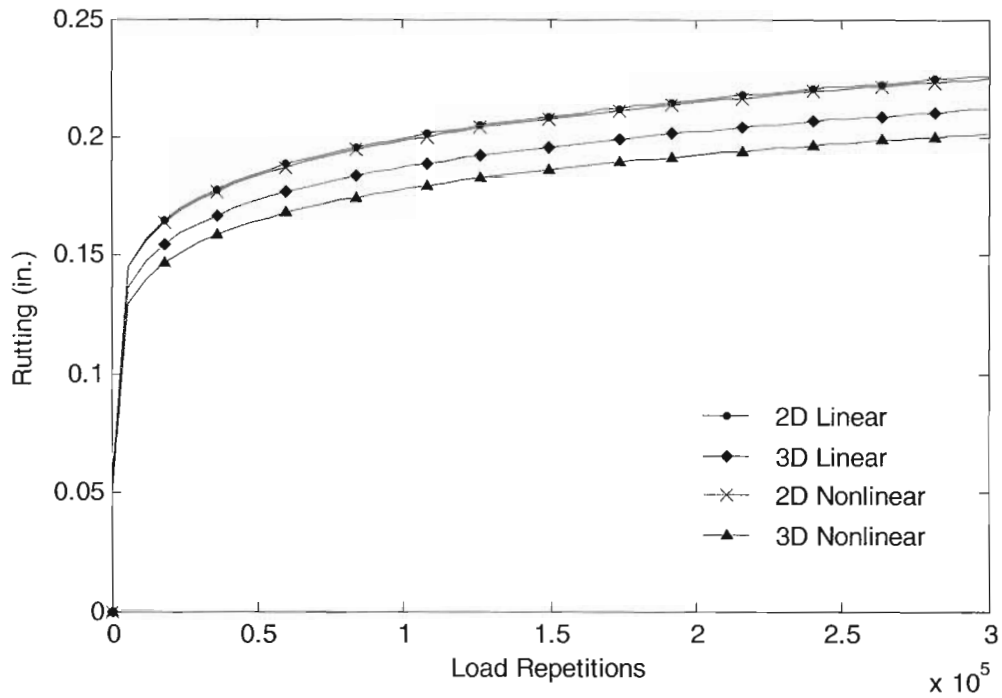
Table 4.1 presents properties of a sample pavement structure used to compare with the different type of models. The models taken into consideration are the ones described in the previous chapter: a linear model that considers all materials in the pavement structure with a linear elastic behavior; and, a nonlinear model that considers pavement materials to be subjected to an iterative process that obtains both confining pressure and deviatoric stress and implements the constitutive model shown in Equation 3.1, with the exception of the ACP layer which remains linear elastic. Results of such analyses are graphed on Figure 4.1 for a 9 kips (40 KN) single axle, with 114-psi tire pressure. Similar loading conditions result in similar results for rutting on the four available cases, both two- and three-dimensional linear and nonlinear analyses. Furthermore, the rutting obtained from the 2D FE linear analysis compares well with the ones obtained through VESYS 5, as shown in Figure 4.2 for a single axle load.

**Table 4-1 Sample Material Parameters for Asphalt Concrete, Base and Subgrade Layers.**

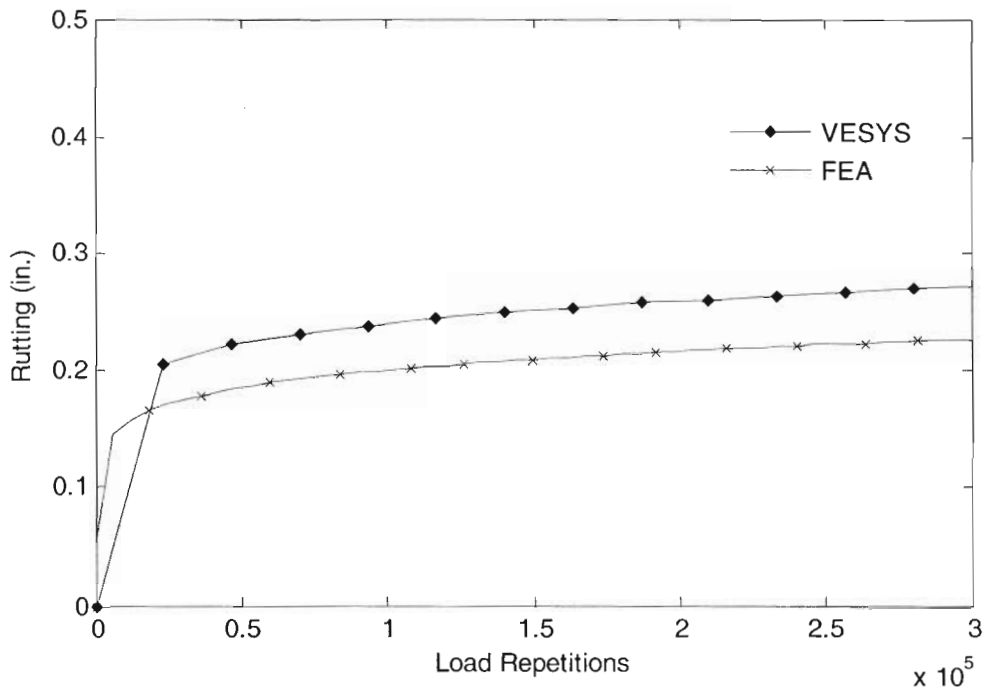
Layer	Thickness (in)	Modulus (ksi)	Material Properties			
			$\alpha$	$\mu$	$k_2$	$K_3$
ACP	3	500.0	0.78	0.35		
Base	12	50.0	0.87	0.25	0.20	-0.20
Subgrade	40	8.0	0.90	0.28	0.20	-0.05

Variation in material properties with respect to time (due to temperature variation) can be simplified into five seasons, as shown in Table 4.2. These parameters shown for the asphalt concrete layer were obtained from US281 near Jacksboro, TX (Zhou and Scullion, 2002). Typical cross-section of the site consists of an 8-in. (203 mm) asphalt concrete layer, a 15-in. (381 mm) base layer on top of subgrade. The effect of seasonal changes on rutting is evident as shown in Figure 4.3 where it is evident that rate of rutting is greater at higher temperatures.





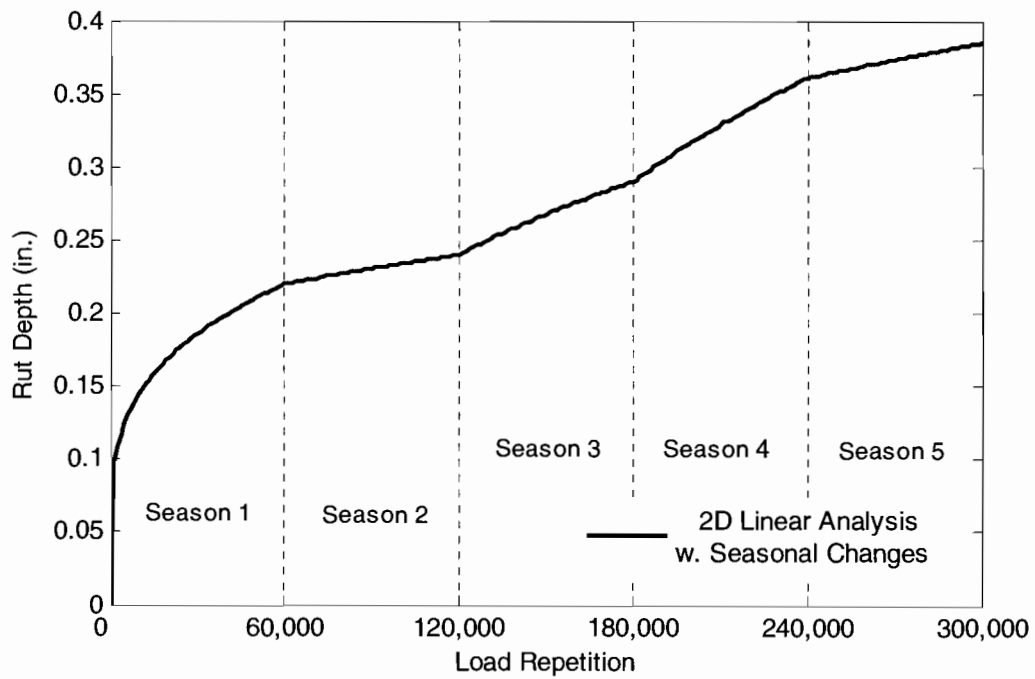
**Figure 4.1 – Sample pavement structure results for different models: 2 and 3-D models for both linear elastic analysis and nonlinear analysis using Equation 3.1 constitutive model.**



**Figure 4.2 - Rutting comparison VESYS vs. FEA 2D linear for a similar pavement structure.**

**Table 4-2 Sample Seasonal Variation for Asphalt Concrete Layer.**

Season	Temp (°F)	Modulus (ksi)	$\alpha$	$\mu$
1	89	211	0.610	0.260
2	84	243	0.638	0.263
3	92	194	0.598	0.250
4	95	180	0.568	0.245
5	91	200	0.598	0.259



**Figure 4.3 - Seasonal variation effects on rut depth.**



## **CHAPTER FIVE - GIS-BASED ROUTING APPLICATION DEVELOPMENT**

### **INTRODUCTION**

A Geographic Information System (GIS)-based automated tool to aid in the selection of routes that integrates pavement damage evaluation methodologies was developed to facilitate the process of evaluating feasible routes for super heavy trucks. This chapter describes the development of this GIS tool, the associated transportation network and the highway's pavement structure attributes. This software tool integrates the FE program described in Chapter 3 to calculate the permanent deformations caused by the super heavy loads being hauled on the NYDOT network of roads and compares the damage generated against a typical standard truck. The damage comparison generated by this "Pavement Damage Prediction" (PDP) tool can be used to estimate permit costs.

### **GEOGRAPHIC INFORMATION SYSTEM**

Although varied software exist for GIS application purposes, ArcView, the most popular desktop mapping and GIS software, was selected for the development of the GIS tool. The selection of ArcView was based on previous positive experience of the research group in the development of other TxDOT projects. In addition to the basic ArcView's package, *Network Analyst* was used to include automated routing capabilities in the GIS tool.

### **HIGHWAY NETWORK PREPARATION**

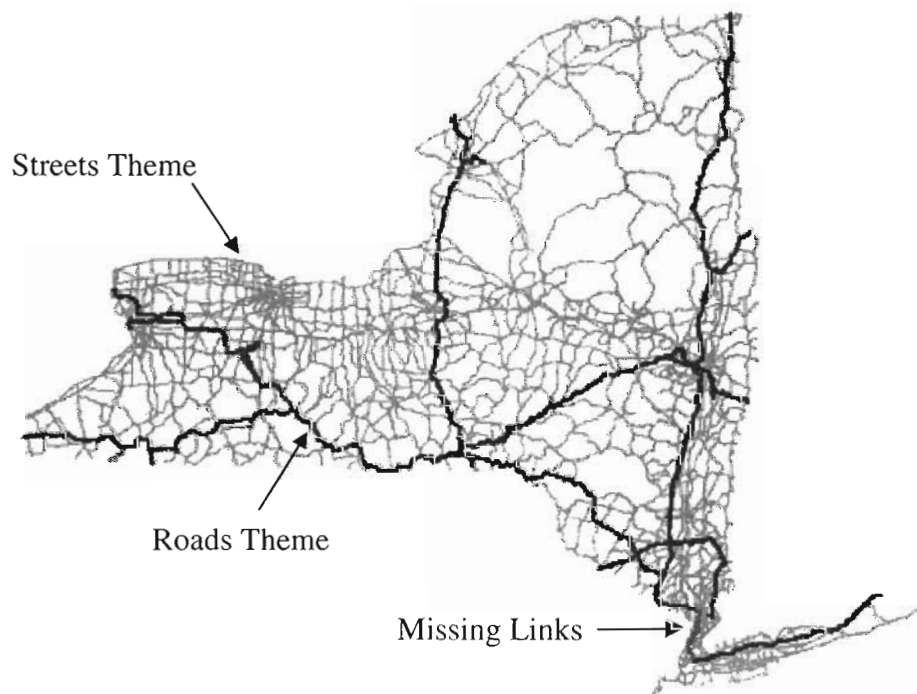
Digitized maps were provided by the New York Department of Transportation (NYDOT) that included state and interstate highways. The maps were provided in database format and included the following tables:

- *Sufficiency03*: NYDOT 2003 Sufficiency table included the information for creating a digitized "line" layer representing the New York State network of roads. It contains varied information for each line feature on the map, such as route number, state highway number, and others.

- *Surficial\_aashto*: surface geology table from the New York State Museum included polygon features showing the American Association of State Highway and Transportation Officials (AASHTO) soils classification.
- *Surficial\_deposition*: surface geology table from the New York State Museum included polygon features showing different types of soil deposit.

In addition, the NYDOT provided copies of permits issued by the Central Permit Office identifying the superload corridors based on the Special Hauling Route Survey for over-dimensional vehicles. A road shapefile (*Roads theme*) was generated from the *Street* network by extracting specifically those highways that represent these corridors. Figure 5.1 presents the New York State highway network (*Street theme*) with super-corridors highlighted (*Roads theme*).

In order to define the Origin and Destination used in the routing algorithm, a point feature theme called OD was created. Given that the Roads theme represents the highway system for superheavy trucks, the geographic network was generated from this theme, enabling the pavement damage prediction and comparison tool to work on it specifically. The Streets theme is used as visual reference to locate geographic features as shown in Figure 5.1.



**Figure 5.1 – New York State highway network**

Two new fields in the *Roads* attributes table were created and populated:

- *ONEWAY*: to prepare the “line” layer for directions as required by *Network Analyst* rules.
- *RelaDamage*: to temporarily store the damage comparison during execution of the tool.

As implemented in the GIS tool, *Network Analyst* finds the best route using the traveled distance as the cost in the shortest path algorithm.

## PAVEMENT PROPERTIES DATABASE

A pavement properties database was created to facilitate the extraction of pavement structural parameters and material properties to evaluate the pavement damage on the individual links that form the selected route. The pavement properties database was created under the assumption of a pavement consisting of no more than six layers: top asphalt, binder, concrete, base, subbase and subgrade. For each layer there are seven parameters that define its characteristics:

- Thickness: defined in inches.
- Poisson ratio
- Elastic modulus: defined in ksi.
- $\alpha$ : rate of decrease in permanent deformation (see Equation 3.3).
- $\mu$ : constant of proportionality between permanent and elastic strains (see Equation 3.3).
- $k_2$ : nonlinear parameter (see Equation 3.1).
- $k_3$ : nonlinear parameter (see Equation 3.1).

Since, only pavement type and thickness were provided for some road links on the highway network, other pavement properties were temporarily assumed during the development of the GIS tool. A sample of these properties is shown on Table 5.1.

**Table 5-1 Pavement Structural Parameters.**

<i>Layer</i>	<i>Thickness</i> (in.)	<i>Poisson</i> <i>Ratio</i>	<i>Elastic</i> <i>Modulus</i> (ksi)	$\alpha$	$\mu$	$k_2$	$k_3$
Top	1	0.30	500	0.78	0.40	N/A	N/A
Binder	1.5	0.30	500	0.78	0.40	N/A	N/A
Concrete	8	0.18	4,000	N/A	N/A	N/A	N/A
Base	6	0.35	50	0.75	0.25	0.20	-0.20
Subbase	12	0.35	30	0.75	0.25	0.20	-0.20
Subgrade	40	0.40	5	0.90	0.21	0.20	-0.05

N/A – Not available

## PAVEMENT DAMAGE PREDICTION INTERFACE

A Graphical User Interface (GUI) was developed in Visual Basic to allow for the definition of pavement truck parameters (number of axels, axle load, axle and tire spacing, etc.) and control route selection and pavement damage calculation. This user interface was designed to interact with ArcView through the use of the Dynamic Data Exchange (DDE) protocol to initiate the routing algorithm and extract all necessary data from the GIS databases. Once the route is selected, the program extracts, through DDE, the pavement properties for every link and

calculated the permanent damage by creating an input file and calling the Pavement Distress Program (FE program). The pavement damage is calculated for every link in the route.

To obtain a comparative measure of damage of a specific super-heavy truck compared with a standard vehicle, the damage caused by both vehicles should be calculated. As part of the user interface, the user can select one standard vehicle which could be either a T3-S2, or a T3-S4. The user can verify and modify the configuration of standard vehicles and save any modifications to a text file. The process of predicting pavement damage will be performed twice for every road link along the route: one for the standard vehicle, another for the specific super-heavy truck. A final report containing the relative damage results for the route will be automatically generated and viewable in WordPad and the links will be highlighted with different colors corresponding to the different levels of damage ratios

A new extension called Pavement Damage Prediction (PDP) Extension (pdp.avx), was created and copied to the default directory for ArcView extensions. This extension adds a new button to ArcView's interface. Pressing this button starts the Pavement Damage Prediction (PDP) extension after it verifies the presence of *Network Analyst*. Afterwards, it initializes the network and finally establishes communication with the external program developed in Visual Basic. See APPENDIX B for a description of the PDP interface.

## **CHAPTER SIX - SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK**

### **SUMMARY AND CONCLUSIONS**

Different models have been developed over the years to evaluate pavement distresses. 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 that were focused on pavement analysis as described in this report. This makes it more suitable than other FEA software since pavement geometry is better addressed, 3D state of stress and various load configurations can be considered, besides being more flexible than neural networks.

Furthermore, this finite element program was integrated on a GIS application to evaluate pavement on a given route. An application to automate the selection of routes and evaluation of their pavements for super-heavy vehicles was developed using GIS technology. The procedure developed uses a network representation of state highway corridors for super-heavy trucks embedded on a roadways map where it is possible to find the shortest path between two locations, an Origin and a Destination. The selected route is later evaluated for damage (i.e. rutting) inflicted by the traveling truck. Finally, truck damage is expressed in relative terms to that of the one developed by a standard truck.





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## **APPENDIX A**

### **PAVEMENT DISTRESS GRAPHICAL USER INTERFACE MANUAL**



## APPENDIX A – PAVEMENT DISTRESS GRAPHICAL USER INTERFACE

The software to calculate rutting was developed into a stand alone executable program which has the following characteristics:

- Easy-to-use interface.
- Convenient data input.
- Integrated FEA model, developed in Matlab®.
- Graphical display of results.

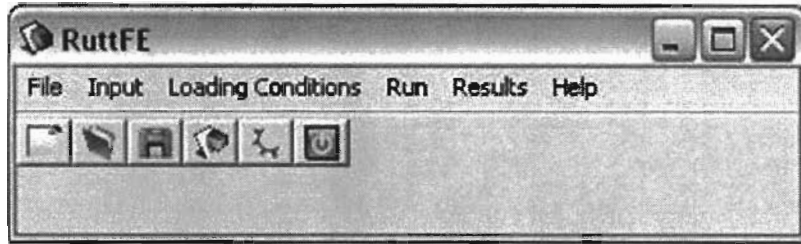
The software may be used for the following purposes:

- Rutting calculation for a given pavement structure and traffic loading scenario by means of finite element analysis, layer theory and Asphalt Institute procedure.
- 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.

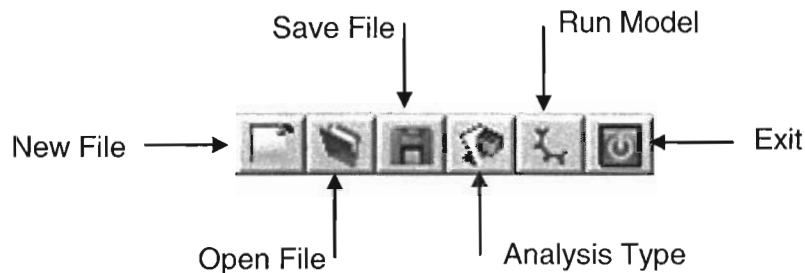
### MAIN WINDOW OVERVIEW

Executing the software prompts a main window that displays the main menu with a list of options, as shown in Figure A.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, and Exit. Figure A.2 presents the list of each button and the corresponding action.

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



**Figure A.1 – Main window.**

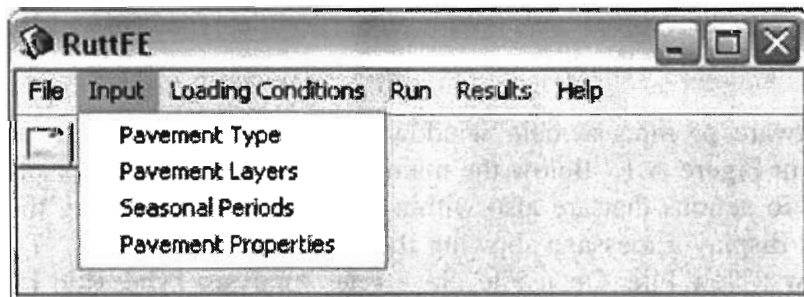


**Figure A.2 – Button activities.**

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.

## PAVEMENT STRUCTURE

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.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 A.4.

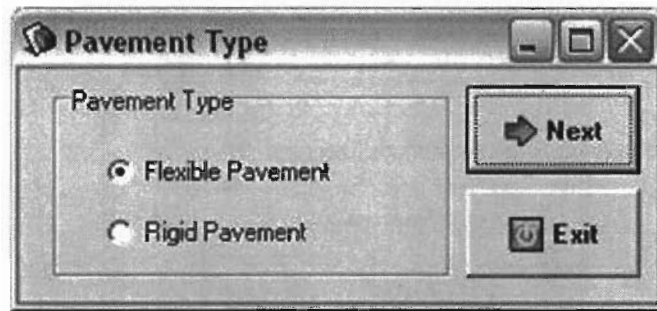


Figure A.4 – Pavement type selection.

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 concatenated menu items to select whatever item the user wants to edit. The following menu item is the **Pavement Layers** window that asks 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.5 shows the displayed window.

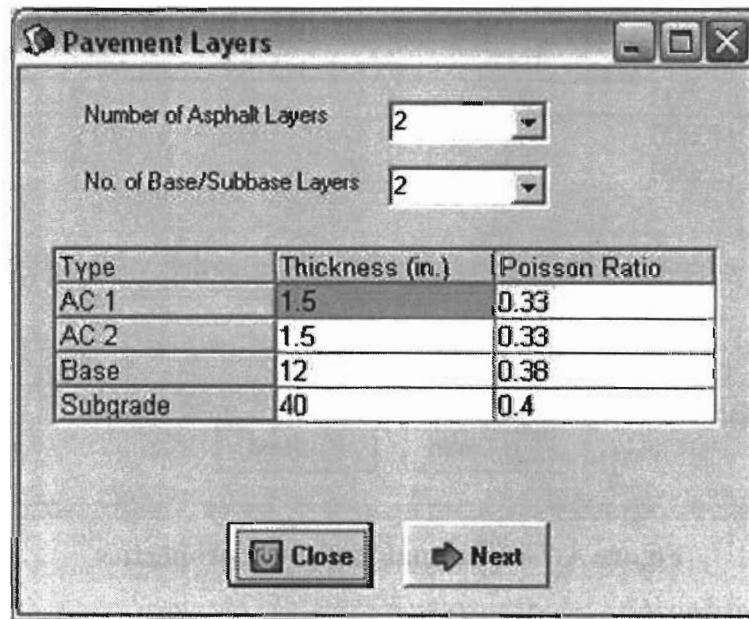


Figure A.5 – Number of pavement layers and structural properties.

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 should be within the analysis period and the season duration in days, as shown in Figure A.6.

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,  $\alpha$ ,  $\mu$ , and nonlinear parameters  $k_2$  and  $k_3$ . The window on Figure A.7 shows sample properties on a selected layer.



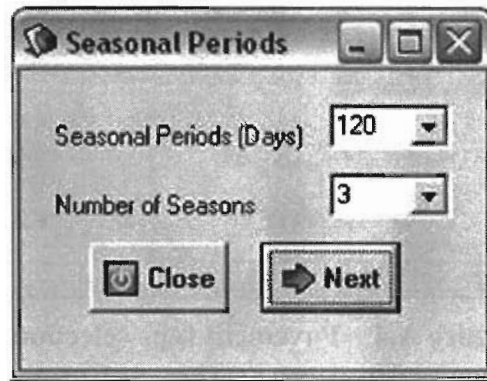


Figure A.6 – Seasonal period analysis.

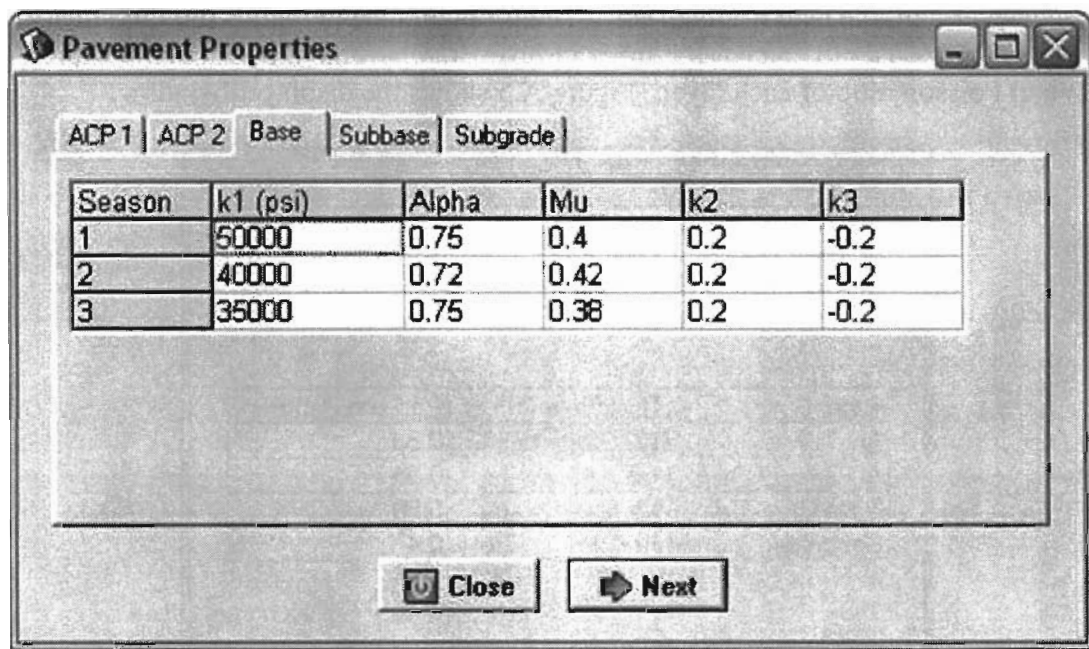


Figure A.7 – Seasonal pavement properties

## 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 A.8.

The prompted window asks the user the required traffic information such as the daily number of repetitions, traffic growth and the analysis period. Furthermore, it asks the user to specify if the analysis has to be done for a specific axle or for a truck relative damage compared with a standard truck. From this point, the analysis may follow two different paths and results are displayed in a different manner.

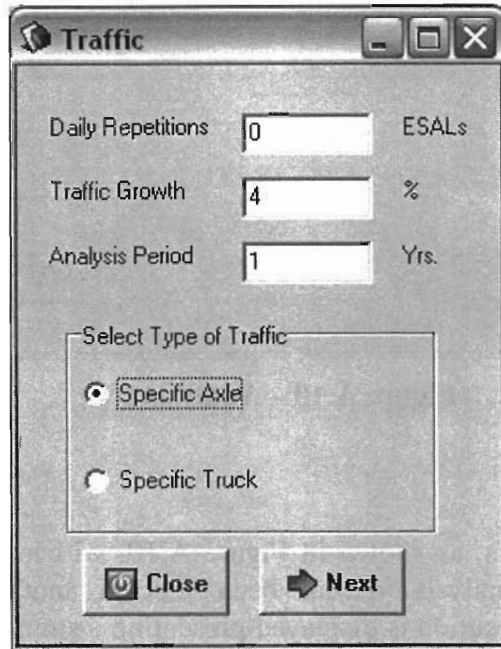


Figure A.8 – Seasonal pavement properties.

### SPECIFIC AXLE

The first option, **Specific Axle**, sends the user to the window shown in Figure A.9. This form asks the user for information regarding the axle loading and other properties such as tire radius, axle spacing and tire spacing depending on the number of axles within the axle group to be analyzed. The following window, shown on Figure A.10, prompts the user to select an **Analysis Type** which consist on a linear or nonlinear analysis that can be two- or three-dimensional.

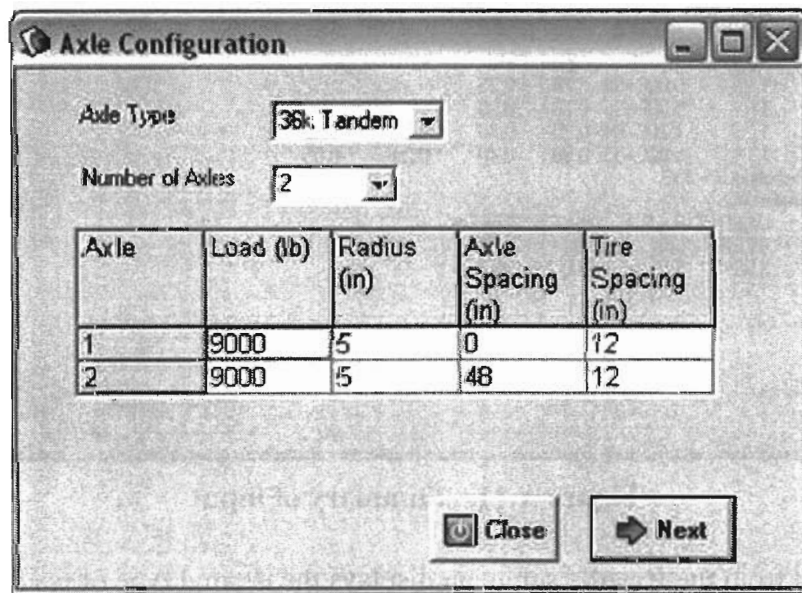


Figure A.9 – Axle loading and properties

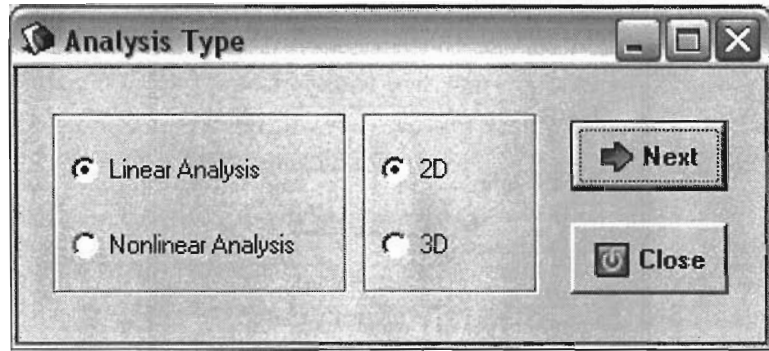


Figure A.10 – Analysis type

### 2-D Model

Selecting a 2D model analysis, as shown in Figure A.10, will lead to an axisymmetric finite element analysis. 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.11. Clicking the **Run** button will execute the finite element program. As soon as the execution process is finished, the results will be available to the user. A sample graph obtained from the results is depicted on Figure A.12.

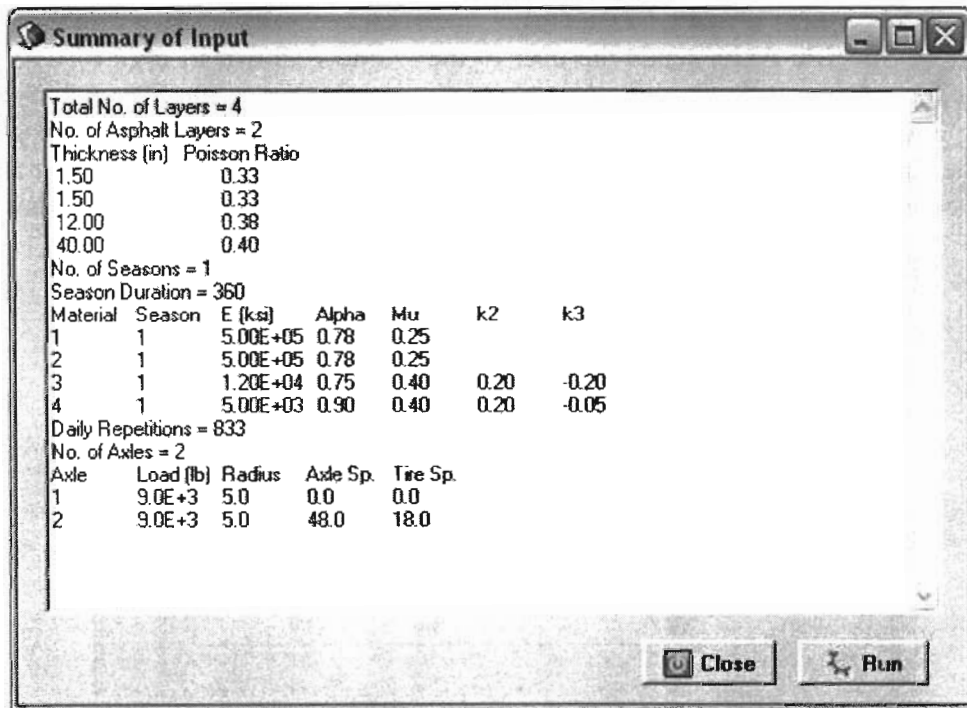


Figure A.11 – Summary of input

Selecting an option from the **Results** submenu displays the desired type of results. The first item is titled **Rutting**, and selecting it 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.

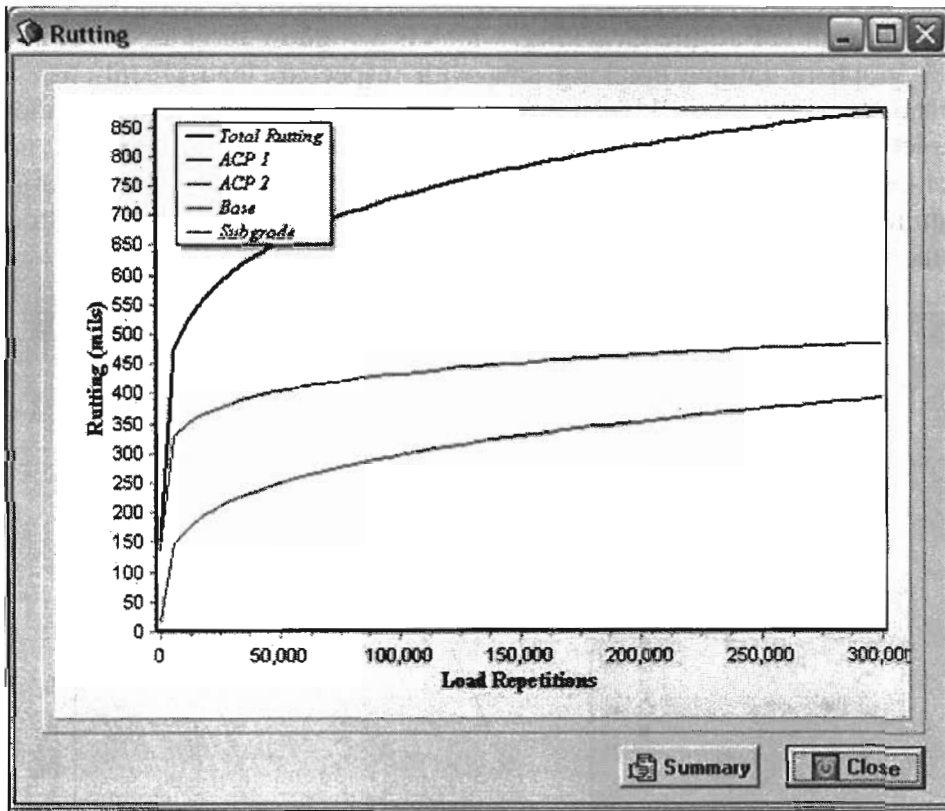


Figure A.12 – Rutting vs. load repetitions.

Along with the graph there is a button titled **Summary** that lets the user get the total rutting at the end of each season, and the contribution of each layer at the end of the total analysis period in terms of percentage, as shown in Figure A.13. This information may be saved into an ASCII text file.

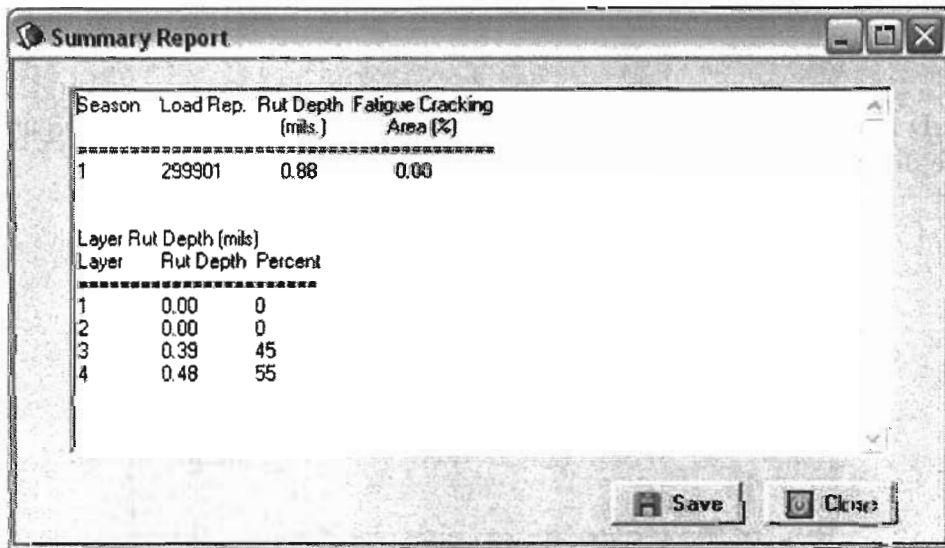


Figure A.13 – Summary of results.

Another available result is **Fatigue Cracking**, which is a window form as shown in Figure A.14 that displays a graph of fatigue cracking area with respect to load repetitions. The default method of calculation 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 **Calculate** button. Similar to the rutting form, the fatigue cracking form has a summary button that displays the summary of results form, but the button will not be active unless the rutting form has been selected first.

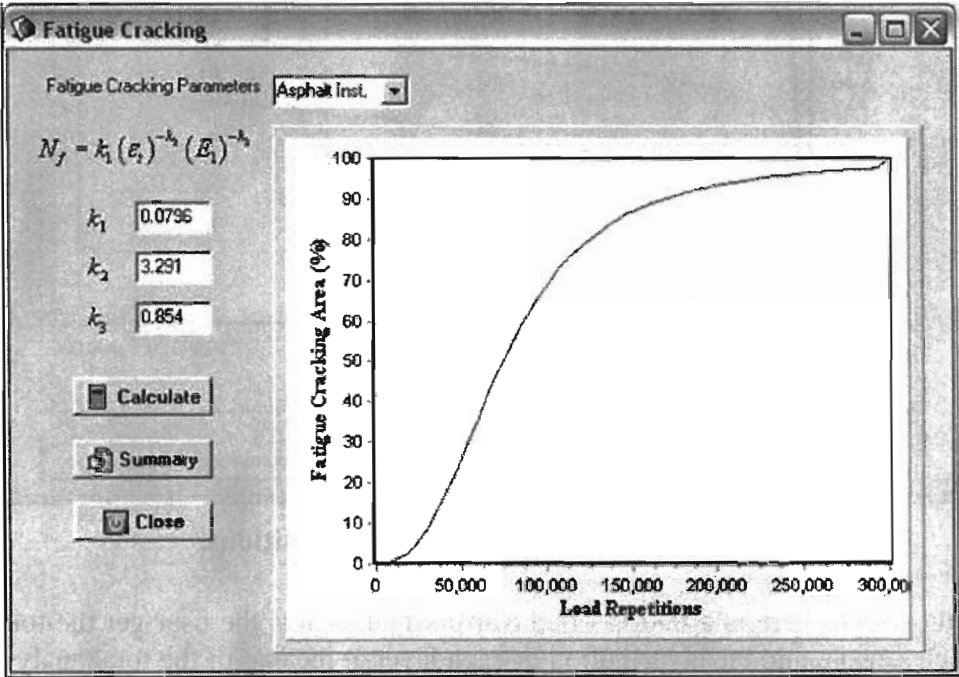


Figure A.14 – Fatigue cracking results.

**3-D Model**

Selecting a 3-D model analysis from the **Analysis Type** window, as shown in Figure A.15, will lead to a three-dimensional finite element analysis.

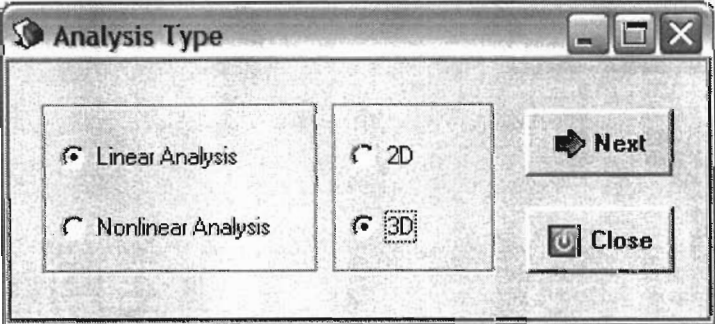


Figure A.15 – Analysis type, selecting a 3D model.

This option leads the user through similar steps as the ones described for the 2-D model. That implies that a summary sheet will be provided before execution of analysis and, thereafter, graphic results will be provided to the user through the **Rutting** window. Figure A.16 displays results from a sample 3-D analysis. Fatigue cracking results will also be available for this type of analysis through means of the **Fatigue Cracking** option shown in Figure A.14.

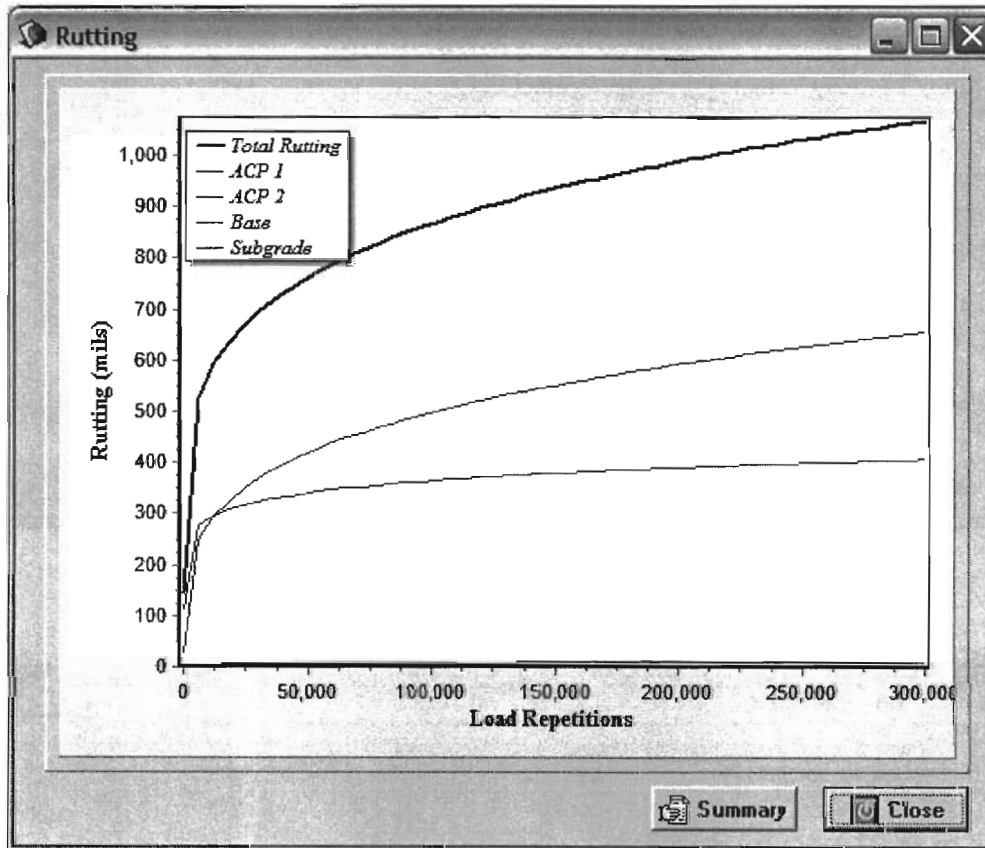


Figure A.16 – Rutting results.

## SPECIFIC TRUCK

On the other hand, the second option of the traffic form, **Specific Truck**, sends the user to a different form where a new and standard vehicle must be selected, as shown in Figure A.17. 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.18, 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.

**Truck Vehicle Selection**

Standard Vehicle

Gross Vehicle Weight (GVW)  kips

Empty Vehicle Weight  kips

---

Comparable Truck

Gross Vehicle Weight (GVW)  kips

Empty Vehicle Weight  kips

Figure A.17 – Truck vehicle selection.

**Truck Characteristics**

Number of Axle Groups

Steering Axle |  Front Axle |  Rear Axle

Axle Type

Number of Axles  Tires

Axle	Load (lb)	Radius (in)	Axle Spacing (in)	Tire Spacing (in)
1	9000	5	0	12
2	9000	5	45	12
3	9000	5	48	12

Figure A.18 – 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.19. There are three analyses available, the first one consisting on a comparison based on the equivalent axle load factor for each truck, 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.19 – Compare vehicles form.

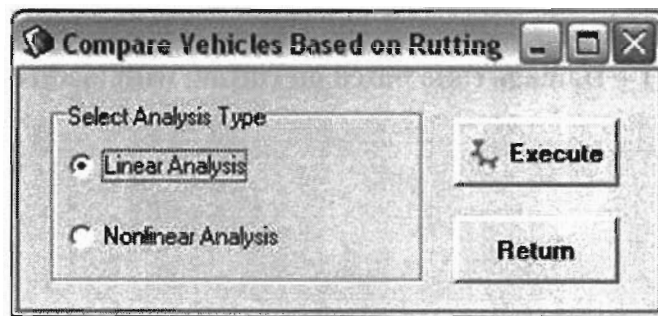


Figure A.20 – Analysis type for comparison.

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.20.

Selection of the rutting comparison will open a new graph displaying the ratio of damage factor based on rutting of the new truck to the standard truck. Similarly, fatigue cracking comparison displays a similar chart. Figure A.21 presents a sample graph of the rutting comparison.



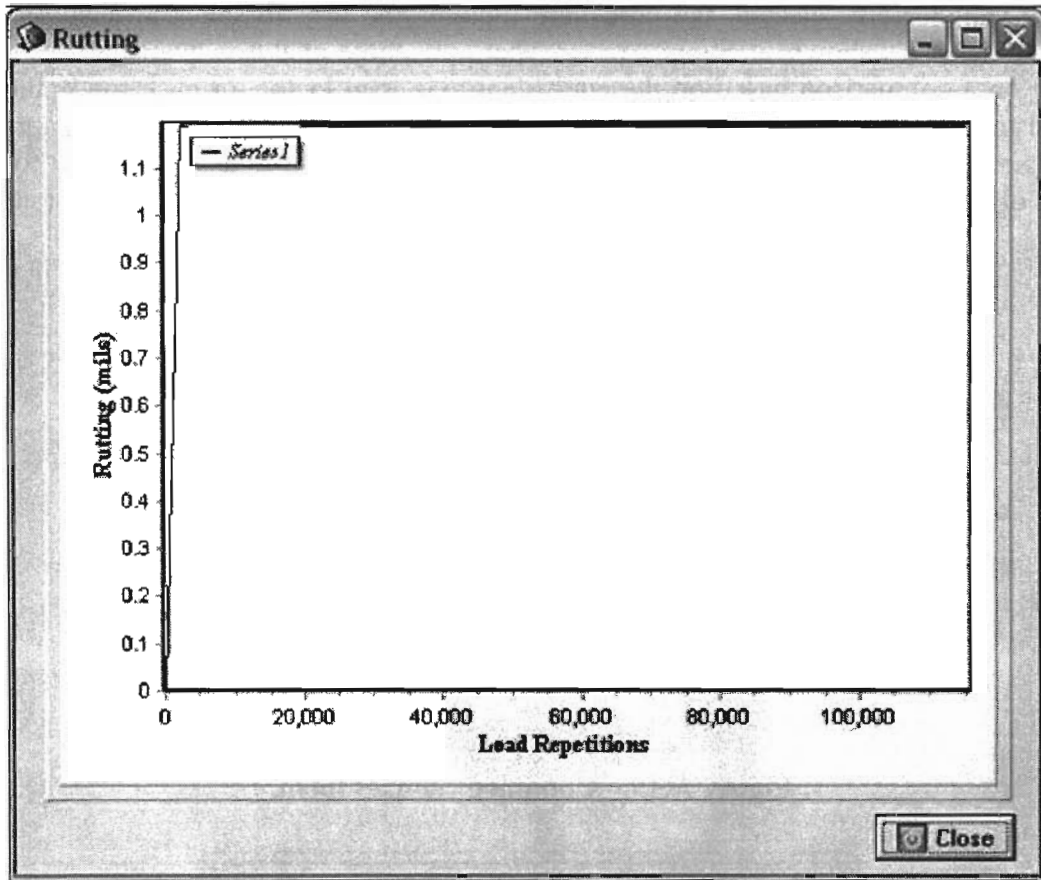


Figure A.21 – Damage ratio based on rutting with load repetitions.

## **APPENDIX B**

### **PAVEMENT DAMAGE PREDICTION (PDP) AND GIS NETWORK MANUAL**



## APPENDIX B - PAVEMENT DAMAGE PREDICTION (PDP) AND GIS NETWORK MANUAL

An add-in was developed for the geographic information system (GIS) network called Pavement Damage Prediction program. This program evaluates the damage on pavement generated by a super-heavy vehicle compared to a standard truck. In this appendix, the process of selecting an Origin-Destination, execution of shortest path algorithm, and route pavement damage evaluation is explained.

### ARCVIEW GIS

ArcView GIS is opened from Desktop or Start Menu program and deploys the main window as shown in Figure B.1, with a smaller window with a welcome message appears with different options. The user must create a new project as a **blank project** when the user accesses this program for the first time. Selecting this option adds new buttons that appear on the title bar corresponding to the Views, Tables, Charts, Layouts and Scripts menu options. Double clicking the **Scripts** tab, a new Script window appears, see Figure B.2. Selecting the **Load Text File** button will prompt a Load Script dialogue, as shown in Figure B.3, where a script file titled *Load4.txt* must be selected. This script must be compiled and once executed, the user will be prompted to load a map or a theme.

The user must load a map, and by following instructions shown on screen lets the user load three themes required for executing the Pavement Damage Prediction (PDP) program. These themes are titled *Streets.shp*, *Roads.shp* and *OD.shp*, which correspond to the state highway network, the state supercorridors network, and the Origin-Destination algorithm. These themes are loaded into a View named *New York*. Figure B.4 presents all opened views up to this step. The PDP program automatically saves the project file as *NewYork.apr* and a backup file named *NewYorkPDP.apr* into the *...\maps\* directory.

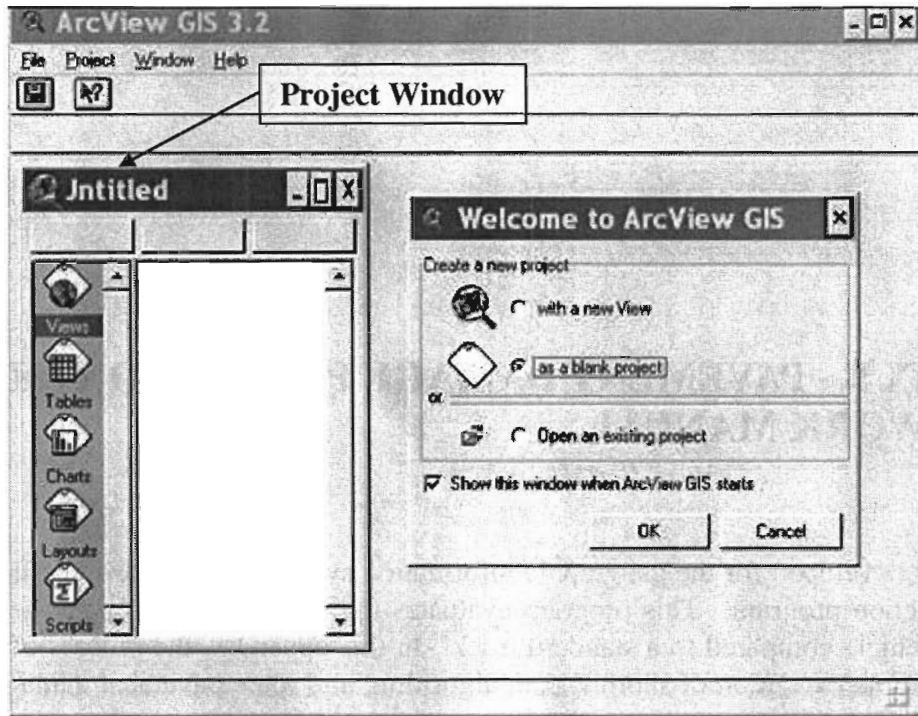


Figure B.1 – ArcView GIS main window.

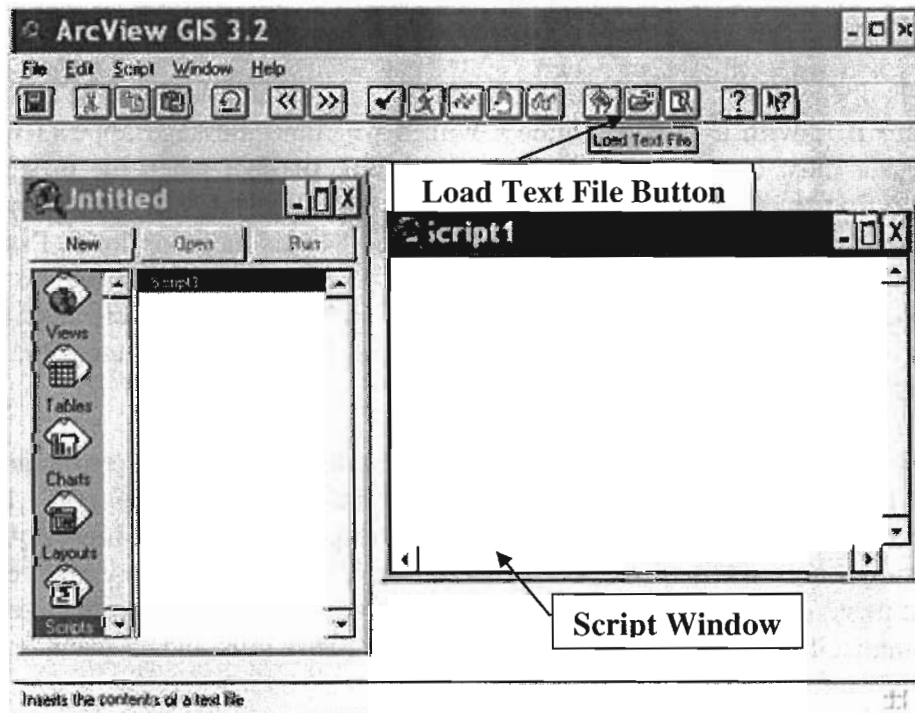


Figure B.2 – Creating a new project.

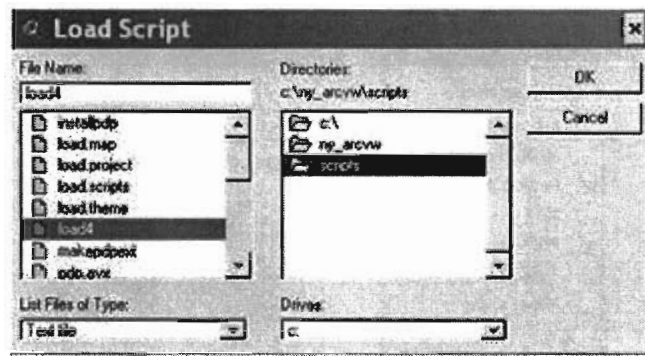


Figure B.3 – Load script dialog.

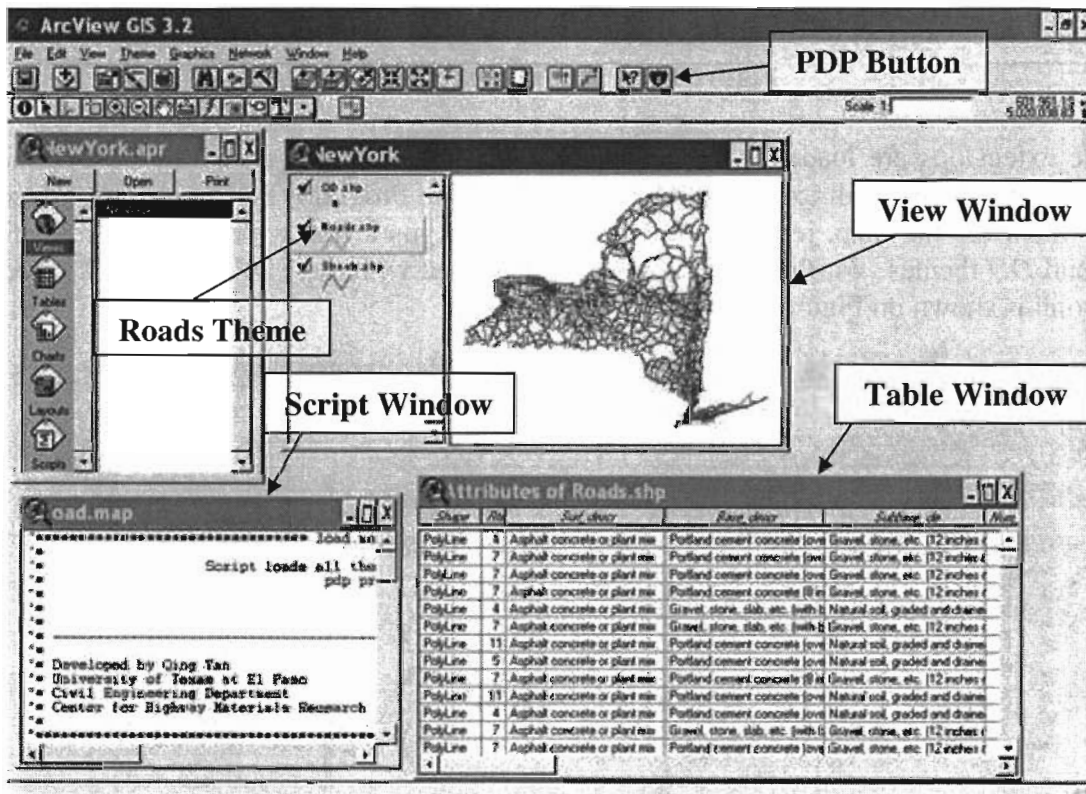


Figure B.4 – New York State Map and Themes.

## ADDING EXTENSIONS: NETWORK ANALYST AND PAVEMENT DAMAGE PREDICTION (PDP)

In order to execute the Pavement Damage Prediction (PDP) program, it is required to add extension into ArcView. Selecting **File** → **Extensions** on the menu opens the Extensions Dialog window shown in Fig. B.5. In this dialog, Network Analyst and PDP extensions must be checked from the available list of extensions. To avoid this step again, it is possible to default loading these two extensions whenever opening the project file again by selecting *Make Default*.

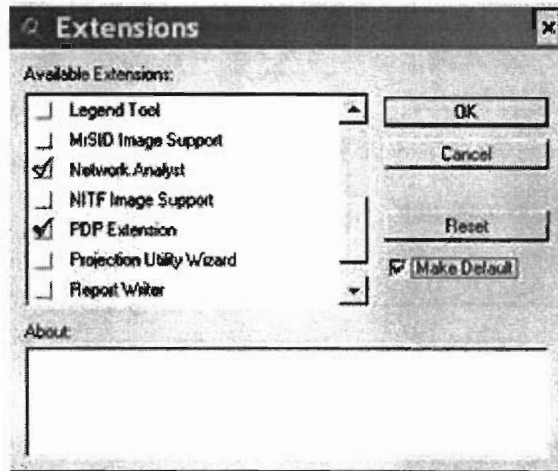



Figure B.5 – Adding extensions.

Once the extensions are loaded, a U.S. Interstate icon  will appear on the buttons bar. Clicking on this button will execute the Pavement Damage Program (PDP) program. Execution of PDP initializes the map, removes previous paths; assigns a line width and color for Roads, Streets and OD themes. Furthermore, a window is opened with the PDP toolbox. A screenshot to this point is shown on Figure B.6.

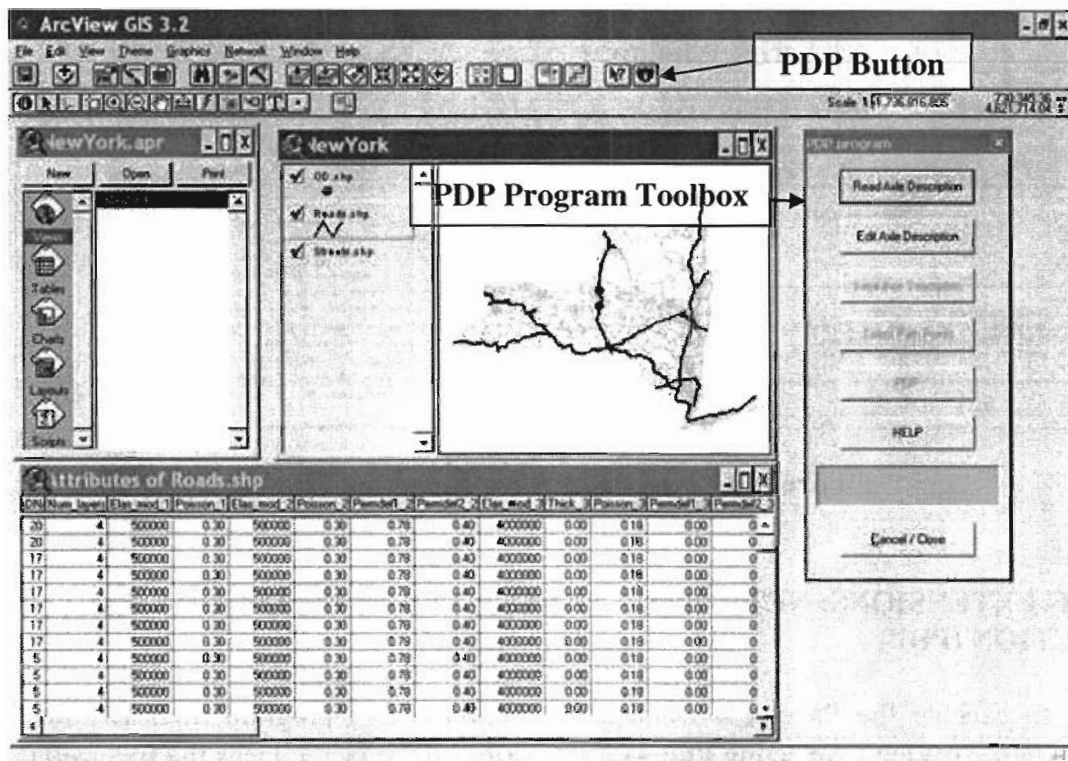


Figure B.6 – PDP extension added.

The PDP toolbox contains seven command buttons and a panel that displays status messages, as shown on Figure B.7.

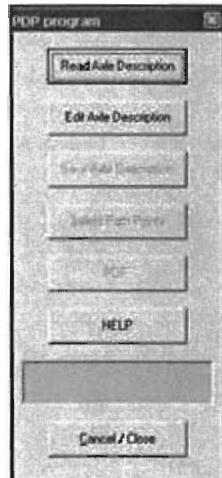


Figure B.7 – PDP toolbox.

## PAVEMENT DAMAGE PREDICTION

Selecting **Read Axle Description** button on the PDP toolbox displays a dialogue window, shown in Fig. B.8 requesting the user to a text file with axle information stored under the `\veh_lib\` folder. After selecting the text file, the user must select **Edit Axle Description** on the PDP toolbox to open another window that provides vehicle information from the selected text file as Fig. B.9 presents. The user has the option of editing the information and saving the axle description onto another file. A *Vehicle data saved* message will appear on panel.

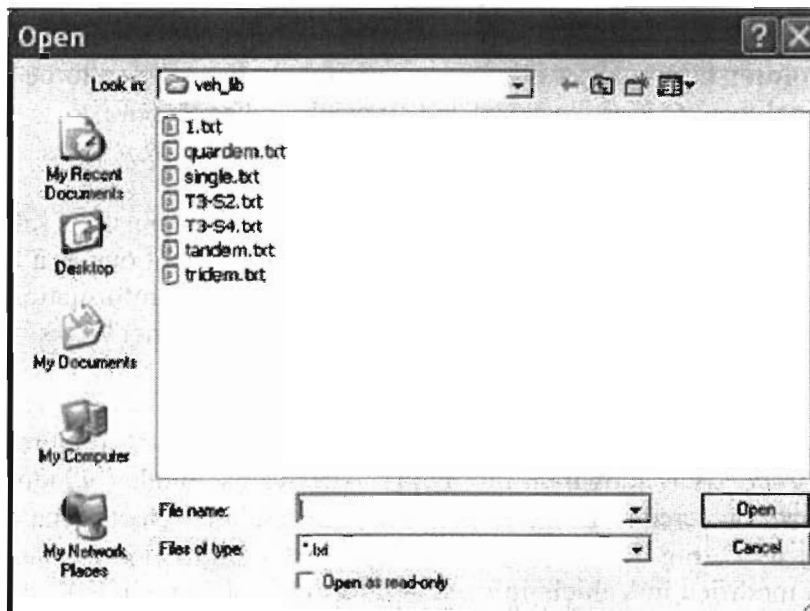


Figure B.8 – Open dialog to select vehicle properties text file.



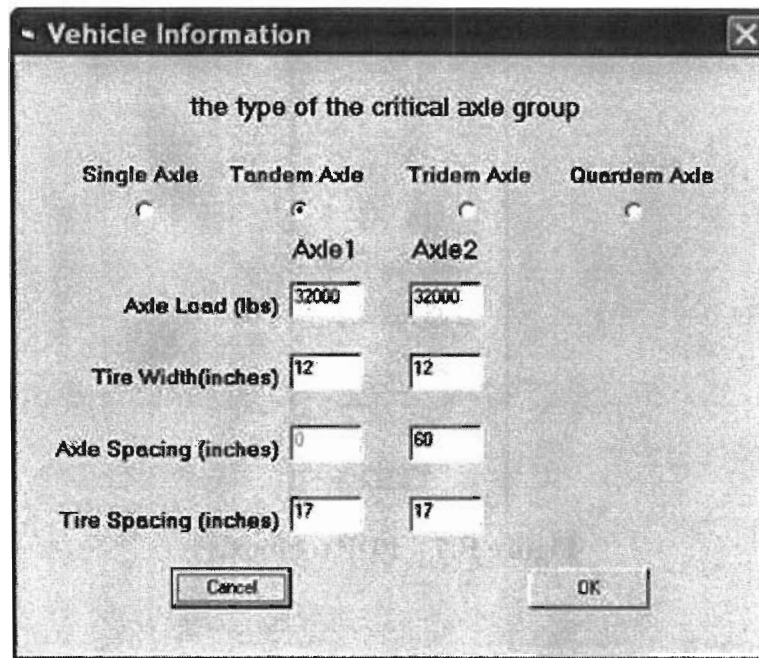


Figure B.9 – Vehicle information.

The Origin and Destination points may be selected by two different methods.

- Draw points: OD theme is set as a working theme by clicking **OD.shp** tab on the New York view window. **Theme** → **Start Editing** is selected from main menu, this displays a dash line that appears around the check box of **OD.shp**. Using **Draw Point** button on tools bar displays a highway network as a thick blue line on map. Storing edits are performed through **Theme** → **Save edits** and **Theme** → **Stop editing**.
- Move existing points: OD theme must be made editable as explained above. Then, selecting **Pointer** button allows the existing point shown on map to be moved anywhere on map. Finally, edits must be saved and stopped on theme menu.

Figure B.10 shows the main buttons used to perform this operation.

After editing the location of points, the **Clear Selected Features** must be selected to unselect points. The first point drawn is considered as an Origin while the last one as a Destination point. **Select Path Points** on PDP toolbox allows the program read OD information. Help files are available on the PDP toolbox under **Help**. In order to exit PDP, **Cancel/Close** must be selected. This closes dynamic data exchange between ArcView and PDP.

Selecting **PDP** on **PDP toolbox**, displays a save dialogue that prints the final report. The default directory is under *\reports\* as shown on Fig. B.11. Afterwards, another window titled **Analysis Parameters** is shown on screen. Both temperature and standard vehicle type (T3-S2 or T3-S4) must be defined by user. Fig. B.12 shows this window. Configuration of standard vehicle also can be defined and modified in Vehicle Information form by clicking on **Edit Axle Description**.

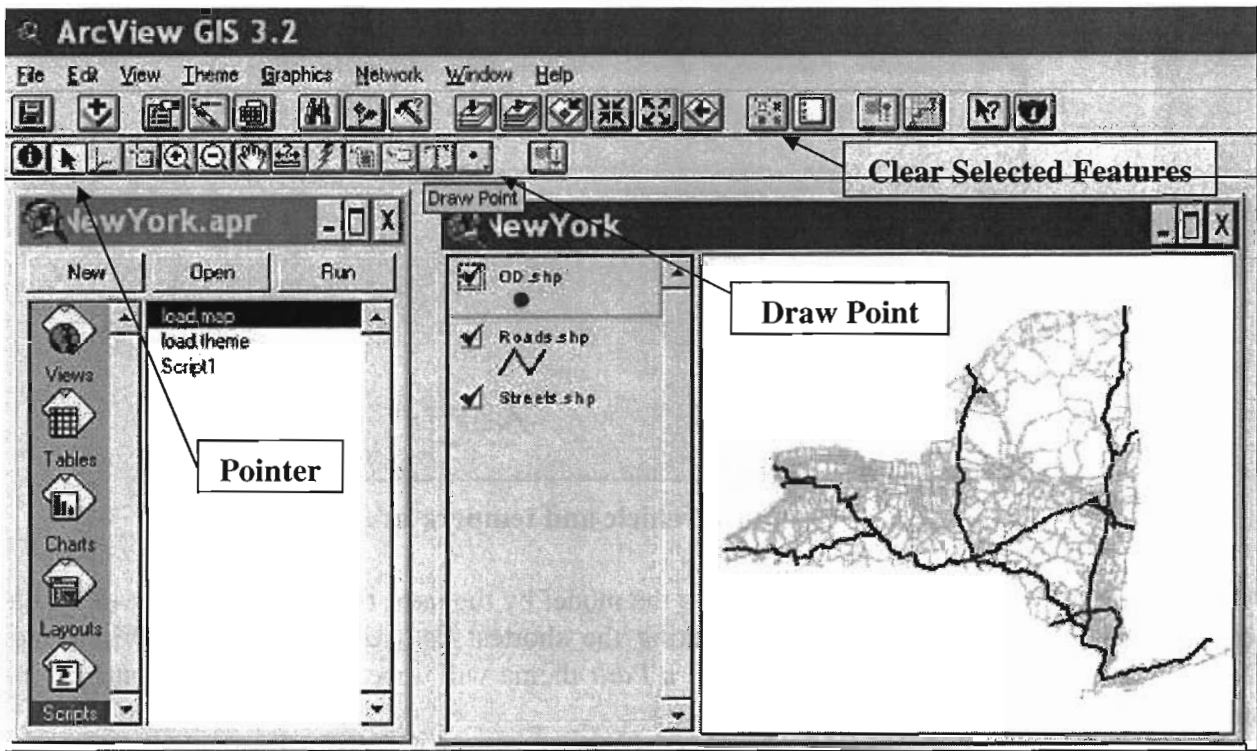


Figure B.10 – Defining Origin and Destination points.

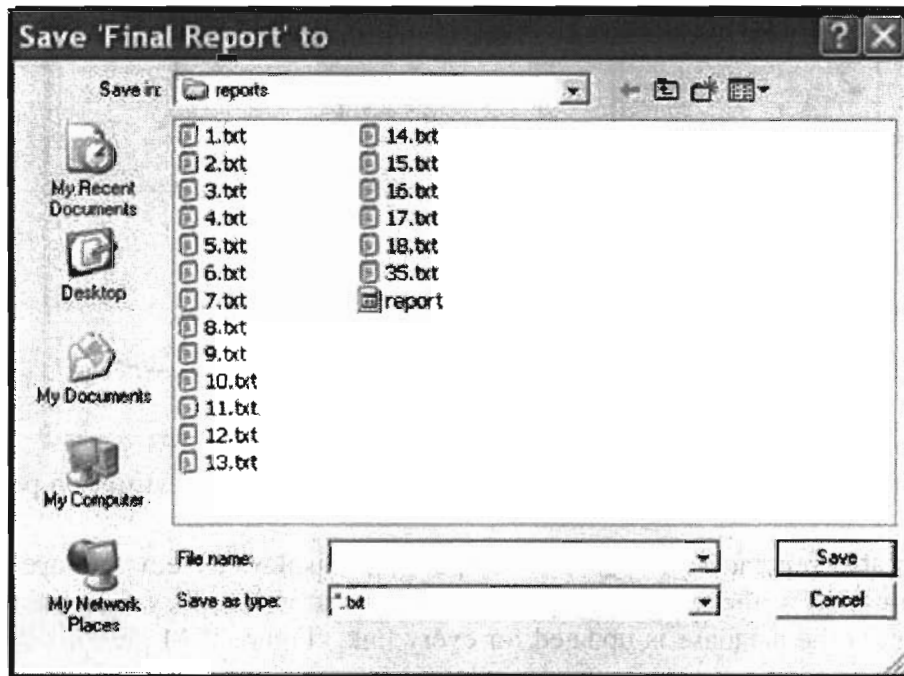
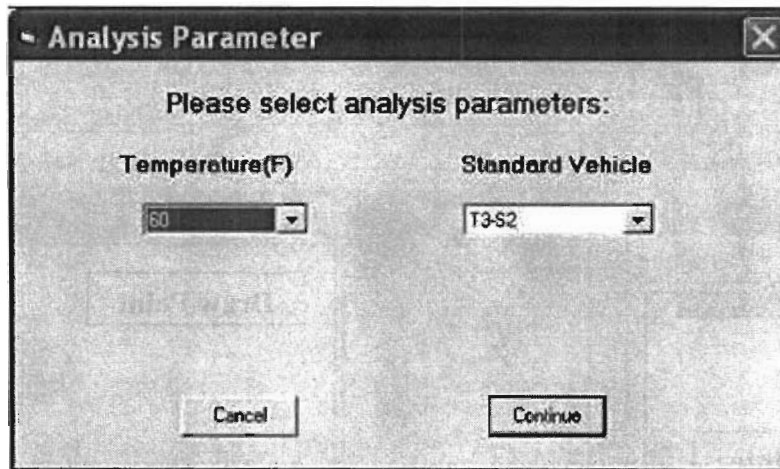
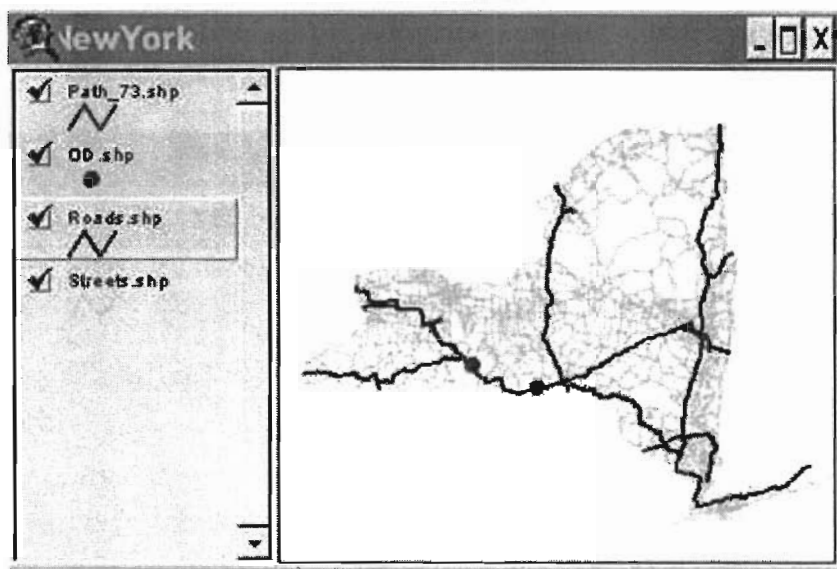


Figure B.11 – Save final report dialog.



**Figure B.12 – Standard vehicle and temperature defined.**

After all this information is incorporated into the model by the user, the PDP program will find a shortest path. A thicker red line representing the shortest path connecting both Origin and Destination points is displayed on map, and a *Path* theme will appear on Table of Contents, as shown in Figure B.13.



**Figure B.13 – Shortest route found between Origin and Destination points**

Furthermore, it also generates a **Progressive Report** that displays pavement properties along the shortest path found. For the time being, pavement information for every road link is assumed to be identical unless the database is updated for every link. Figure B.14 presents the Progressive Report window.

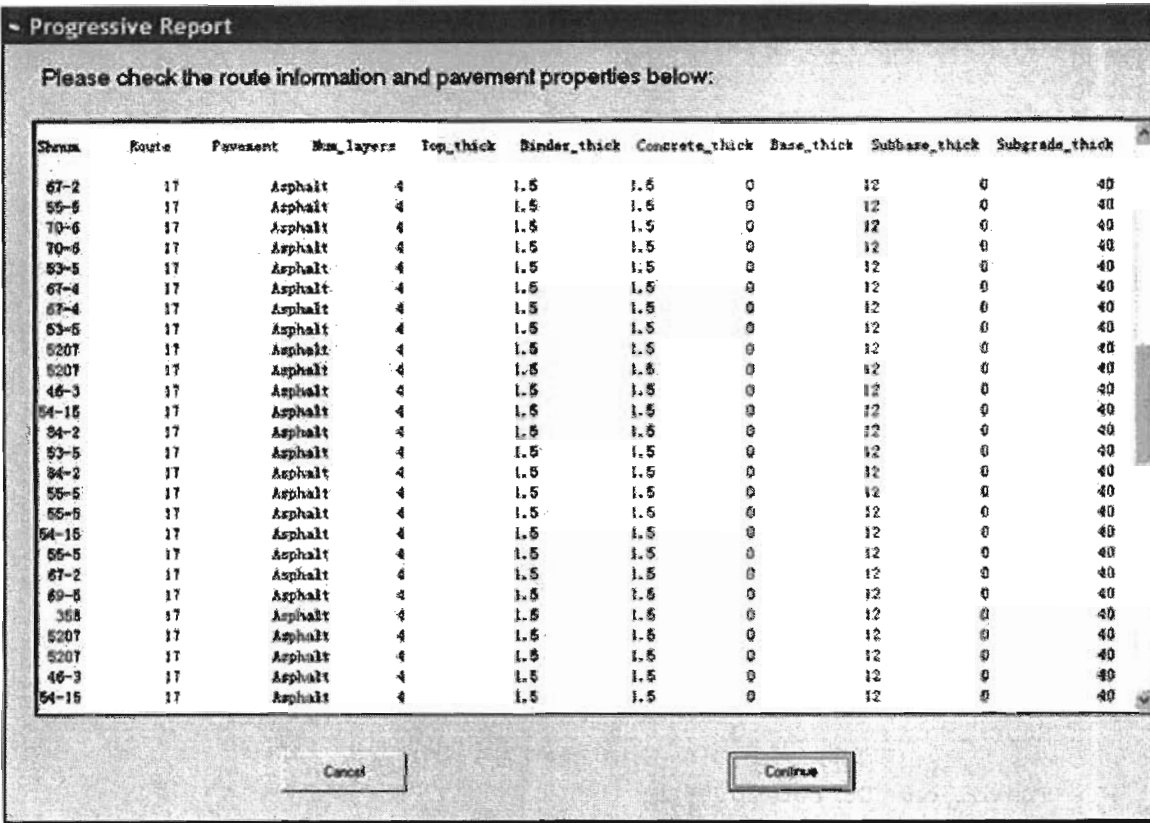


Figure B.14 – Complete shortest path links pavement properties

Clicking **Continue** accepts the information displayed on Progressive Report, and PDP calls the finite element program to analyze pavement permanent deformation for every road link. As said before, each link will be analyzed twice: one analysis for the standard vehicle, another one for truck to be compared with. Then, the relative damage will be obtained through a damage ratio between the specified truck generated rutting to that of the standard vehicle. Last, a final report will be written and displayed with the input information for each truck, and the obtained damage ratio.

An excerpt is presented below from a sample final report showing vehicle description, route description and relative damage for the route between origin and destination points.

```
***                               Vehicle Description and Pavement Properties
***
```

```
Algorithm: Shortest Path
```

```
---Super Heavy Vehicle Critical Axles Group Description---
```

```
Super Heavy Vehicle:    TANDEM
```

```
Number of axles    2
```

Axle load(lbs)	Tire width(in)	Axle spacing(in)	Tire spacing(in)
32000	12	000	17
32000	12	060	17

---Standard Vehicle Critical Axles Group Description---

Standard Vehicle: T3-S2

Number of axles	Axle load(lbs)	Tire width(in)	Axle spacing(in)	Tire spacing(in)
2	18000	12	000	17
	18000	12	060	17

-----Analysis Parameter Description-----

Temperature = 60

----- Route Description -----

Geographic Coordinates (Degrees)

Stop	Longitude	Latitude
0	315156	4684420
1	395166	4656310

Starting from Stop 0  
 Turn right onto 86  
 Travel on 86 for 20.96 mi  
 Continue straight onto 17  
 Travel on 17 for 45.61 mi  
 Turn right into Stop 1

Total distance traveled is 66.58 mi

----- Asphalt Pavement Damage Description -----

Num	Shnum	Top	Binder	Concrete	Base	Subbase
Subgrade	Total					
01	67-2	Relative Damage =	1.8			
T3-S2		-0.0003	0	0.0066	0	0.0768
.0831						
TANDEM		-0.0006	0	0.0118	0	0.1365
.1477						
-----						
02	55-5	Relative Damage =	1.8			
T3-S2		-0.0003	0	0.0066	0	0.0768
.0831						
TANDEM		-0.0006	0	0.0118	0	0.1365
.1477						
-----						
03	70-6	Relative Damage =	1.8			
T3-S2		-0.0003	0	0.0066	0	0.0768
.0831						
TANDEM		-0.0006	0	0.0118	0	0.1365
.1477						
-----						
04	70-6	Relative Damage =	1.8			

T3-S2		-0.0003	0	0	0.0066	0	0.0768
.0831							
TANDEM		-0.0006	0	0	0.0118	0	0.1365
.1477							
-----							
05	53-5	Relative Damage =		1.8			
T3-S2		-0.0003	0	0	0.0066	0	0.0768
.0831							
TANDEM		-0.0006	0	0	0.0118	0	0.1365
.1477							
-----							
06	67-4	Relative Damage =		1.8			
T3-S2		-0.0003	0	0	0.0066	0	0.0768
.0831							
TANDEM		-0.0006	0	0	0.0118	0	0.1365
.1477							
-----							
07	67-4	Relative Damage =		1.8			
T3-S2		-0.0003	0	0	0.0066	0	0.0768
.0831							
TANDEM		-0.0006	0	0	0.0118	0	0.1365
.1477							
-----							
08	53-5	Relative Damage =		1.8			
T3-S2		-0.0003	0	0	0.0066	0	0.0768
.0831							
TANDEM		-0.0006	0	0	0.0118	0	0.1365
.1477							
-----							