PAVESIM

Simulation of Pavement Damage

Due to

Heavy Vehicles

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PREFACE

In past assessments of the fair and reasonable cost responsibilities of any form of heavy vehicle, the greatest unknown has been the magnitude of damage to roads and bridges caused by these vehicles. Some researchers have concluded that heavy vehicles impose considerable damage, while others contend that weather and other non-vehicle factors are even more important. Dynamic simulation techniques have shown great potential to resolve the issue of cost occasioned by heavy vehicles on roads. If the attributes of both vehicle and pavement are accurately represented, dynamic simulation can shed light on how the two interact and can estimate much more effectively the costs of heavy vehicle use for a given pavement design. Similarly, simulation can estimate the change in vehicle use costs that would result if a pavement were upgraded. This is precisely the tool set required for highway investment benefit-cost analyses and cost allocation studies that consider vehicle use and pavement upgrade alternatives.

PaveSim, a dynamic simulation environment, has been created to help develop performance-based operations policy. Integrated into PaveSim is another simulation program called *TruckSim*, which was developed at the University of Michigan to model heavy vehicles. Using the dynamic wheel loads from TruckSim, PaveSim simulates the performance of jointed concrete pavements. *RigidPav*, a finite element program, performs the detailed calculation of deflections and stresses in the pavement. Within the PaveSim environment it is possible to quickly vary vehicle parameters such as number of axles and axle spacing, suspension type and characteristics, and payload and distribution. We can also estimate the effects on pavement life of pavement characteristics such as thickness, subgrade support, and joint types.

This report presents an overview of the PaveSim environment and its user interface. Most of the report is written as a PaveSim tutorial to be used by pavement designers and policymakers in state and federal departments of transportation.

ACKNOWLEDGMENTS

It has been a pleasure working with this great group of people.

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CHAPTER 1
INTRODUCTION

Under the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), states are not allowed to authorize the operation of Longer Combination Vehicles (LCVs) unless their operation was allowed prior to ISTEA. Federal policy during the six-year period of ISTEA legislates a more complete study of the implications of alternative LCV practices. Because one of the most important policy issues is the question of what infrastructure changes are needed, the benefits and costs of LCVs are major topics of debate for all states.

Different states allow various configurations of LCVs to operate on designated portions of their road systems, with widely varying restrictions. Most existing size and weight limits were first introduced by states and were based on their local experience and environment. National size and weight limits are based on a compromise among state laws to create some uniformity among state regulations. They are not necessarily based on physical size and weight limits to assure safe LCV operation or to limit pavement wear. Regulations based on vehicle performance would provide an incentive to the trucking industry to develop designs that maximize productivity and safe operation while minimizing pavement damage. Where such performance-based regulations have been implemented in other industrialized nations, they have resulted in the development of innovative vehicle configurations and pavement designs.

In past assessments of the fair and reasonable cost responsibilities of any form of heavy vehicle, the greatest unknown has been the magnitude of damage to roads and bridges caused by these vehicles. Some researchers have concluded that heavy vehicles impose considerable damage (Small, Winston, and Evans 1989), while others contend that weather and other non-vehicle factors are even more important (Newbery 1988). Dynamic simulation techniques have shown great potential to resolve the issue of cost occasioned by heavy vehicles on roads. If the attributes of both vehicle and pavement are accurately represented, dynamic simulation can illuminate ways in which the two interact and estimate much more effectively the costs of heavy vehicle use for a given pavement design. Simulation can also estimate the change in vehicle use costs that would result if a pavement were upgraded.

The importance of estimating dynamic effects should not be overlooked. Recent Midwest Transportation Center reports (Stoner et al. 1991, 1992) show that dynamic wheel forces can be much greater than measured static axle loads as a result of irregularities in the road surface. Depending on the vehicle speed, dynamic characteristics, and road conditions, dynamic loads can be 70 to 80 percent higher than static loads. Regulations extrapolated from static wheel loads and limited truck types are probably not appropriate for LCV use. We need a more rational procedure that will allow us to develop realistic guidelines for the operation of LCVs and other heavy vehicles on the nation's highways.

PaveSim is a dynamic simulation environment created to help develop performance-based operations policy. TruckSim software developed at the University of Michigan (UMTRI 1995) has been integrated into PaveSim to model heavy vehicles. Using the dynamic wheel loads from TruckSim, PaveSim is able to simulate the performance of jointed concrete pavements. RigidPave, a finite element program, performs the detailed calculation of deflections and stresses in the pavement. Within the PaveSim environment, it is possible to quickly vary vehicle parameters such as the number of axles and axle spacing, suspension type and characteristics, and payload and distribution. It is also possible to estimate the effects on pavement life of pavement characteristics such as thickness, subgrade support, and joint types.

PaveSim currently supports the following four components.

ROAD RATER SIMULATION

Designed to simulate an Iowa Road Rater test (Potter and Dirks 1989), this component validates simulation-based procedures. During this simulation the system performs linear elastic analysis of the pavement supported on a subgrade. Applied loads are the same as those used in the actual road test. Agreement between simulation and field data is quite reasonable, especially considering the uncertainty of subgrade conditions and variability in the test execution.

PAVEMENT CONSUMPTION

Pavement consumption is estimated as a function of the number of trucks that pass over a specific pavement. TruckSim estimates dynamic wheel loads for a given truck configuration and roadway profile, then RigidPav performs pavement analysis considering fatigue, cracking, and degradation of subgrade support. This analysis reports different pavement damage indices after a specified number of truck passes. The analysis continues until the maximum specified number of truck passes is reached or pavement fails due to a full depth crack at one or more locations. Using different pavement damage indices reported by RigidPave, an equivalent pavement thickness is determined as a function of the number of truck passes.

PERFORMANCE COMPARISON

Pavement deflection from any truck type and weight is compared to deflection from a standard truck. TruckSim simulates dynamic wheel loads from different trucks, performs a pavement analysis using these wheel loads, and reports maximum deflection values compared to those for a standard truck. These data can be used to develop performance-based guidelines for the operation of alternative truck types.

PAVEMENT RESPONSE

This component performs nonlinear analysis of a given pavement subjected to loadings specified by the user. Additional research applications are an option; for example, a continuously reinforced pavement model can be created using essentially the same element types used for the other options. It is also a simple matter to create a model that takes into account shoulders, different joint types, and other highway characteristics.

Chapter 2 presents an overview of the PaveSim environment and its user interface. Chapter 3 briefly introduces TruckSim and provides examples of loads from a few trucks (a standard 18-wheel tractor-semitrailer, a 10 percent overloaded truck, and a truck with walking beam suspension). Chapter 4 briefly describes the finite element model used in the RigidPav program and Chapter 5 contains typical simulations to illustrate the capabilities and usefulness of the simulation environment. Appendix A describes the Iowa Road Rater test in more detail. A comparison of PaveSim results and actual test data is also included. Appendix B contains instructions on how to convert road profile data (IRI data) into a form suitable for TruckSim, and Appendix C defines some of the keywords used in TruckSim input screens.

CHAPTER 2
SIMULATION ENVIRONMENT

PaveSim is a software package designed to analyze the damage caused by heavy trucks as they pass over a section of highway pavement. The program generates simulated truck and pavement data for use by the different components to quantify damage suffered by the pavement. The user moves between components using a mouse, enters data where required, and chooses output from one component for further analysis in another.

TruckSim is an associated program accessible from within the PaveSim environment and can simulate the behavior of heavy trucks and combination vehicles. More information regarding TruckSim is provided in Chapter 3.

Each of PaveSim's four components (Road Rater, Pavement Consumption, Performance Comparison, and Pavement Response) can be accessed from PaveSim's startup screen, presented in Figure 2–1. TruckSim data can be used with some of these components, as shown in the organizational chart in Figure 2–2. When a component needs dynamic wheel load data, TruckSim is automatically called. The startup screen also includes a button to go directly to TruckSim for situations where truck simulation is needed without pavement performance simulation.
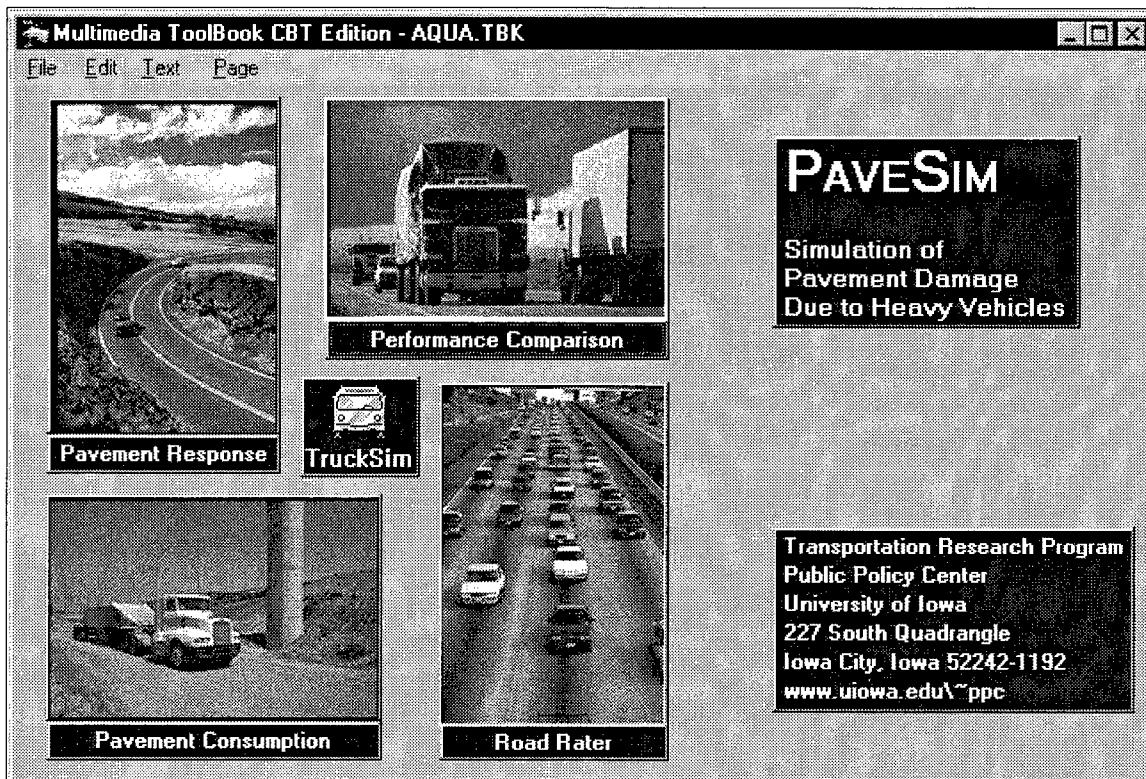
Figure 2–1. PaveSim startup screen
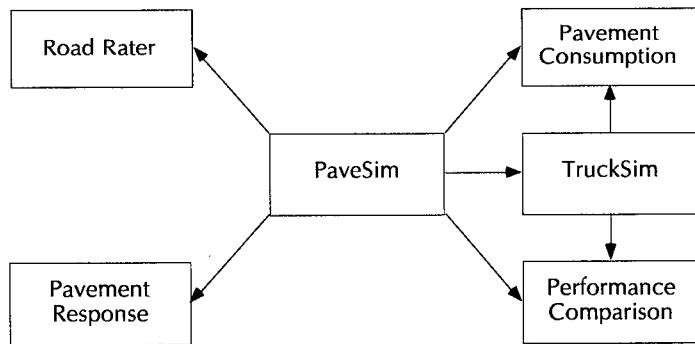
Figure 2–2. PaveSim organizational chart

Some components can also be accessed from the menu bar shown in Figure 2–3. The first four menus (*File, Edit, Text,* and *Page*) contain items that are fairly standard in window-based applications, such as facilities for opening and closing files, printing, cutting, and pasting. The *Analysis* menu allows the user to go straight to any of the four PaveSim components without going back to the startup screen. Similarly, the *Post Processing* menu takes the user to any of the post-processing screens. The *Help* menu provides detailed explanations of the parameters that are needed by the program.
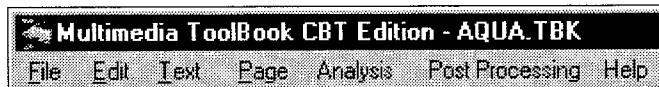
Figure 2–3. PaveSim menu bar

The four PaveSim components operate in a similar way. Each begins with an input screen displaying only those parameters to be used in that particular component.

ROAD RATER

The input screen for the first component, Road Rater, is shown in Figure 2–4. Road Rater is a computer simulation of the data that would be gathered by the actual Road Rater. Test Method No. Iowa 1009–B and has been shown to correlate very favorably with field test data. Appendix A contains the results of a study that supports this correlation.

Values that can be input in the Road Rater component include slab dimensions, concrete properties, dowel properties, and subgrade moduli.

Road Rater's output is the amount of deflection occurring in the defined pavement as a result of a point load. This data can be useful alone, or can become part of the analysis performed in the Pavement Consumption or Pavement Response components.

PAVEMENT CONSUMPTION

PaveSim's Pavement Consumption component evaluates the quality of pavement, predicting the fatigue life of the pavement under user-defined conditions. This component applies finite element analysis to the repeated passes of a user-chosen truck and load over a section of pavement that has an initial thickness also chosen

by the user. The resulting ratios of crack volume and crack depth, as well as the effective pavement depth remaining, are given as output. The input screen for Pavement Consumption is shown in Figure 2–5.
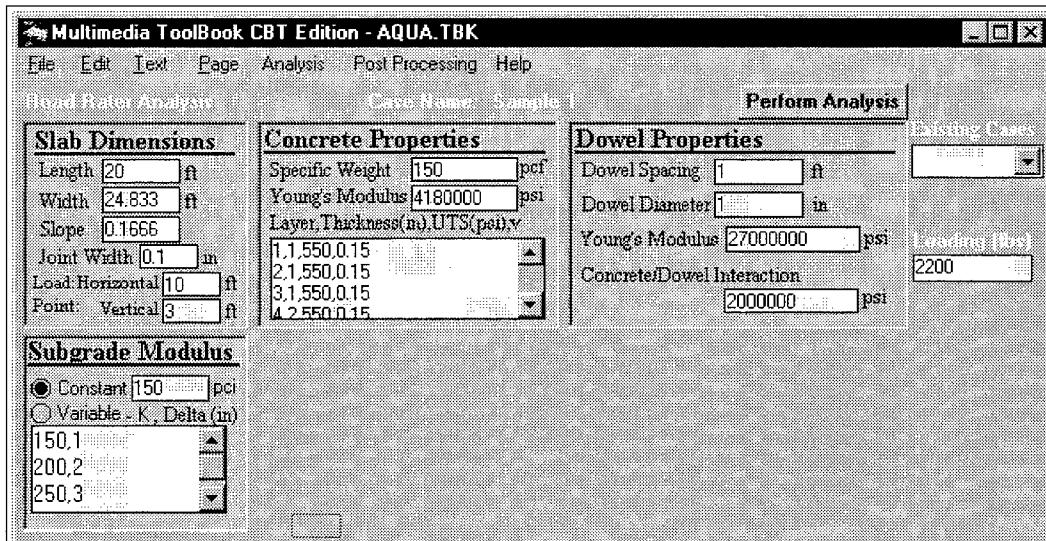
Figure 2–4. *Road Rater* input screen
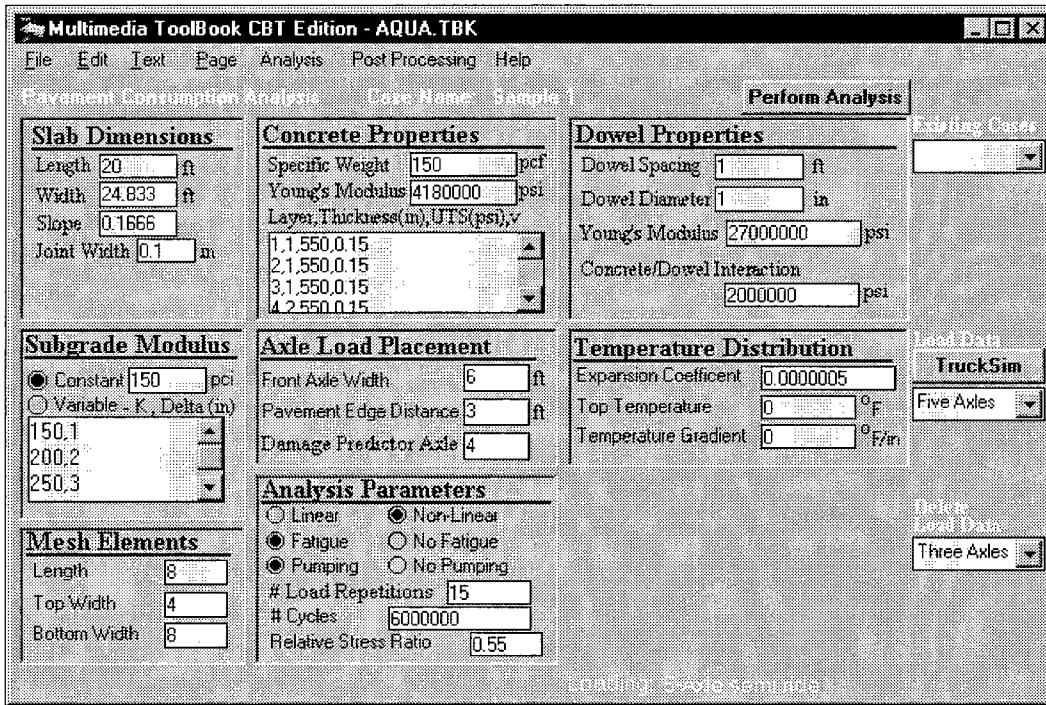
Figure 2–5. *Pavement Consumption* input screen

The input parameters of Pavement Consumption include slab dimensions, concrete properties, dowel properties, subgrade moduli, axle load placement, temperature distribution, mesh elements, and analysis parameters, as well as axle load data provided by TruckSim.

PERFORMANCE COMPARISON

Performance Comparison offers an analysis similar to that performed in the Pavement Consumption component, except that the analysis is linear and therefore proceeds more quickly. This component only considers one truck pass, so neither fatigue nor pumping damage is included. Compare the input screen for Performance Comparison in Figure 2–6 with that of Pavement Consumption in Figure 2–5.

In the Performance Comparison component, the user selects a truck and load to be analyzed from among those data files generated by TruckSim and a comparison is made between the deflection caused by that combination and the deflection caused by a standard 18-wheel tractor-semitrailer or other truck of the user's choice.
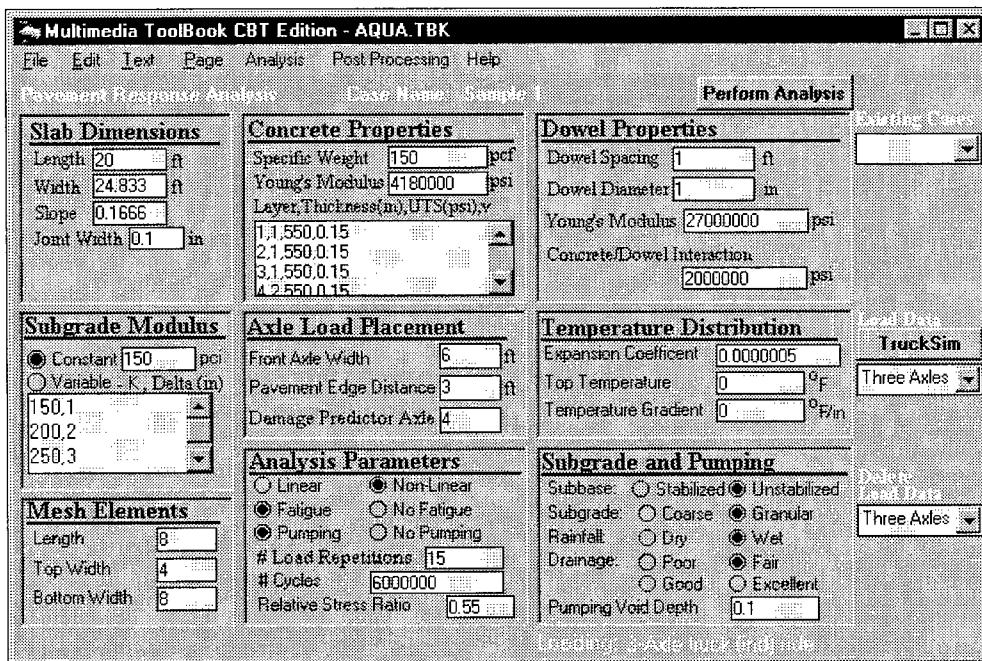
Figure 2–6. *Performance Comparison* input screen

PAVEMENT RESPONSE

Analysis in TruckSim's nonlinear Pavement Response component is similar to analysis in the Pavement Consumption component, but the user controls all input parameters, rather than bringing data in from Road Rater or TruckSim. The Pavement Response component constitutes the true "What if...?" opportunity available in PaveSim. Figure 2–7 shows the variables that are applied in this component. These variables comprise all of the parameters applied by Pavement Consumption plus parameters for subgrade and pumping.

PaveSim allows the user flexibility in choosing linear or nonlinear analysis, in modifying input variables, and the choice of applying simulated or empirical data to the finite element analysis of pavement damage. Chapter 3 describes the use of TruckSim while Chapter 5 will take the user through Road Rater, Pavement Consumption, Performance Comparison and Pavement Response in further detail.
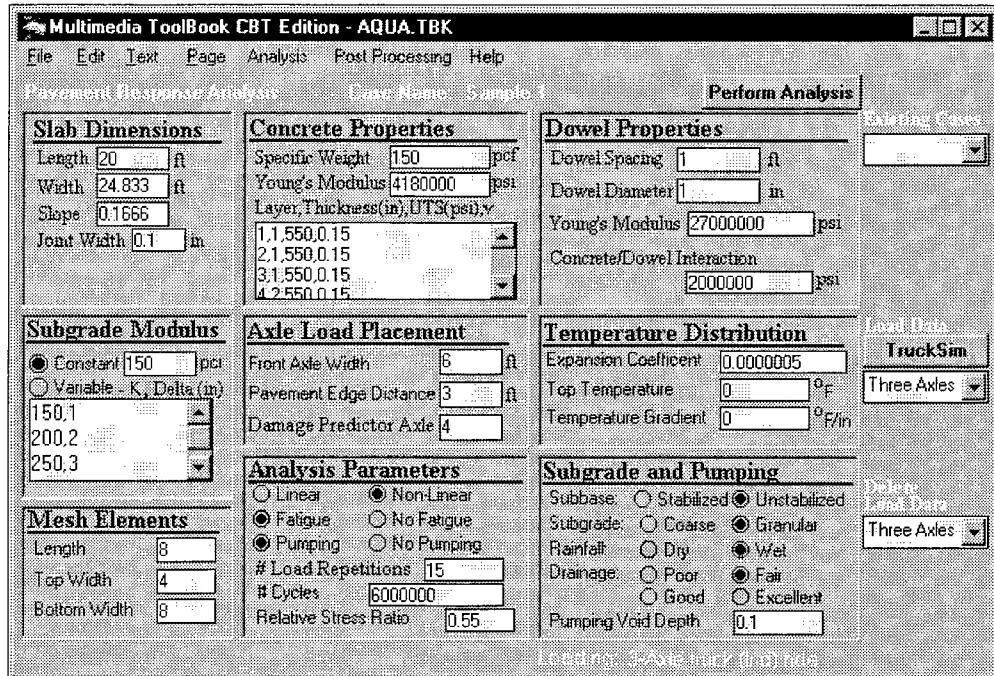
Figure 2–7. *Pavement Response* input screen

CHAPTER 3
DYNAMIC WHEEL LOADS USING TRUCKSIM

TruckSim is an integrated set of computer tools for simulating and analyzing the behavior of heavy trucks and combination vehicles. The software presently includes two modules: 2-D Ride and Dynamic Pavement Load and 3-D Handling and Roll. PaveSim only allows use of the 2-D Ride/Loading module, which predicts (1) vehicle vibrations due to road roughness and (2) the dynamic pavement loads that are the result of these vibrations. Vehicle designers and owners are generally interested in vehicle accelerations, while highway research agencies are more likely to be interested in pavement loads.

TruckSim was developed at the University of Michigan Transportation Research Institute (UMTRI) with funding from the Motor Vehicle Manufacturers of America under a research project called "Truck Simulation for the 90s," with additional funding from the Great Lakes Center for Truck and Transit Research.

This chapter introduces the TruckSim environment and some of its capabilities. To access TruckSim, click on the TruckSim button at the Pavement Consumption input screen or at the PaveSim startup screen. The TruckSim startup screen shown in Figure 3–1 will appear.
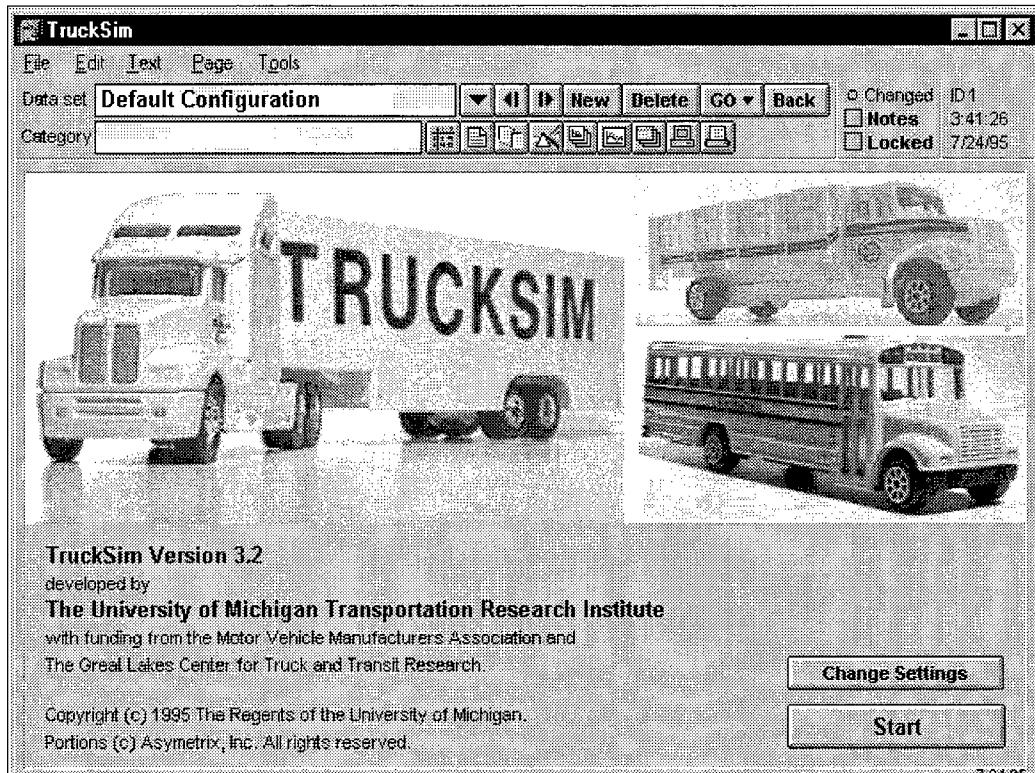
Figure 3–1. TruckSim startup screen

To begin a run simulation, click on [Start] in the lower right corner of the screen. The *Runs* screen as shown in Figure 3–2 will appear.
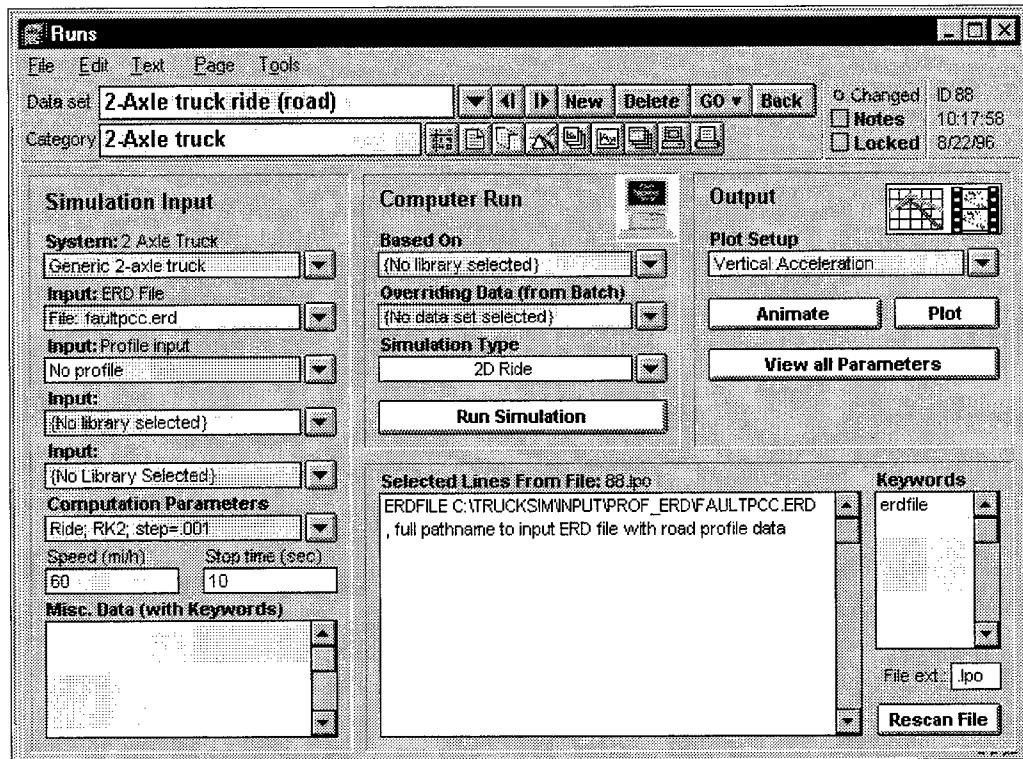
Figure 3–2. *Runs* screen

EXPLORING TRUCKSIM

Two buttons in the top ribbon menu allow the user to move freely within TruckSim: [GO▼] provides a link to any input screen and [Back] returns the user to the previous screen.

Click on [GO▼] and highlight *more*. All *TruckSim* screens are displayed in this menu, as illustrated in Figure 3–3. Highlight *tractors\3axle\3a_tract.tbk* to view a dimensioned sketch of the 3-axle tractor. Click [Back] to return to the *Runs* screen.

Try moving to other screens using [GO▼]. Return to the *Runs* screen directly by clicking [GO▼] and highlighting *runs\runs.tbk*, or click on the [Back] button until the desired screen appears. Explore a little, then return to the *Runs* screen.

> *NOTE:* [GO▼] is generally the preferred link within TruckSim. *Back* can only recall up to four moves, but is faster for single screen moves.

Another way to move within TruckSim is to use the data sets directly. Several simulation runs are available as part of the default information within TruckSim. Click and hold the [▼] button next to the *Data set* field to reveal a menu of simulations. For example, under *2-Axle truck*, four runs will be listed: 2-axle truck in lane change, 2-axle truck ride (bump), 2-axle truck ride (road), and 2-axle truck in step steer. Drag the mouse down to reveal the other major categories (*3-Axle truck*,

3-Axle semi, and *5-Axle semi*) and all the runs that are currently available under each category.

Highlight *5-axle semi* and *Standard 18-wheel* and release the mouse button. The screen shown in Figure 3–4 will appear.

To directly view the data to be used in the run simulation, click on and hold the ▼ button next to the *System* field in the *Simulation Input* section on the left side of the screen and highlight *Go To Data Set* in the pop-up menu. (The same screen can be reached using *GO* and highlighting *5a_semi\5a_semi.tbk*.) Figure 3–5 shows the data set screen that will appear.

Look at more detailed sketches of the truck by selecting any of the menus in the lower third of the screen. For example, when you click and hold on the ▼ button next to the *Unladen Semi* field and highlight *Go To Data Set*, you will see the screen shown in Figure 3–6. Next, to look at the data set for the *Unladen Tractor*, click on the ▼ button next to that field and highlight *Go To Data Set*. Figure 3–7 shows the screen that will appear.

One of the *Simulation Input* parameters is the road profile. *Road Bump* and several other actual road profile files (IRI files) are currently available in TruckSim. The default, however, is *no profile*. Appendix B contains detailed instructions for the creation of new road profile data sets.
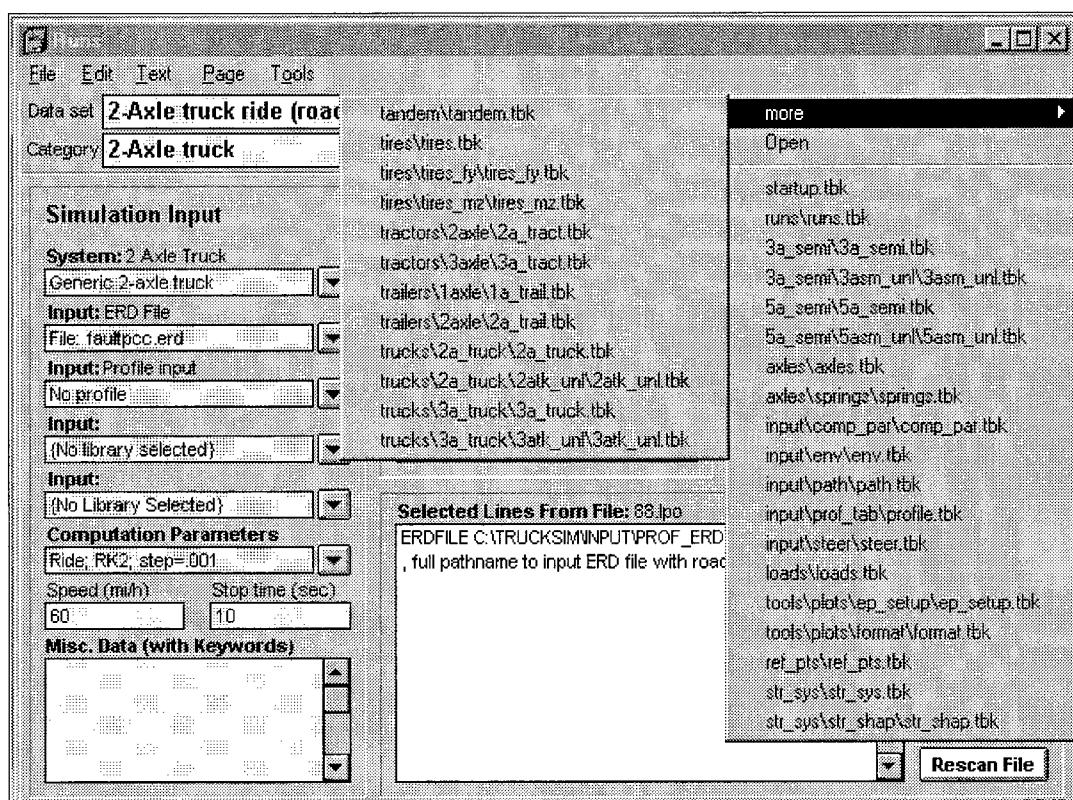
Figure 3–3. *GO* **menu**
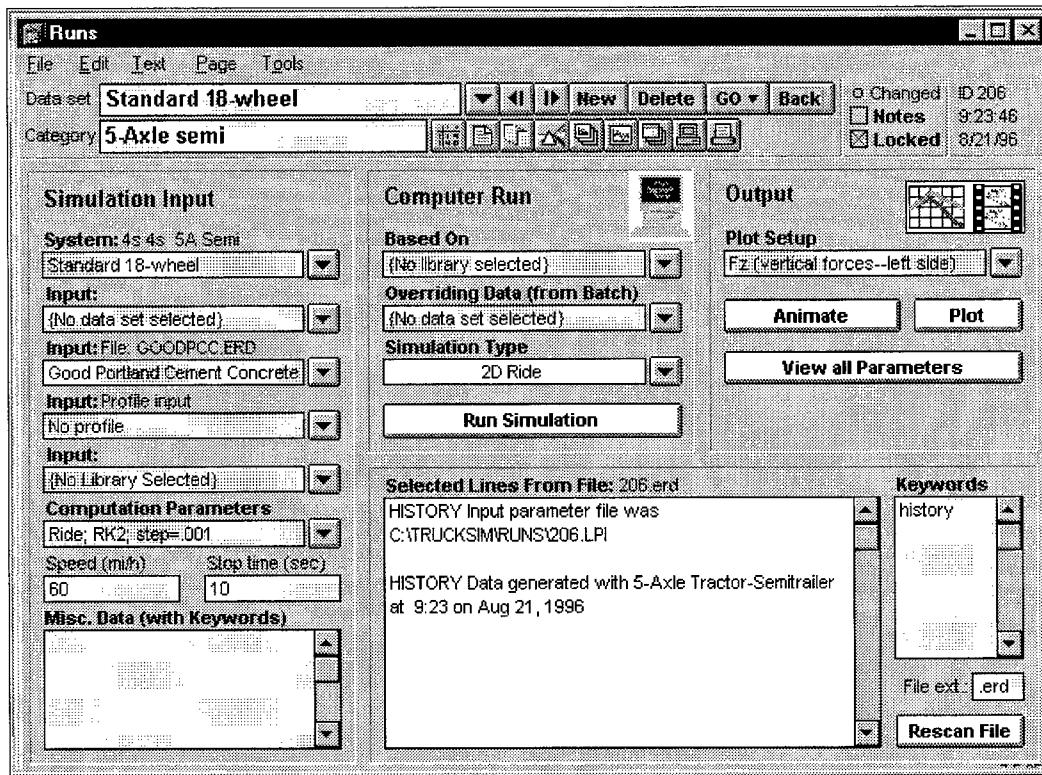
Figure 3–4. *Runs* screen for standard 18-wheel tractor-semitrailer
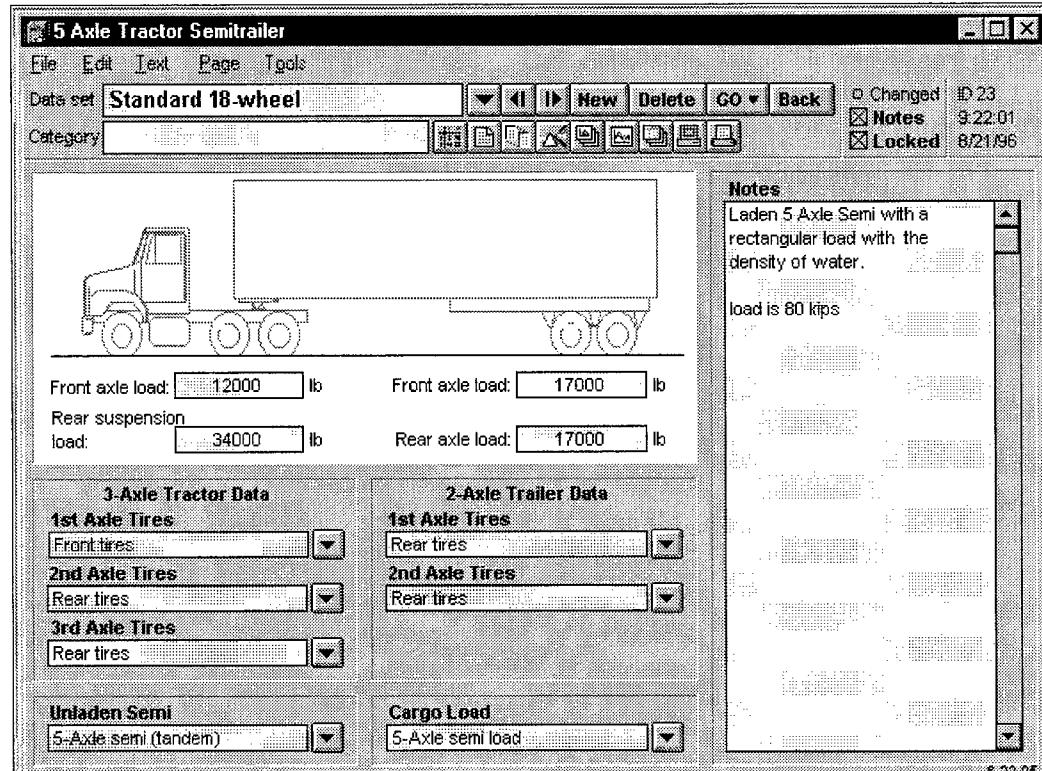
Figure 3–5. *Data Set* screen for standard 18-wheel tractor-semitrailer
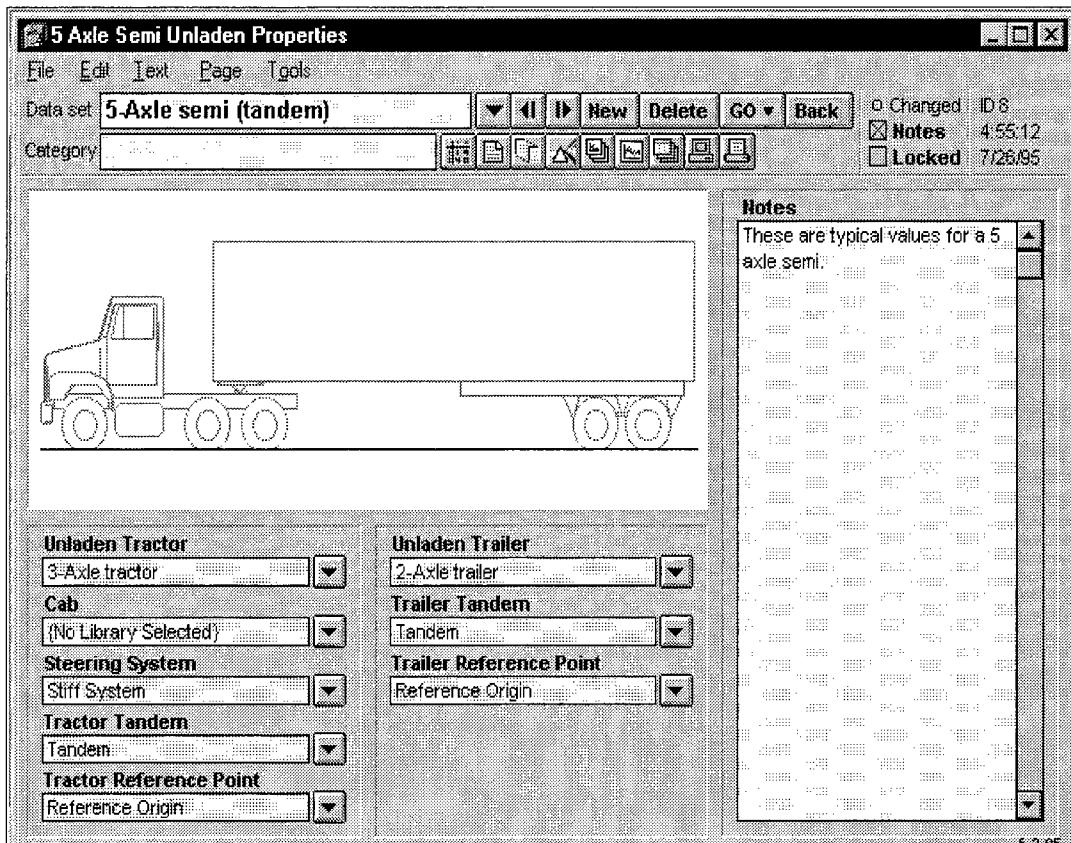
Figure 3–6. *Data Set* screen for unladen tractor-semitrailer
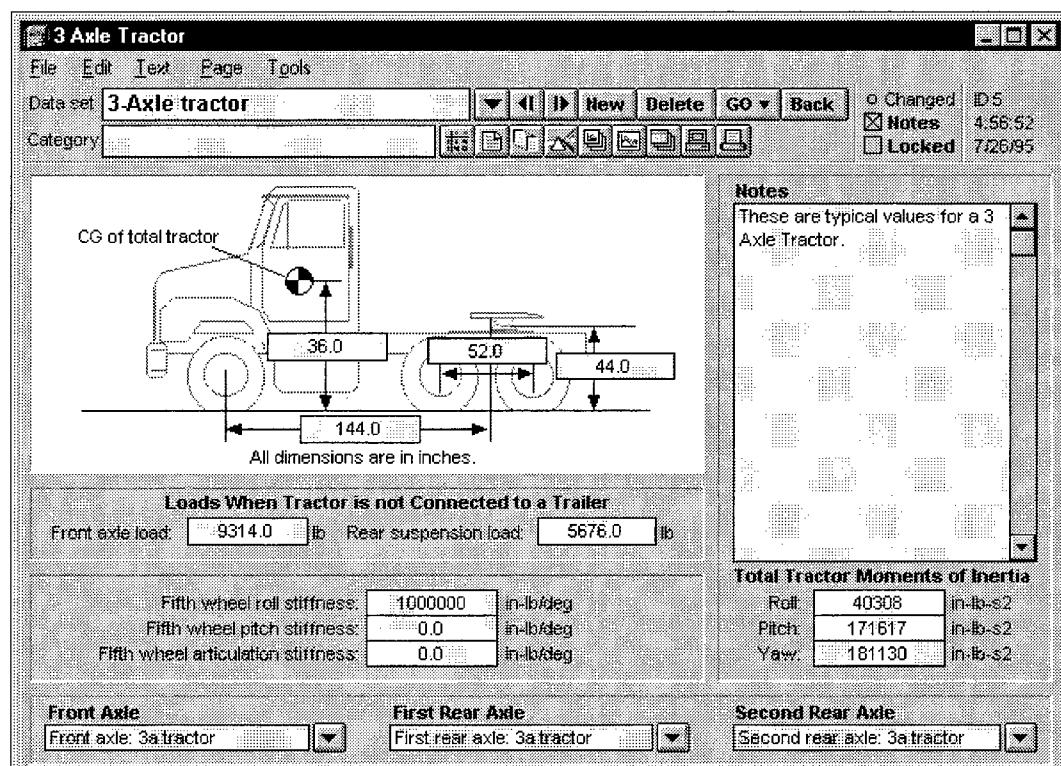
Figure 3–7. *Data Set* screen for unladen tractor

Return to the *Runs* screen using either [Back] or [GO▼].

IMPORTANT: Click on the *Computation Parameters* [▼] button (near the bottom of the column on the left side of the screen) and highlight *Go To Data Set*. (If a pop-up screen asks whether you wish to update the data, click the [NO] button.) Figure 3–8 shows the *Computation Parameters* screen.
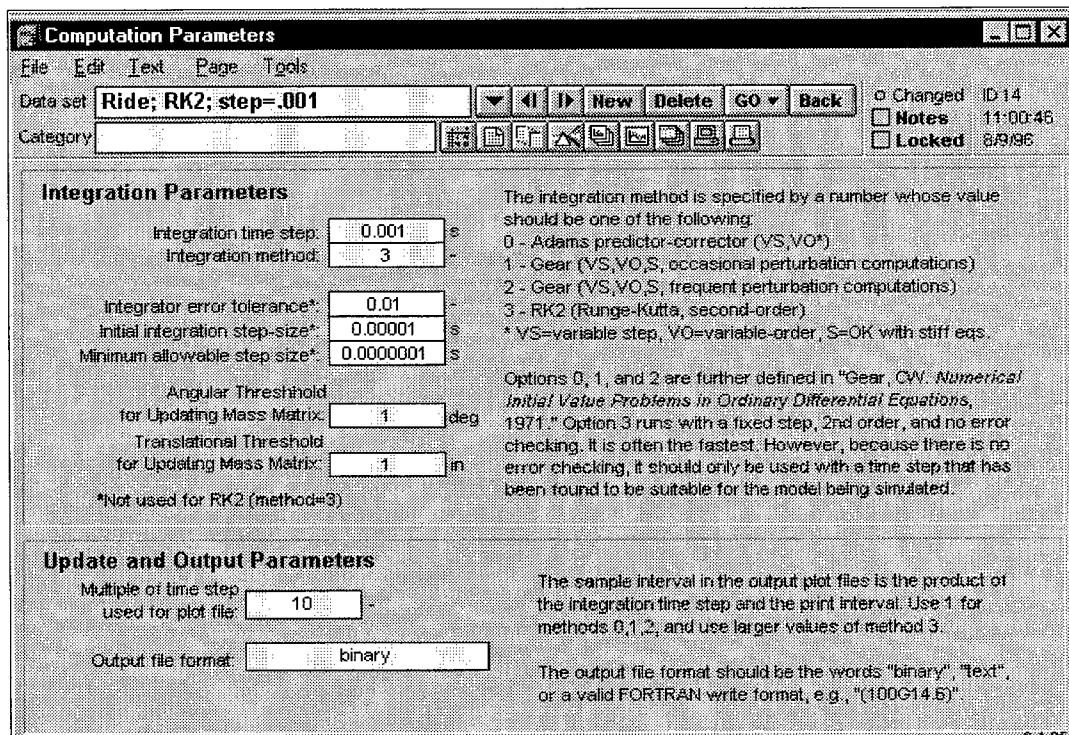
Figure 3–8. Incorrect *Computation Parameters* screen

This screen shows several items that control the simulation and format of the output data files. The last item, *Output file format*, is of particular interest. **Data resulting from the simulation must be stored in a text file.** To specify this format, the last input box on the Computation Parameters screen must contain a FORTRAN format statement: either *(100G14.6)* or *(200G14.6)*. If it does not, click on the box, delete the existing message, and type in either Fortran statement. Figure 3–9 shows a *Computation Parameters* screen that has been correctly filled in. When the format is correct, use the [Back] button to return to the *Runs* screen.

NOTE: The default for TruckSim output files is binary, so the *Output file format* in the Computation Parameters screen **must** be checked and set to (100G14.6) or (200G14.6) before simulating a truck run. The Pavement Consumption and Performance Comparison components will not be able to locate the data needed if the files are not in this form.

TruckSim simulations generate many types of data related to the forces that affect a truck as it travels over the highway. A partial list includes data on axles, hitch, suspensions, tires, vehicle motion and steering wheel input. The data that will be gathered for use in the Pavement Consumption and Performance Comparison components are the vertical forces of the left tires and the distances between the axles of each truck type. Chapter 5 contains more information about the actual applications of TruckSim output within *PaveSim*.
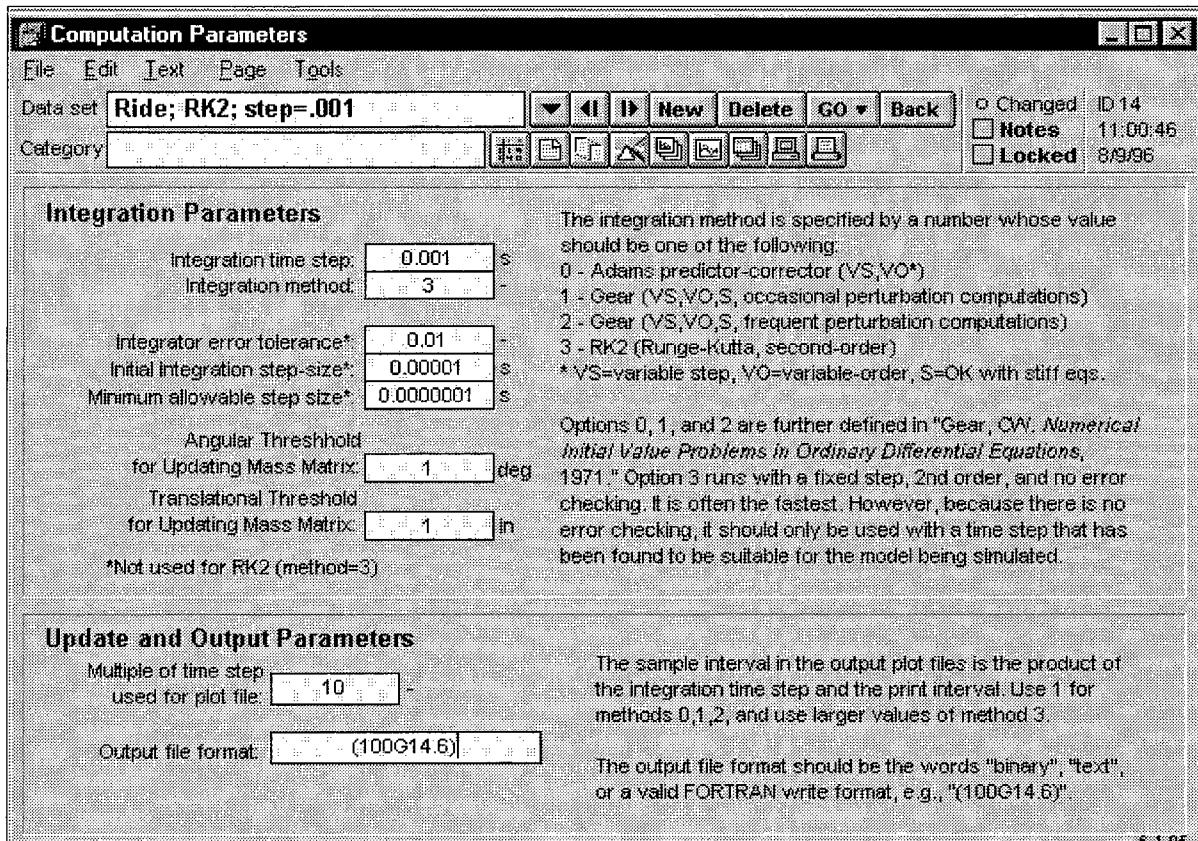
Figure 3–9. Correct *Computation Parameters* screen

The results of a simulation can be viewed using a plotter called WinEP. For example, to view the vertical tire loads on the *Standard 18-wheel* simulation, go to the *Output* section on the right side of the screen. Click and hold the ▼ button beside the *Plot Setup* field. Drag down until *Tires* is highlighted and then highlight *Fz (vertical forces—left side)* and release. A screen will appear as the data are gathered from the output file, then the graph shown in Figure 3–10 will appear.

NOTE: The graph on the computer screen shows each wheel's vertical load in a different color.

To read the load values on each axle, select "Scan Data Points" under *Data* in the top menu bar. Click in the graph at the desired position and the x (time in seconds) and y (force in pounds) coordinates will appear in the upper right corner of the screen. The color of each set of x and y coordinates corresponds to the color of an axle listed in the legend on the right side of the graph. "FZ L1" indicates the vertical forces on the left tire of axle 1, and if "FZ L1" appears in black in the legend, then the load values for axle 1 will appear in black in the plot and in the upper right corner of the screen. To toggle among the axles and their load values, press the *<tab>* key until the one you are interested in appears. The *<left arrow>* and *<right arrow>* keys on the keyboard will move the cursor along the x-axis of the graph. The *<up arrow>* and *<down arrow>* keys move the cursor to the maximum and minimum load values, respectively, for the axle chosen using the *<tab>* key.

To locate the maximum load value on the front tractor axle, select *Scan Data Points* if you have not already done so. Press the *<tab>* key until the black values are
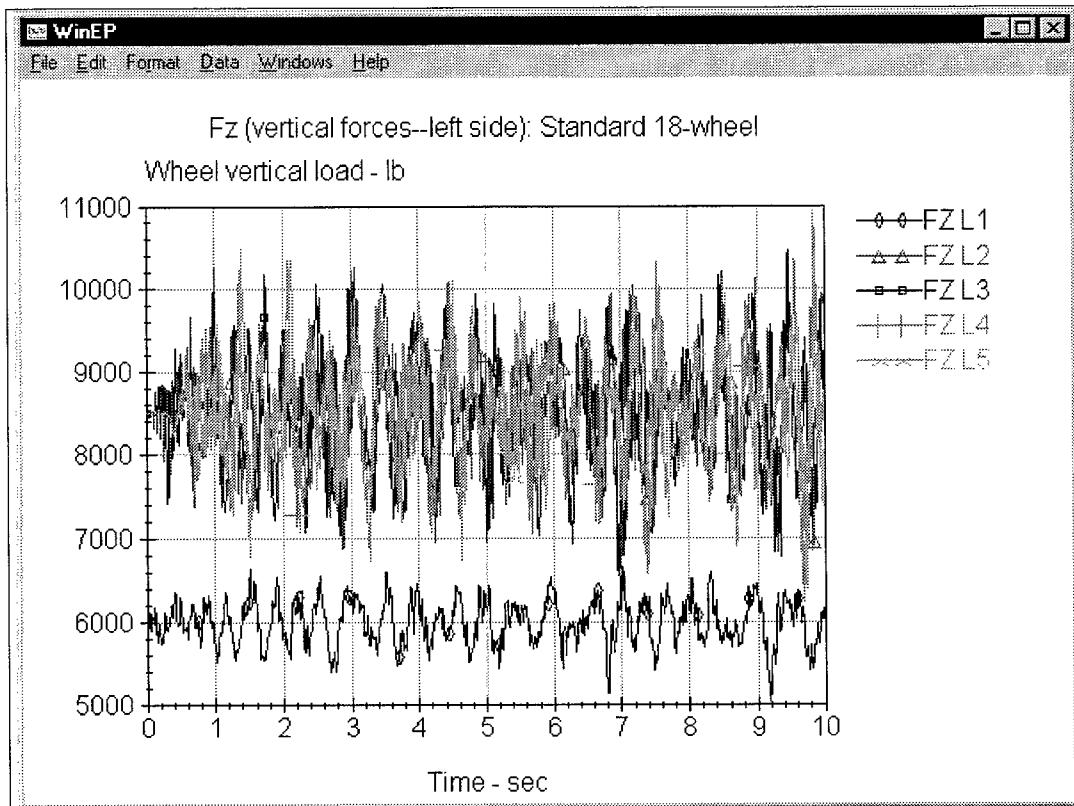
Figure 3–10. Vertical tire loads on standard 18-wheel tractor-semitrailer

chosen and the color of the cursor is also black, then press the *<up arrow>* key and the maximum load value on the front axle will be indicated by the cursor and listed in the upper right corner.

Using the *<tab>* and *<up arrow>* keys, you can find the maximum load on any axle. When you are finished viewing the plot of the data, close WinEP and return to the *Runs* screen by clicking on the ⊠ button in the far upper-right corner of the screen.

Click on the |View all Parameters| button in the *Output* section of the screen to show all of the calculation parameters and the final position values for the simulation. Again, you can return to the *Runs* screen by clicking on the | Back | button.

CREATING A NEW SIMULATION

To create a set of data for a new run simulation, click on and hold down the ▼ button beside the *Data set* field and highlight the type of run you would like to simulate. For this example, highlight *3-Axle truck ride* and release the mouse. *3-Axle truck ride* will appear in the *Data set* field at the top left of the screen. To create a new simulation, click the | New | button. The *Data set* field will now be highlighted and read *3-Axle truck ride#1*.

Although *3-Axle truck ride#1* is an acceptable name for this simulation (each simulation must have a unique name), let's shorten it a bit by typing *Ride#1* in the *Data set* field. Next, look at the box next to the word *Locked* in the upper right corner of the screen. An *X* in the box (**X Locked**) ensures that the input data for this

simulation cannot be changed without being unlocked. Click on the *Locked* box to remove the *X* and unlock the data set (☐ **Locked**).

Next, check the *Computation Parameters* screen to make sure that the *Output file format* is set to *(100G14.6)* or *(200G14.6)*.

NOTE: If TruckSim flashes a black screen and returns to the *Runs* screen, choose *runs\run.tbk* under the GO▼ button and click Run Simulation. *Simulation Type* must always read *2D Ride.*

Click Run Simulation located in the center of the screen. The TruckSim screen should vanish and be replaced by a DOS screen with fast activity that will end with a progress bar similar to the one shown in Figure 3–11. When progress reaches 100 percent completion, the *Runs* screen will return.

At the *Runs* screen, view the data by clicking View all Parameters or plotting the desired set of values in WinEP as described earlier. To plot the vertical wheel loads, select *Tires* and *Fz (vertical forces—left side)* from the menu beside the *Plot Setup* field. After the samples have been sorted, the plot shown in Figure 3–12 will appear. Choose *Scan Data Points* from the *Data* menu in the top menu bar; use the *<tab>* key to toggle among the axles and the *<up arrow>* key to select the maximum value.

Progress (percent complete):

0   50   100

= = = = = = = = = = = = = =
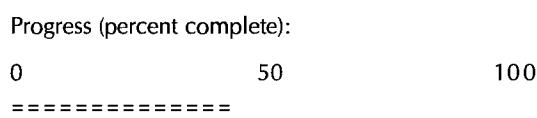
Figure 3–11. DOS progress bar

To return to the *Runs* screen from WinEP, select *Close* under the *File* menu in the top menu bar or click the ☒ button in the upper right corner of the screen.
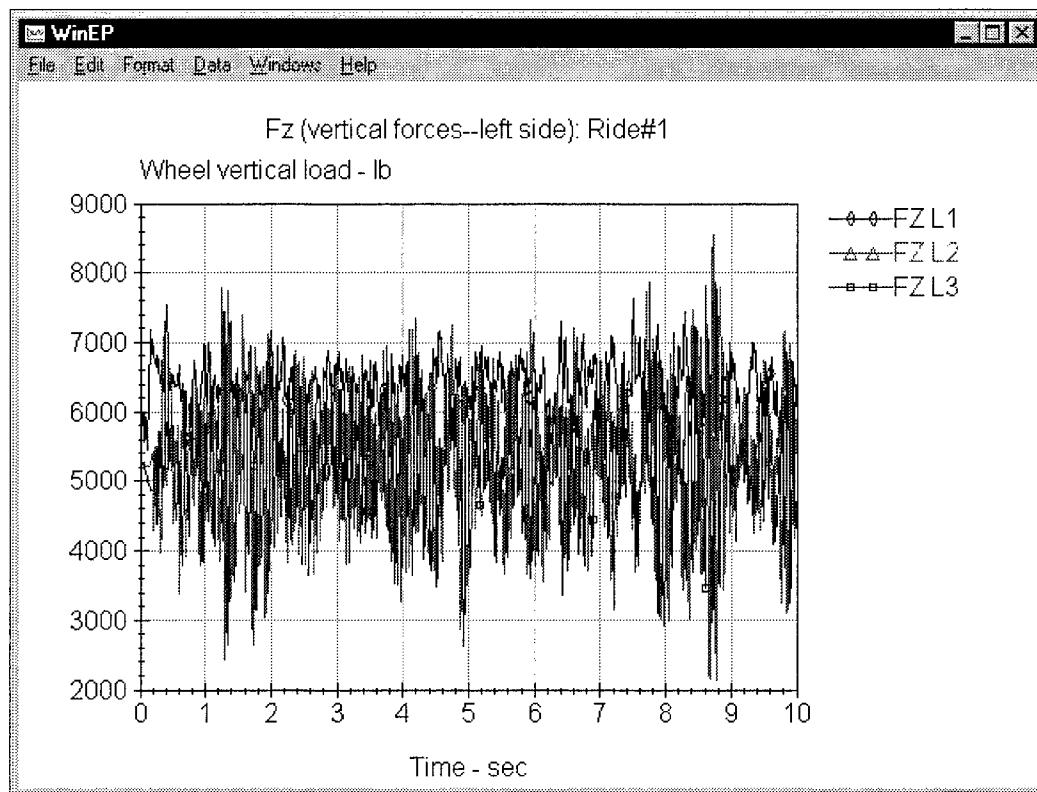
Figure 3–12. Vertical load data from Ride #1

MODIFYING INPUT DATA

The user can make simple modifications to the data used in the simulations from the *Runs* screen. Select *3-Axle truck* and *3-Axle truck ride* from the ▼ menu. Click the [New] button and rename the data set *Ride#2*. Next, locate the *Speed* field in the left column of the *Runs* screen. The default speed in TruckSim is 60 miles per hour. Click in the yellow field and change the speed to *50*.

Do not run the simulation at this time. This simulation will be part of your *Batch Runs* trial in the next section.

An example of a more complicated modification would involve choosing a different suspension for the rear axles of a 5-Axle semi. Beginning at the *Runs* screen, complete the steps in the following table to change the rear suspension.

Click on:	Perform the following action:
1) ▼ (beside the *Data set* field)	Highlight *5-Axle semi* and *5-Axle semi (tandem) ride*.
2) [New]	Name the run *Walking Beam*.
3) [GO▼]	Highlight *axles\axles.tbk* (Figure 3–13 shows the next screen).
4) [New]	Rename the data set *Walking Beam*.
5) ▼ (beside the *Spring* field)	Highlight *Drive: Tandem Axle* and *Walking Beam; Leaf; NA; 65K*. Lock the data set.
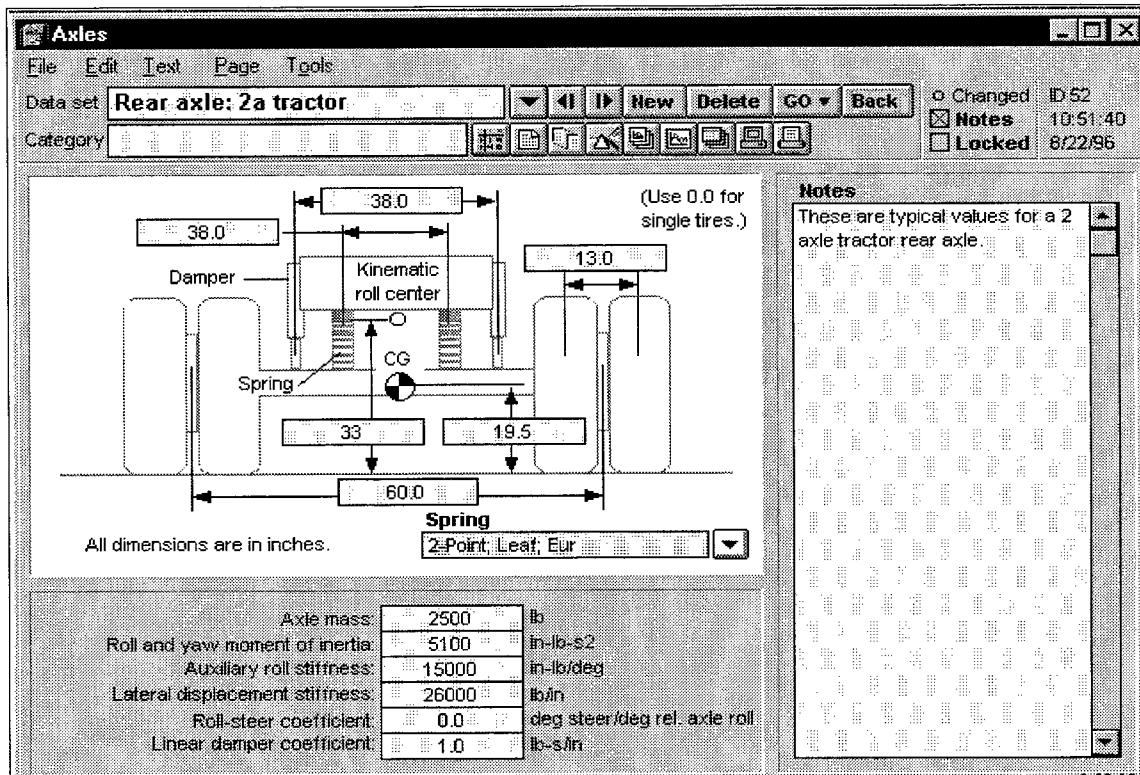
Figure 3–13. *First Axle* **data screen**

Use either the [Back] or [GO ▼] button to return to the *Runs* screen when you are finished. Click the *Locked* box (**✗Locked**), then click the [Run Simulation] button.

To examine the load data at the conclusion of the *Walking Beam* simulation, highlight *Fz (vertical forces—left side)* in the *Plot Setup* menu, then click the [Plot] button to use WinEP. The loads are plotted as shown in Figure 3–14.
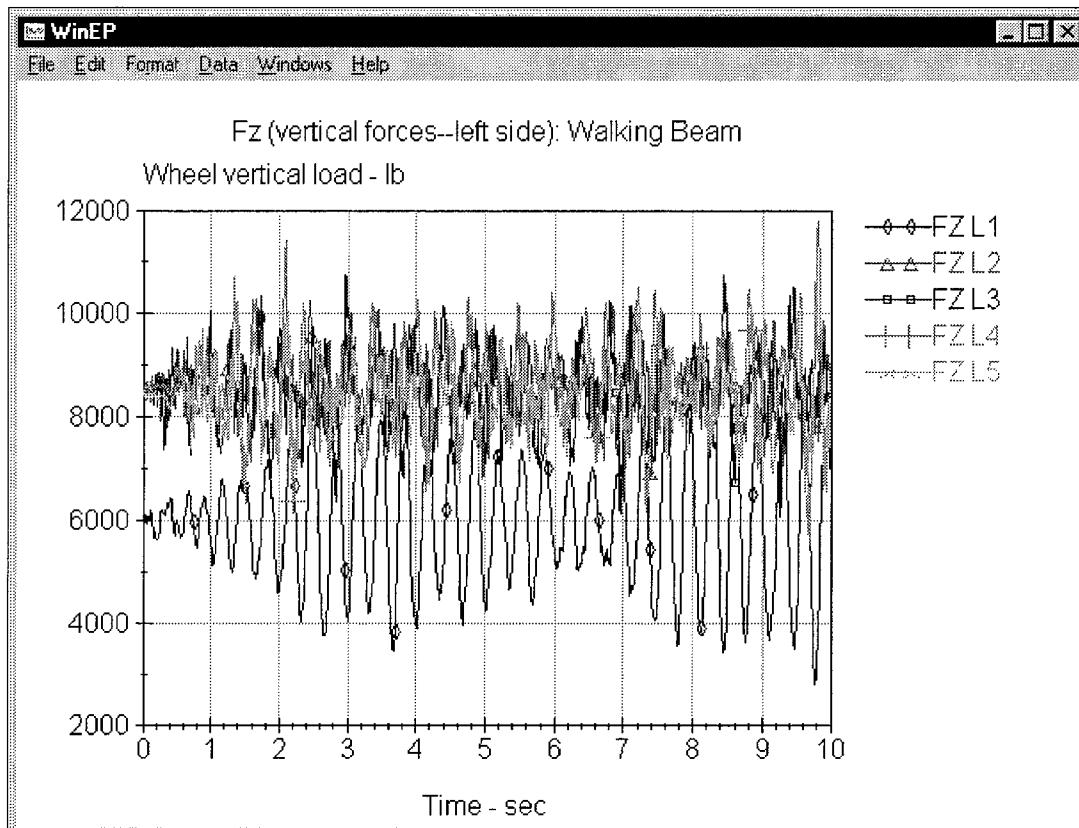
Figure 3–14. *Walking Beam* **vertical load data**

The user may wish to create a new set of system values for a simulation type that will be used several times. One example would be a cargo of 10 percent overload (or 88,000 lbs) on a 5-axle semitrailer. To create a new data set for this modification, start at the *Data set* field on the *Runs* screen and select *5-Axle semi* and *5-Axle semi (tandem)* as the type of simulation. Click the [New] button and rename the data set *Overload*, then click the [▼] button next to the *System* field. Highlight *Go To Data Set* and release the mouse button. The screen that appears is the same as that in Figure 3–4.

Click [New] and enter the name "10% overload." In the yellow fields beneath the sketch, enter the new load values:

Front axle load:	12000	Front axle load:	19000
Rear suspension load:	38000	Rear axle load:	19000

In the *Notes* field, enter "total load is 88 kips," then click in the box next to *Locked* in the upper right corner of the screen (☒ **Locked**). The completed screen for the *10% overload* data set is shown in Figure 3–15.
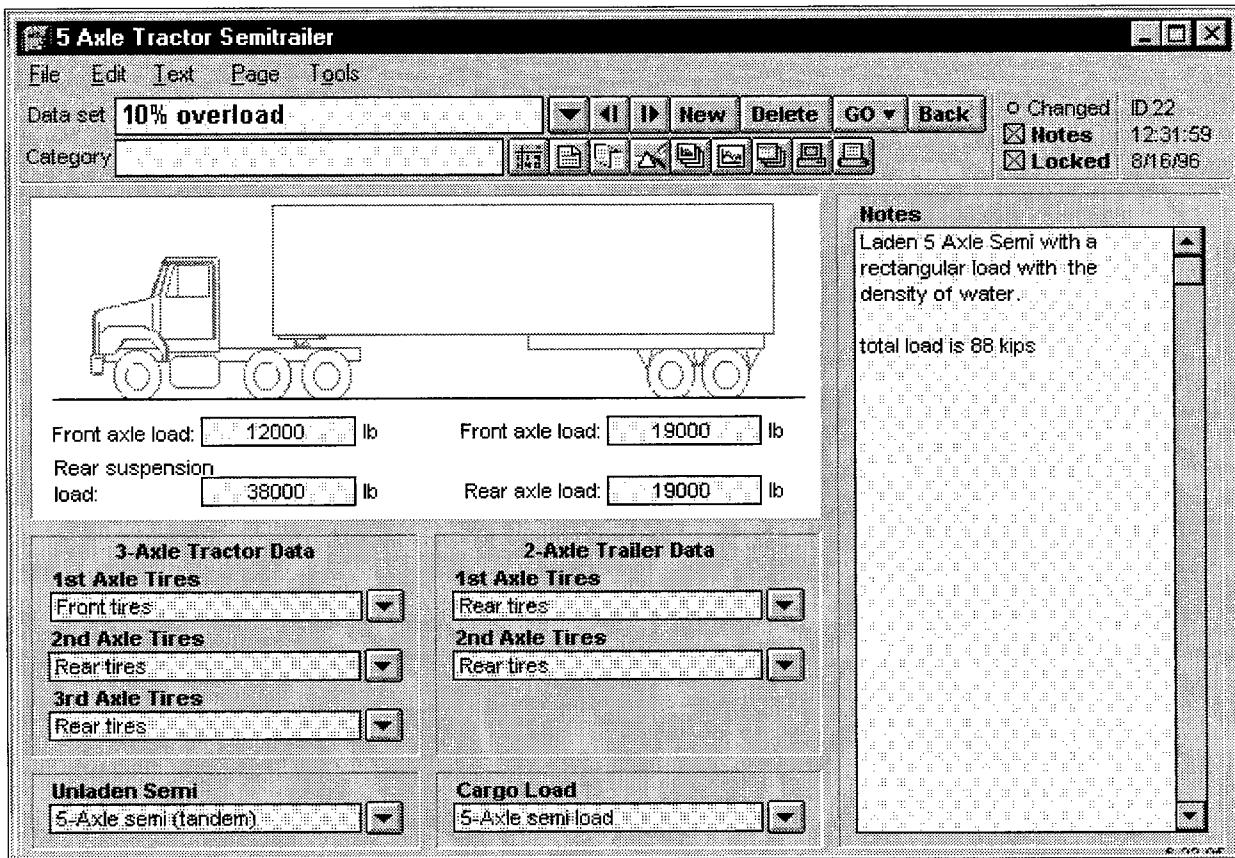
Figure 3–15. TruckSim data set screen for ten percent overload

Return to the *Runs* screen and click the *Locked* box (☒ **Locked**). ***Do not click the*** ⎕ Run Simulation ⎕ ***button***; this simulation will be part of the *Batch Runs* trial that follows.

BATCH RUNS

The *Batch Runs* feature of TruckSim is useful for running numerous simulations because it allows the user to generate several data sets and simulate all of them with just one click of the mouse. More simulations mean more time savings. *Batch Runs* can also be used to advantage when the same small number of parameters must be changed for many existing data sets.

From the *Runs* screen, click the ⎕ button (*Batch Runs*, third from the right in the lower ribbon bar at the top of the screen). When the *Batch Runs* screen appears, click ⎕ New ⎕ and type "Trial" in the *Data set* field. Clear any statements that appear in the *Overriding Data Parameters* fields. These will be discussed later.

Data sets to be run in this batch are selected from the *Data Sets from Runs Library* field. Highlight *Ride#2* and click the ⎕ Add ⎕ button above the field *Data Sets to Run*. Select *Overload* to run in the *Trial* batch and click the *Locked* box (☒ **Locked**). The completed screen will appear as shown in Figure 3–16.
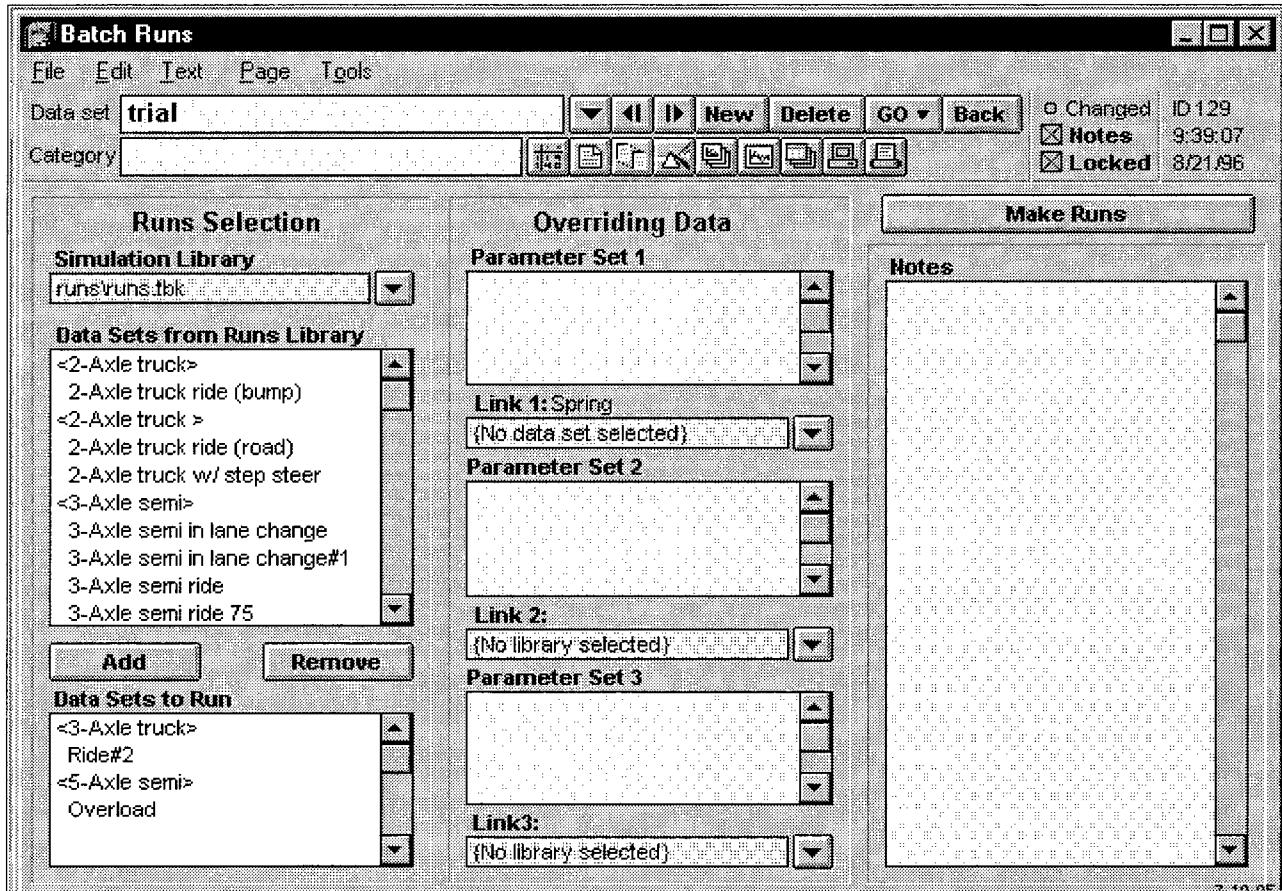
Figure 3–16. *Trial Batch Runs* screen

To start the simulation, click on ⌈ **Make Runs** ⌉ (*Ride#2* and *Overload* will be simulated consecutively). The visible screens will shift from DOS to *Runs* to *Batch Runs* as each simulation is run and completed. When screen activity comes to rest at the *Batch Runs* screen, click anywhere on the screen to remove the message describing how to break the batch mode.

To change one or two parameters in several data sets and run a new simulation on each, use the *Batch Runs* feature. For this example, the suspension on the front axle of several trucks will be changed, and the speed will be changed from 60 mph (the default value) to 75 mph. Return to the *Runs* screen to begin.

To preserve the original data sets, a new set should be made for each truck simulation that will be changed. Select and rename the data sets as indicated in the following table. **Do not Lock these sets** as locking will not allow the overriding parameters to be applied.

Original name	New name
Ride#2	Ride 75
3-Axle semi ride	3-Axle Semi Ride 75
5-Axle semi ride	5-Axle semi ride 75

Click on the ⊞ button (*Make New Library*, third from the left in the second ribbon bar at the top of the page). This feature will allow the user to change the category of a data set. One at a time, highlight the three sets that were just created and ⌐ >>Add>> ⌐ them to the *Selected data sets* field. Figure 3–17 shows the screen that will appear after the sets are added.
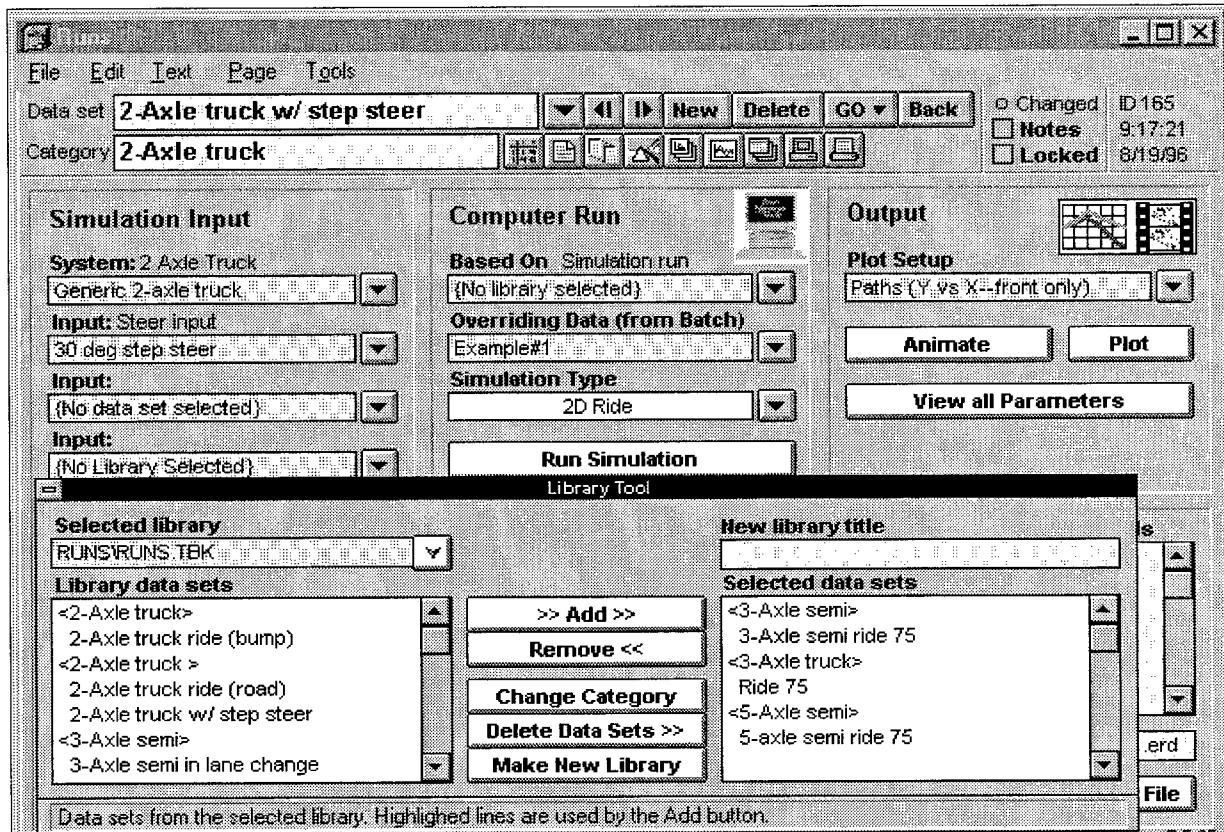
Figure 3–17. *Make a New Library* screen

Click on the ⌐ Change Category ⌐ button in the center of the window, give the new category the name "Trial 75," and click ⌐ OK ⌐. Check the new category by scrolling to the bottom of the *Library data sets* field. The new category will be listed along with its three data sets. Close the window by clicking the ⊟ button in the upper left corner of the screen; control will return to the *Runs* screen.

Click on the ⊞ button (*Batch Runs*). The overriding parameters must be declared first. Click ⌐ New ⌐ and rename the data set "Trial 75." Type the following statements in the field labeled *Overriding Data/Parameter Set 1*:

> *iaxle 1* <return>
>
> *speed 75*

"iaxle" and "speed" are keywords recognized by TruckSim as simulation parameters. "iaxle" indicates which axle (the first axle in this case) will be affected by the change of spring suspension in the *Spring* menu below the *Overriding Data/Parameter Set 1* field.

> *NOTE:* A list of keywords is provided in Appendix C and in the *View All Parameters* screen.

From the *Link 1: Spring* ▼ menu, highlight *Example* and *Front 12K rated flat leaf.*
Figure 3–18 shows the *Batch Runs* screen with the correct parameters.
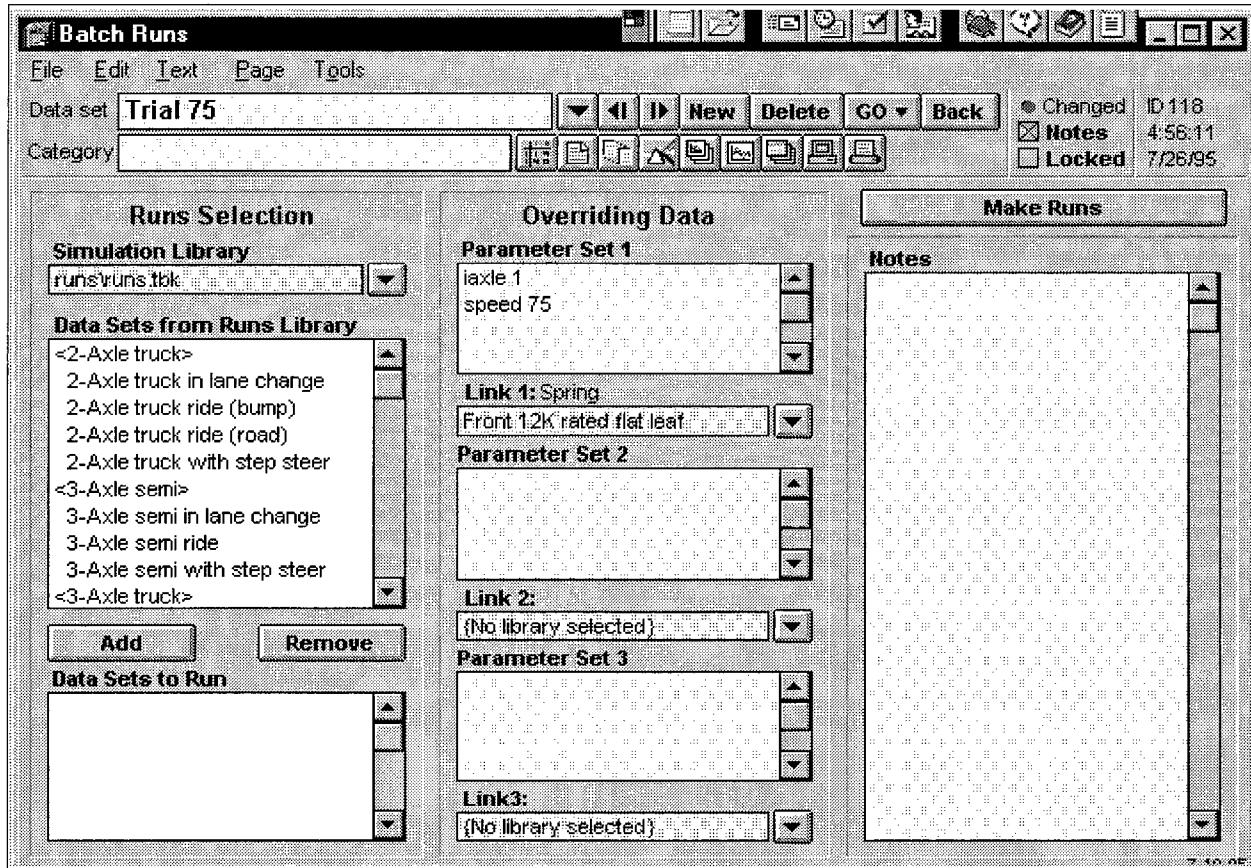
Figure 3–18. *Batch Runs* **screen with parameters for** *Trial 75*

Move to the *Data Sets from Runs Library* field, highlight *Trial 75* and click [Add].
Trial 75 is moved to the *Data Sets to Run* field (see Figure 3–19).

Next, click on the [Make Runs] button to simulate each of the data sets in turn,
applying the changed parameters of front axle suspension and speed. Upon
completion, return to the *Runs* screen by using either [GO▼] or [Back]. As usual, the
results of the simulation can be viewed using either [View all Parameters] or [Plot].

RETURN TO PAVESIM

To exit TruckSim, click on the [X] button in the extreme upper right corner of the
Runs screen. Control returns to the *Pavement Consumption* screen as in Figure 3–
20. Click on [OK]; PaveSim will read the TruckSim output files and select the
values of wheel vertical loads for each axle and the spacing between axles and store
them for later use. To see the list of completed simulations, click on the menu below
the [TruckSim] button, and highlight *Two Axles, Three Axles, Five Axles* or *Others.*
Using these files in PaveSim will be described in Chapter 5 where the Pavement
Consumption and Performance Comparison components are discussed.

Within PaveSim, TruckSim simulates the behavior of trucks and generates the axle
load data required for the finite analysis completed in the *Pavement Consumption*

and *Performance Comparison* components. This chapter has outlined the steps involved in using TruckSim for this purpose and described the TruckSim environment. Further information about TruckSim can be found in the *TruckSim Tutorial* (UMTRI 1995) or requested from the University of Michigan Transportation Research Institute.
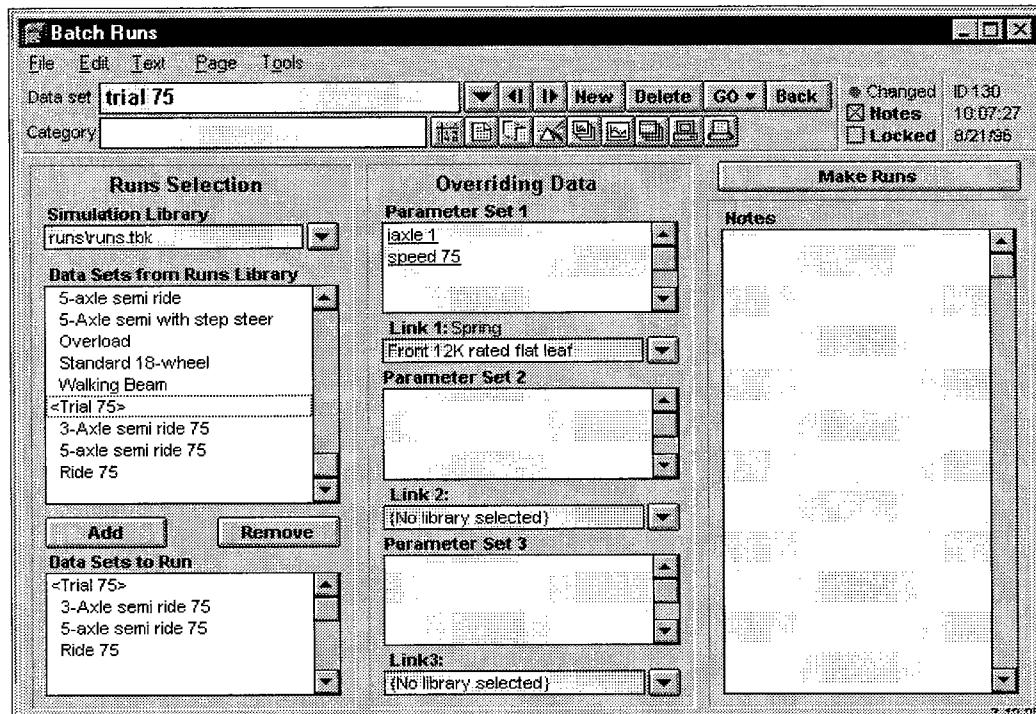
Figure 3–19. Completed *Batch Runs* screen for Trial 75
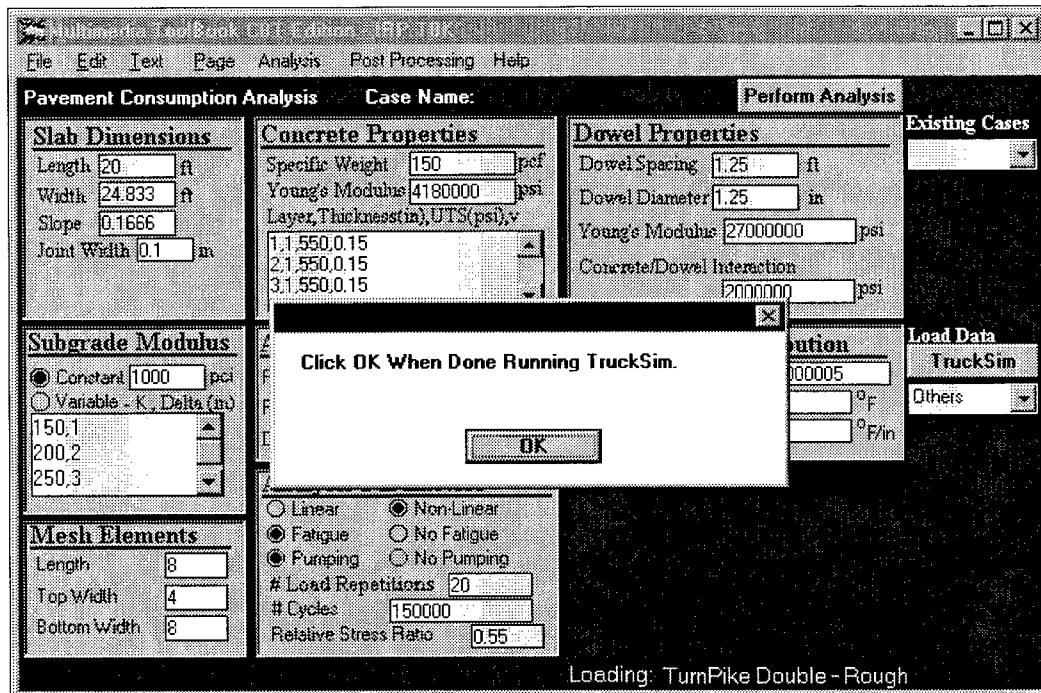
Figure 3–20. *Pavement Consumption* screen after exiting TruckSim

CHAPTER 4
CONCRETE PAVEMENT MODELING

Actual analysis of the pavement is performed by RigidPav, which is based on improved finite element representation of concrete pavements. The model takes into account pavement characteristics such as nonlinear properties of the concrete and subgrade, discontinuities in the slab, fatigue of the structural elements, and pumping of the subgrade. This chapter gives a summary of the models and procedures used.

FINITE ELEMENT MODEL FOR CONCRETE PAVEMENTS

As shown in Figure 4–1, the basic finite element model is a nine-node quadrilateral-plate element based on the Mindlin's plate theory. A layered representation is used to model different materials and their nonlinear material properties. This pavement model is capable of including characteristic behaviors of concrete in compression and tension and the impacts of cyclic loading. Dowels are represented such that the relative deformation of the bars with respect to the concrete slab is accounted for; the model also estimates dowel and joint fatigue. The subgrade model can represent pumping of the fine material with repetitious load.

Concrete in compression

The yield surface is defined as an extended Von Mises criteria accounting for the influence of hydrostatic pressure on the loading function. This function (Figueiras and Owen 1984a, 1984b) can be written as:

Element definition   Layer discretization
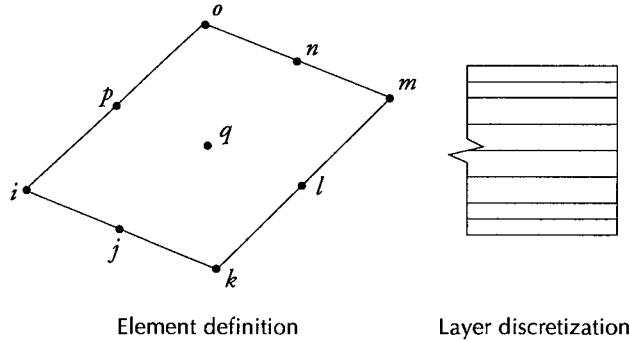
Figure 4–1. Basic finite element model

$$f(I_1,J_2) = \sqrt{3\beta J_2 + \alpha I_1} - \bar{\sigma} = 0$$

where:

I_1 = first invariant of the stress tensor,

J_2 = second invariant of the stress tensor,

$\bar{\sigma}$ = equivalent effective stress, and

α, β = material parameters.

Material parameters α and β can be found empirically by curve-fitting experimental results. Figueiras and Owen (1984b) calculated their values based on the results of Kupfer, Hilsdorf, and Rusch (1969) as:

$$\alpha = 0.355\bar{\sigma} \qquad \beta = 1.355$$

Crushing failure is controlled by an expression similar to the yield function, but in strain space. This expression can be written as:

$$f\left(I_1', J_2'\right) = \sqrt{3\beta J_2' + \alpha I_1'} - \varepsilon_u = 0$$

where:

I_1' = first invariant of the strain tensor,

J_2' = second invariant of the deviatoric strain tensor,

ε_u = ultimate total strain from a uniaxial compression test, and

α, β = material parameters.

Computer implementation uses the matrix formulation for elasto-plastic materials presented by Nayak and Zienkiewicz (1972a, 1972b).

Concrete in tension

The response of concrete in tension is assumed to be elastic until the maximum tensile stress reaches the value of the concrete tensile strength, f_t'. A crack then forms perpendicular to the maximum tensile stress. The material is assumed to behave orthotropically after cracking has occurred, with the principal axes of orthotropy parallel and normal to the crack. Young's modulus and Poisson's ratio in the direction normal to the crack are set to zero and a reduced shear modulus is employed. If 1 and 2 are the principal directions with 1 being normal to the crack, the stress-strain relation for a point that has cracked in one direction is

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \\ \tau_{13} \\ \tau_{23} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & E & 0 & 0 & 0 \\ 0 & 0 & G_{12}^c & 0 & 0 \\ 0 & 0 & 0 & G_{13}^c & 0 \\ 0 & 0 & 0 & 0 & 5G/6 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix}$$

where

$$G_{12}^c = 0.25G\left(1.0 - \frac{\varepsilon_1}{0.004}\right) \text{ if } \varepsilon_1 < 0.004$$

$$= 0 \text{ otherwise,}$$

$$G_{13}^c = G_{12}^c, \text{ and}$$

$$\varepsilon_1 = \text{a tensile strain in the direction 1.}$$

When the principal stress in direction 2 reaches the value of f_t', a second crack forms perpendicular to the first one. The stress strain relation becomes

$$
\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \\ \tau_{13} \\ \tau_{23} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5G_{12}^c & 0 & 0 \\ 0 & 0 & 0 & G_{13}^c & 0 \\ 0 & 0 & 0 & 0 & G_{23}^c \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix}
$$

where:

$$G_{23}^c = 0.25G\left(1.0 - \frac{\varepsilon_2}{0.004}\right) \text{ if } \varepsilon_1 < 0.004$$

$$= 0 \text{ otherwise,}$$

$$G_{12}^c = 0.5G_{23}^c \text{ if } G_{23}^c < G_{13}^c$$

$$= 0.5G_{13}^c \text{ otherwise,}$$

ε_1 = tensile strain in the direction 1, and

ε_2 = tensile strain in the direction 2.

Due to the bond effect between steel reinforcement and the surrounding concrete, a certain amount of tensile stress can be carried across the crack by the concrete. In this work, we adopt a gradual release of the concrete stress component normal to the cracked plane. The process of unloading and reloading is assumed to follow a linear elastic behavior with a fictitious modulus E_i given by

$$E_i = \frac{\alpha f_t'}{\varepsilon_i}\left(1 - \frac{\varepsilon_i}{\varepsilon_m}\right) \quad \varepsilon \le \varepsilon_i \le \varepsilon_m$$

using the following definitions:

α, ε_m = material parameters and

ε_i = maximum value reached by the tensile strain.

The stresses normal and parallel to the crack are obtained from:

$$\sigma_i = \alpha f_t'\left(1 - \frac{\varepsilon_i}{\varepsilon_m}\right) \quad \varepsilon \le \varepsilon_i \le \varepsilon_m$$

Steel in compression and tension

Reinforcing steel is considered to be a sequence of layers of equivalent thickness representing unidirectional behavior by resisting forces only in the direction of the bars. An elasto-plastic representation of the material is assumed and the hardening parameter is calculated based on the plastic Young's Modulus as

$$H = \frac{E_{ep}}{1 + \left(E_{ep}/E\right)}$$

Fatigue of concrete in tension

Fatigue performance is generally expressed in terms of an "endurance curve." This curve represents the relation, under a particular loading condition, between the magnitude of the cycling stress and the mean value of the number of load cycles until failure. Figure 4–2 represents a typical endurance curve. Because measures of fatigue damage are rather subjective quantities, they are used to follow the progress of damage under certain conditions of loading and in relation to other structures. In other words, they are best suited to perform a parametric study of the performance of a given set of structures subject to similar conditions.

In order to analyze the effect of traffic consisting of different types of vehicle configurations, the following assumptions are made.

1) All traffic can be classified into a finite number of vehicle types.

2) Pavement damage caused by different types of vehicles is cumulative and independent of the order in which the vehicles travel over the pavement.

3) When a vehicle passes over pavement, all components of the structure (i.e., slabs, subbase, subgrade, and LTD) suffer some fatigue damage. The damage suffered by each structural element depends on the relative magnitude of stresses or strains in that element, and on the fatigue characteristics of the particular element.

Maximum cyclic stress/ flexural strength

Figure 4–2. Endurance curve for concrete in tension under cyclic loading

4) An endurance curve is known for the concrete and there is a minimum stress ratio below which no fatigue damage occurs.

5) Fatigue damage due to one application is independent of any previous history of load applications (i.e., Miner's law applies).

Fatigue in concrete is commonly quantified by the decay in stiffness of concrete and the amount of cracking. The value of the modulus of elasticity of concrete is modified in accordance with the level of stress and the number of load repetitions, assuming that a flexural endurance curve is known. Also, the relation between the modulus of elasticity, the compressive strength and the flexural strength of concrete are known.

Let us assume that the endurance curve of a concrete specimen under constant cyclic load is known, as shown in Figure 4–2. For simplicity let us assume that the specimen consists of an axially loaded concrete cylinder. Given that the relative stress f_r (which is equal to σ_{max}/σ_r) is the damage parameter(where σ_r is the tensile strength of concrete), three cases are possible:

1) If $f_r \geq 1.0$, cracking occurs.

2) If $f_{min} \leq f_r \leq 1.0$, fatigue damage takes place.

3) If $f_r \leq f_{min}$, no damage takes place.

Let N_{app} be the applied number of repetitions of the load and f_{r1} the applied stress level. The fatigue damage calculation consists of two stages:

1) Check whether the specimen is capable of resisting without failure N_{app} load repetitions with a relative stress of f_{r1}.

2) If no failure has occurred with N_{app} repetitions, and if $f_{r1} \geq f_{min}$, calculate the stiffness decay of the material, which is measured as the variation in the value of the modulus of elasticity of concrete.

With the value of f_{r1}, calculate from the endurance curve the number of load repetitions necessary to bring the specimen to failure (i.e., N_{fail}) as shown in Figure 3–2. If the number $N_{fail} \leq N_{app}$, then the material has reached failure due to fatigue and is not able to sustain any further load. Otherwise, the specimen undergoes fatigue damage if $f_{r1} \geq f_{min}$. If $f_{r1} < f_{min}$, then no fatigue damage occurs. Here:

$$f_{min} \geq f_{r1} \leq 1.0 \quad \text{and} \quad N_{app} \leq N_{fail}$$

Since Miner's Law applies, the number of load repetitions necessary to cause failure must be the same, regardless of the sequence in which these cycles are applied. To account for this, a value of relative stress corresponding to N_{diff} is calculated from the endurance curve, being N_{diff}: the difference between the cycles necessary to bring the specimen to failure with a relative stress of f_{r1} and the applied number of cycles (i.e., $N_{diff} = N_{fail} - N_{app}$).

With this new value of the relative stress (f_{r2}), and assuming that the maximum stress (σ_{max}) applied to the specimen remains constant, an updated value of the tensile strength of concrete is calculated as

$$\sigma_r' = \sigma_{max} / f_{r2}$$

and with σ_r', a new value of the modulus of elasticity is obtained as

$$E_c' = E_c'(\sigma_r')$$

By updating the value of the tensile strength of concrete, we are assuring that the material will fail when an additional N_{diff} cycles are applied, under the assumption that the maximum stress remains constant. The initial maximum number of cycles that the structure can withstand does not change. For additional details see Molinas-Vega, Bhatti, and Nixon (1995).

Subgrade model

There are two ways to represent the subgrade: as an elastic liquid foundation(also known as a Winkler foundation) or an elastic half space. Because the Winkler subgrade is unable to transfer shear stresses, the reaction at any point of the base (vertical pressure) is proportional only to the deflection of the slab at that point. This is different from the elastic solid representation of the foundation, where the subgrade is capable of transferring shear stresses. In the latter case, the reaction at a point on the base depends not only on the deflection of the slab at that point, but also on the deflection of adjacent points.

This study assumes that the subgrade behaves as a Winkler foundation. The constant of proportionality between the slab deflection and the reaction is known as the

modulus of subgrade reaction k, defined as the pressure necessary to produce a unit deformation of the subgrade determined through plate loading with a standard plate radius of 15 inches (Ullidtz 1987).

Dowel representation

The basic representation of the dowel bars is that of a thick beam, allowing for shear deformation of the beam. The beam is assumed to have two degrees of freedom per node, a vertical displacement, and a rotation. The beam stiffness matrix is evaluated through the use of an isoparametric finite element formulation. For this stiffness matrix, the bending contribution is fully integrated, whereas the shear contribution is under-integrated to avoid shear-locking problems. The resulting stiffness matrix is

$$K = \begin{bmatrix} \beta & \beta L/2 & -\beta & \beta L/2 \\ \beta L/2 & \alpha + \beta L^2/4 & -\beta L/2 & -\alpha + \beta L^2/4 \\ -\beta & -\beta L/2 & \beta & -\beta L/2 \\ \beta L/2 & -\alpha + \beta L^2/4 & -\beta L/2 & \alpha + \beta L^2/4 \end{bmatrix}$$

where:

$$\alpha = \frac{EI}{L} \qquad \beta = \frac{kGA}{L} \qquad G = \frac{E}{2(1+v)}$$

using the following definitions:

E = modulus of elasticity,

I = moment of inertia,

L = length,

A = cross-sectional area,

G = shear modulus, and

v = Poisson's ratio.

Further modifications have to be performed on the above stiffness matrix in order to model the behavior of a dowel bar embedded in the concrete slab. When load is applied to the dowel bar there is a relative deformation between the dowel bar and the surrounding concrete slab, which further increases displacements that would be obtained with the beam stiffness matrix alone. Figure 4–3 represents these additional deformations.

When the embedded portion of the dowel bar is considered as a beam on an elastic foundation and a shear loading is applied, it can be shown that the deflection and rotation at the face of the slab are given by:
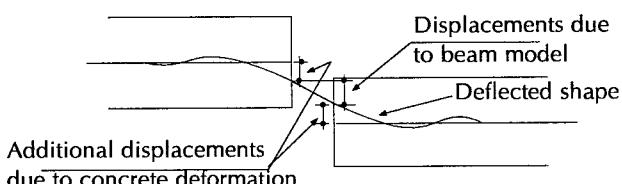
Figure 4–3. Relative deformations between dowel bar and concrete slab

$$\omega_o^p = \frac{P}{2\eta^3 EI} \qquad \theta_o^p = -\frac{P}{2\eta^2 EI} \qquad \eta = \sqrt[4]{\frac{H\phi}{4EI}}$$

where:

ω_o^p = deflection of dowel bar at concrete slab due to applied shear loading,

θ_o^p = rotation of dowel bar at concrete slab face due to applied shear loading,

P = applied shear loading,

η = modulus of relative stiffness between concrete slab and dowel bar,

H = modulus of concrete-dowel interaction,

ϕ = dowel diameter,

E = modulus of elasticity of dowel bar, and

I = moment of inertia of dowel bar.

In the same way, it can be shown that when a moment loading is applied on the dowel bar, the deflection and rotation at the face of the concrete slab are given by

$$\omega_o^m = \frac{M}{2\eta^3 EI} \qquad \theta_o^m = -\frac{M}{2\eta^2 EI}$$

using the following definitions:

ω_o^m = deflection of dowel bar at concrete slab due to applied moment loading,

θ_o^m = rotation of dowel bar at concrete slab face due to applied moment loading, and

M = applied moment loading.

Therefore, the relative deformation between the dowel bar and concrete slab can be represented by a lengthless "spring" element, where the stiffness matrix is given by:

$$K_{spring} = \begin{bmatrix} 2\eta^2 & \eta & -2\eta^2 & -\eta \\ \eta & 1 & -\eta & -1 \\ -2\eta^2 & -\eta & 2\eta^2 & \eta \\ -\eta & -1 & \eta & 1 \end{bmatrix}$$

Finally, the dowel bar can be represented by an element composed of a beam element (to account for the behavior across the joint) and two generalized springs (as described above) attached to the ends of the beam.

Effect of repetitive loading on the load transfer efficiency of dowels

The most comprehensive study of the effect of repetitive loading on the load transfer efficiency of dowels was carried out by Teller and Cashell (1958). Their study examined the effects of variables such as joint width, dowel diameter, dowel length, and number of load repetitions; they concluded that there is an exponential relation between dowel diameter and load-transfer capacity and that the decrease in joint width increases the load-transfer capacity. But the most relevant result is that the load transfer efficiency of the bars is in direct relation to the initial dowel looseness, which increases with the number of load applications. Based on the results of Teller

and Cashell, Larralde (1984) developed an equation using linear regression analysis and including several of the variables affecting the load transfer efficiency. The expression is given by

$$R_f = \frac{0.0457 \log_{10}(N)}{0.268 + 1.123 f_{rb}} \qquad f_{rb} = \frac{P_d}{P_c} \qquad P_c = \frac{3\phi(h-\phi)f_t}{2\left(1 + \frac{w}{\ell_\phi}\right)}$$

using the following definitions:

R_f = reduction factor,

N = number of load repetitions,

f_{rb} = relative loading acting on the dowel,

P_d = shear load acting on dowel, and

P_c = cracking load given by:

ϕ = dowel diameter,

ℓ_ϕ = embedded length of dowel,

h = thickness of the slab, and

f_t = tensile strength of concrete.

The reduction factor affects the value of η, or modulus of relative stiffness between concrete slab and dowel bar.

MODELING DAMAGE TO RIGID PAVEMENTS CAUSED BY SUBGRADE PUMPING

Pumping is a leading cause of damage to and failure of rigid pavements. Water infiltrates the pavement at the edges, joints, and cracks and accumulates between the slab and subgrade. When the pavement deforms under vehicle loading, this water is ejected at high speeds, often carrying subgrade material with it. As this action continues, voids are formed beneath the pavement. These voids allow the accumulation of even more water, perpetuating the process. The loss of subgrade support resulting from this pumping action leads to greater deflections and cracking in the slab, thus decreasing the pavement's service life.

Description of Larralde's pumping model

A pumping model developed by Larralde (1984) is currently the best available model. This model was developed using pumping data gathered during the American Association of State Highway Officials Road Test (AASHO 1962). Based on the passage of a series of Equivalent Single Axle Loadings (ESALs), Larralde empirically fit an equation for pumping prediction to the AASHO data. This equation expresses pumping damage in terms of the total deformation energy imposed on the pavement by traffic loading.

Larralde computed constant energy of deformation values for single 18,000-pound axle loads placed on each of the AASHO test's pavement configurations. These values were obtained from a finite element analysis of the pavement using the formula

$$E = \sum_{i=1}^{n} k_i A_i w_i^2$$

where:

E = the energy of deformation for a single load application,

n = the number of nodes with a deflection exceeding 20 mils (0.020 inches),

k_i = the subgrade modulus associated with node i of the finite element mesh,

A_i = the area associated with node i, and

w_i = the deflection of node i.

The deflection limit implies that if nodal deflection does not exceed a minimum value of 20 mils, no pumping will occur beneath that node.

Loading data from the AASHO test were converted into ESAL values. Multiplying the ESAL value by the deformation energy gives the total deformation energy imposed by a given loading on a given pavement configuration. Larralde was able to fit a pumping equation to this data using the computed deformation energy parameters and pumping quantities recorded in the road test. This equation has the form

$$NPI = \exp\left[1.652\log_{10}\left(\frac{(\Sigma ESAL)(E)}{10,000}\right) - 2.884\right] \qquad [1]$$

in which:

NPI = normalized pumping index,

$\sum ESAL$ = traffic loading expressed in $ESAL$s, and

E = energy of deformation for a single load application.

The pumping index is a measure of the volume of subgrade material pumped per unit length of the pavement. Pumping indices were normalized to account for the fact that slab lengths of various sizes were used in the AASHO test. The normalized pumping index is obtained by dividing the reported pumping index by the number of transverse joints per 100 feet of pavement length.

Having determined the normalized pumping index, the total volume of material pumped can be computed. This is accomplished using the formula

$$V = NPI \times L \times N_j \qquad [2]$$

where:

V = total volume of material pumped from beneath the pavement,

NPI = normalized pumping index,

L = length of the individual pavement slabs, and

N_j = number of transverse joints per 100 feet of pavement length.

This estimate of the volume of material pumped is used to define a void beneath the pavement slab. Larralde assumed the void to have a uniform depth over the entire area of the slab affected by pumping.

Modifications to the pumping model

Several weaknesses are inherent in Larralde's model in view of its current application at the University of Iowa. Three basic changes were made to the model to make it a more suitable tool for pumping prediction.

1) The method of computing the deformation energy imposed on the slab was altered to include the effects of vehicle configuration.

2) The method in which the volume of pumped material is distributed beneath the slab to form voids was modified.

3) A set of parameters developed specifically for use with the Larralde pumping equation was incorporated into the model to account for variation in climatic and subgrade conditions.

Calculation of deformation energy. Larralde's use of ESALs in calculating deformation energy fails to take the configuration of the vehicle causing the loading into consideration. The ESAL approach assumes each single or tandem axle to act independently on the slab to cause deformation. In reality, however, the relative position and weight of the remaining axles also contribute to the overall deformation of the slab. Rather than use Larralde's ESAL approach, the model was modified to calculate deformation energy based on a single passage of the entire truck over the pavement.

To implement this new computational method, a reference slab and joint in the pavement are defined. This arrangement is shown in Figure 4–4. The reference joint is located at the center of a number of pavement slabs. In order to ensure continuity, the number of slabs allows the length of the truck to be supported entirely on either side of the reference joint with one slab remaining unloaded on each end. The reference slab covers a region spanning one half the slab length to either side of the reference joint and is indicated by the dashed lines in Figure 4–4.

To calculate deformation energy for the passage of a truck, each axle is in turn placed at the reference joint with the remaining axles appropriately spaced over the pavement. A running sum of the deformation energy imposed on the reference slab is computed as
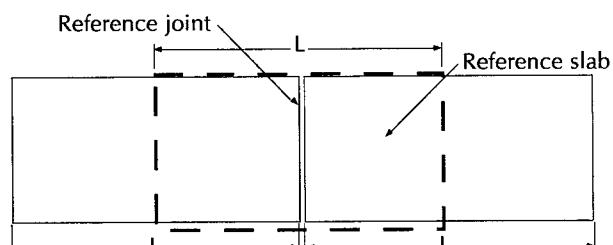
Figure 4–4. Definition of pavement reference slab and joint

each individual axle is placed at the reference joint. It was found that placing only the heaviest axle of a tandem axle combination at the reference joint avoids redundancy in the deformation energy computation. Thus three individual calculations are required for the passage of a standard tractor-trailer combination. The total deformation energy found in this manner is used in Larralde's model to calculate the normalized pumping index. Equation 2 (on page 35) is then applied to determine the total volume of material pumped from beneath the slab. It is assumed that the deformation energy and therefore the pumping damage experienced by the reference slab and joint will be representative for all other similar slabs and joints comprising the pavement.

Distribution of voids. Studies have indicated that pumping is initially more severe along the joints and edges of the pavement (Gulden 1983, Yoder and Witczak 1975). This makes Larralde's assumption of a uniform void depth beneath the slab seem improbable. Therefore, rather than distribute the volume of pumped material in this manner, the model was altered to distribute the voids as a function of slab deformation. This produces larger values for pumping and void depth near the edges and joints of the slab where the greatest deflections occur, and more accurately reflects the observed behavior of the pumping process.

By assuming the deformation energies calculated for the various nodes to be proportional to the volume of material pumped from beneath that node, this concept can be incorporated into the pumping model. As an equation this modification takes the form

$$V_i = \frac{E_i}{E_s} V_s$$

where:

V_i = the volume of material pumped from beneath node i,

E_i = the deformation energy associated with node i,

E_s = the total deformation energy imposed on the reference slab (NOTE: this value is represented as $(\Sigma\text{ESAL})(E)$ in the NPI Equation), and

V_s = the total volume of material pumped from beneath the reference slab.

Void depth is assumed to be constant beneath each element. The distribution of voids beneath the slab alters the support conditions of the pavement. This alteration of the subbase support conditions will in turn alter the energy of deformation and thus the amount of pumping associated with each element. This requires an iterative analysis process which converges on the actual size and shape of the area affected by pumping. Pavement analysis software allows the user to specify the total number of load applications and the increment in which they are to be applied. Obviously, a smaller increment will increase model accuracy, but it can also dramatically increase the required computation time.

Introduction of subgrade and climatic parameters. An important aspect not dealt with in Larralde's original model is varying climatic and subgrade material conditions and their effect on pumping magnitudes. The climate of a region including

the overall and periodic rainfall totals can have a tremendous effect on the pumping process. Pavement drainage conditions and the susceptibility of the subgrade material to pumping also play a crucial role. Several adjustment factors, including these parameters, were added to the model. These adjustment factors were developed explicitly for use with Larralde's pumping model (Van Wijk et al. 1989).

With the inclusion of the adjustment factors in the pumping model, Equation 1 (on page 35) takes the form

$$\text{NPI} = F\left\{\exp\left[1.652\log_{10}\left(\frac{(\Sigma\text{ESAL})(E)}{10,000}\right) - 2.884\right]\right\}$$

where F represents the JPCP adjustment factors detailed below.

The adjustment factor F is actually made up of four individual components and is defined by the equation

$$F = f_{sb}f_{d}f_{prec}f_{sg}$$

where:

f_{sb} = subbase adjustment factor,

> 1.0   for unstabilized subbases
>
> $0.65 + 0.18\left(\log\left(\Sigma\text{ESAL}/1\times10^{6}\right)\right)$ for stabilized subbases

f_{d} = drainage adjustment factor,

> 1.0   for poor drainage conditions
>
> $0.91 + 0.12\left(\log\left(\Sigma\text{ESAL}/1\times10^{6}\right)\right) - 0.03(t)$ for fair drainage conditions
>
> $0.68 + 0.15\left(\log\left(\Sigma\text{ESAL}/1\times10^{6}\right)\right) - 0.04(t)$ for good drainage conditions
>
> 0.01   for excellent drainage conditions

f_{prec} = rainfall adjustment factor, and

> $0.89 + 0.26\left(\log\left(\Sigma\text{ESAL}/1\times10^{6}\right)\right) - 0.07(t)$ for dry climates
>
> $0.96 + 0.06\left(\log\left(\Sigma\text{ESAL}/1\times10^{6}\right)\right) + 0.02(t)$ for wet climates

f_{sg} = subgrade adjustment factor.

> 1.0   for granular subgrades
>
> $0.57 + 0.21\left(\log\left(\Sigma\text{ESAL}/1\times10^{6}\right)\right)$ for coarse subgrades

In the preceding equations, t represents the thickness of the pavement slab in inches.

The preceding equations come directly from Van Wijk et al. (1989), as do the definitions for pavement drainage conditions listed in Table 4–1. A more detailed analysis of the development and use of pumping adjustment factors can also be obtained in this work.

Table 4–1. Definition of drainage conditions*

Excellent	• Stabilized or unstabilized subbases with $k > 1,000$ _feet / day_ (with edge drains)
	• Nonerodible stabilized subbases (with edge drains)
Good	• Stabilized or unstabilized subbases with $k > 1,000$ _feet / day_ (no edge drains)
	• Nonerodible stabilized layer (no edge drains)
	• Unstabilized subbases with $k = 250 - 1,000$ _feet / day_ (with edge drains)
	• Slightly erodible stabilized subbases (with edge drains)
Fair	• Unstabilized subbases with $k = 250 - 1,000$ _feet / day_ (no edge drains) or $k = 25 - 250$ _feet / day_ (with edge drains)
	• Slightly erodible stabilized subbases (no edge drains)
Poor	• Unstabilized subbases with $k < 25$ _feet / day_ (with or without edge drains)
	• Erodible stabilized subbases (with or without edge drains)
	• Unstabilized subbases with $k = 25 - 250$ _feet / day_

* k represents the permeability of the subbase.

Limitations of the pumping model

Several limitations inherent to the AASHO test data are introduced to the pumping model. The road test provided a wealth of practical data for use in transportation research. It was not, however, designed specifically to obtain pumping data for research applications.

Measurements of the volume of material pumped from beneath a slab is the sole available indication of the size of voids formed under the pavement. Several factors are not considered in this measurement, however. These include the effect of the sediment transport process on the material volume, the possibility of pumping from the shoulders of the roadway, and the condition of the cracks and joints in the pavement. This introduces a factor of uncertainty into the accuracy of the pumping values recorded in the road test. In addition, data from the road test are specific to the climatic and construction characteristics of the test site (Ottawa, Illinois). The adjustment factors described above (Van Wijk et al. 1989) alleviate some, but not all of these concerns.

The limited data used by Larralde to develop the model are also somewhat suspect. The 202 data points used by Larralde (1984, p. 102) are all values for pavements at the end of the AASHO test's life cycle. The model, therefore, is best suited to predict the behavior of the pavement at failure.

Verification of both Larralde's original model and the extensions made to it on this project are in progress. A discussion of the steps taken to date and those planned for the future can be found in Bhatti, Barlow, and Stoner (1996).

PAVEMENT DISTRESS MEASURES

Several damage indices have been incorporated into the RigidPav program. These indices are reported after a specified number of truck passes, correspond to the reference slab, and are assumed to be the same for any slab in the pavement system used in the analysis.

Surface area affected by cracking

This index represents the percentage of the top surface of the reference slab that has been cracked.

Cracked volume

In the IowaRigidPav program each element is divided into several layers. In each layer the stress calculations are performed at the Gaussian points used for numerical integration of the stiffness matrix. The cracking is therefore monitored at the Gaussian integration points in each concrete layer. Thus it is possible to monitor crack propagation through the thickness of the pavement. To reflect the severity of cracking in the pavement slabs, a "cracked volume index" is defined as

$$C.I. = \frac{1}{V_t} \sum_{i=1}^{N} A_i d_i$$

where:

$C.I.$ = cracking index,

N = total number of cracked integration points,

V_t = total volume of the reference slab,

A_i = area of slab associated with i^{th} integration point, and

d_i = thickness of layer associated with i^{th} integration point.

Volume of subgrade material pumped from underneath the reference slab

This index quantifies the severity of pumping in a given pavement system. Its calculation is outlined in the previous section.

Area over which pumping damage has occurred

The procedure for calculating the area covered by pumping is described in the previous section. It is reported by the IowaRigidPav program as a percentage of the area of the reference slab and represents the extent of the pavement over which there is no subgrade support.

Decay in concrete slab stiffness

This index is associated with the fatigue behavior of concrete and is defined as

$$F.I. = \frac{1}{E_o V_t} \sum_{i=1}^{N} \left(E_o - E_f \right) A_i d_i e$$

where:

$F.I.$ = fatigue index,

N = total number of cracked integration points,

V_t = volume of the reference slab,

A_i = area of slab associated with the ith integration point,

d_i = thickness of layer associated with the ith integration point,

E_o = initial modulus of elasticity of concrete corresponding to the ith integration point, and

E_f = modulus of elasticity at the ith integration point after modifications due to fatigue damage.

CHAPTER 5
TYPICAL SIMULATIONS WITH PAVESIM

This chapter presents typical simulations for the four components of PaveSim (Road Rater, Pavement Consumption, Performance Comparison and Pavement Response). Operation of each of the four components in PaveSim is similar: each begins with an input screen as seen in Chapter 2, with only those parameters to be used in that particular component appearing on its input screen. The *Help* menu in the top menu bar describes each set of parameters. Pavement Consumption, Performance Comparison and Pavement Response require further input from TruckSim (procedures for using TruckSim are discussed in detail in Chapter 3). Post processing varies for each component.

ROAD RATER

Road Rater is the component of PaveSim that returns the amount of deflection the pavement will suffer due to a point load equivalent to that applied during a field road rater test. From the startup screen, clicking on the picture labeled *Road Rater* will take the user to the Road Rater input screen. From any other screen, the *Road Rater* component is accessible under the *Analysis* menu.

The first screen to appear is one that asks for the name of the input file the user wants. If a new file is to be created, type the desired name here. For this example, type "Sample 1" and press <return>. The Road Rater input screen (see Figure 5–1) will appear.
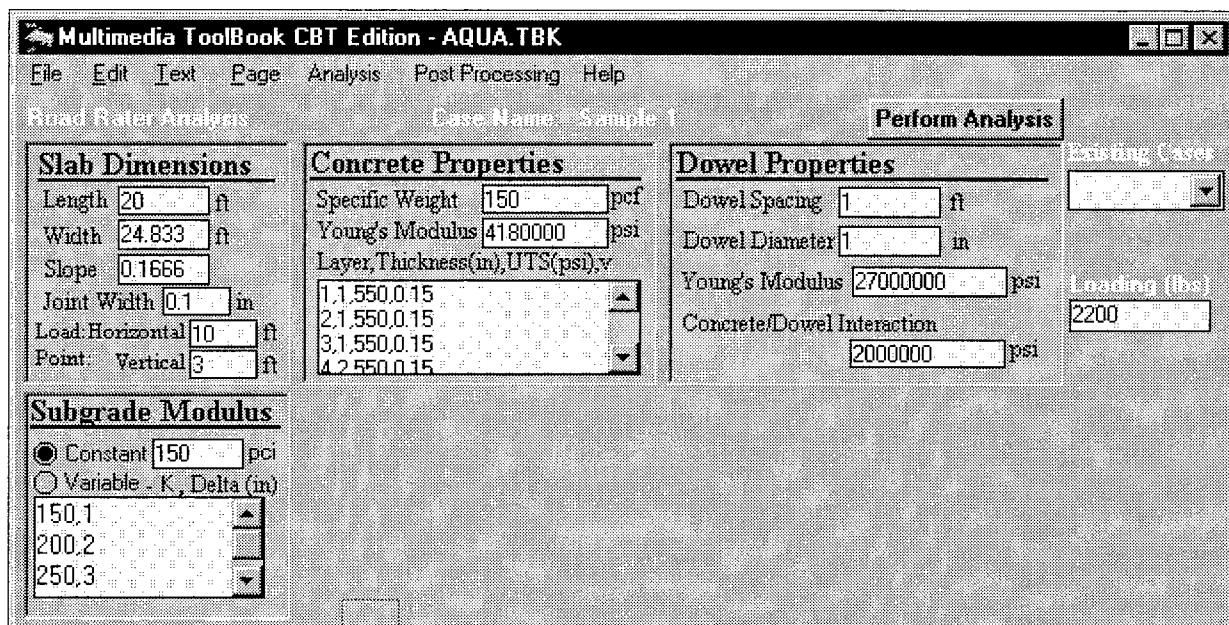
Figure 5–1. *Road Rater* input screen

Sample 1, the newly assigned case name, appears at the top of the screen. The values seen on the screen are those that were input for the most recent case. To modify any of these values, simply move the mouse to the desired location, click in the box and edit the value found there.

NOTE: If you entered the Road Rater component from the startup screen, *Case Name* will be blank.

Only one of the input parameters in Road Rater has default capabilities. If left blank, the value for Young's modulus will be calculated from the tensile strength selected in the field labeled *Layer, Thickness (in), UTS (psi), v.*

A set of input values must be stored for future use. When input is completed, the file can be saved using the standard *Save* or *Save As...* command under *the File* menu at the top of the page. Save the present screen as "Sample 1."

Once saved, the case name will appear in the menu of *Existing Cases* located on the right side of the screen. Click in that box (shown in Figure 5–2) and scroll if necessary to find *Sample 1*.
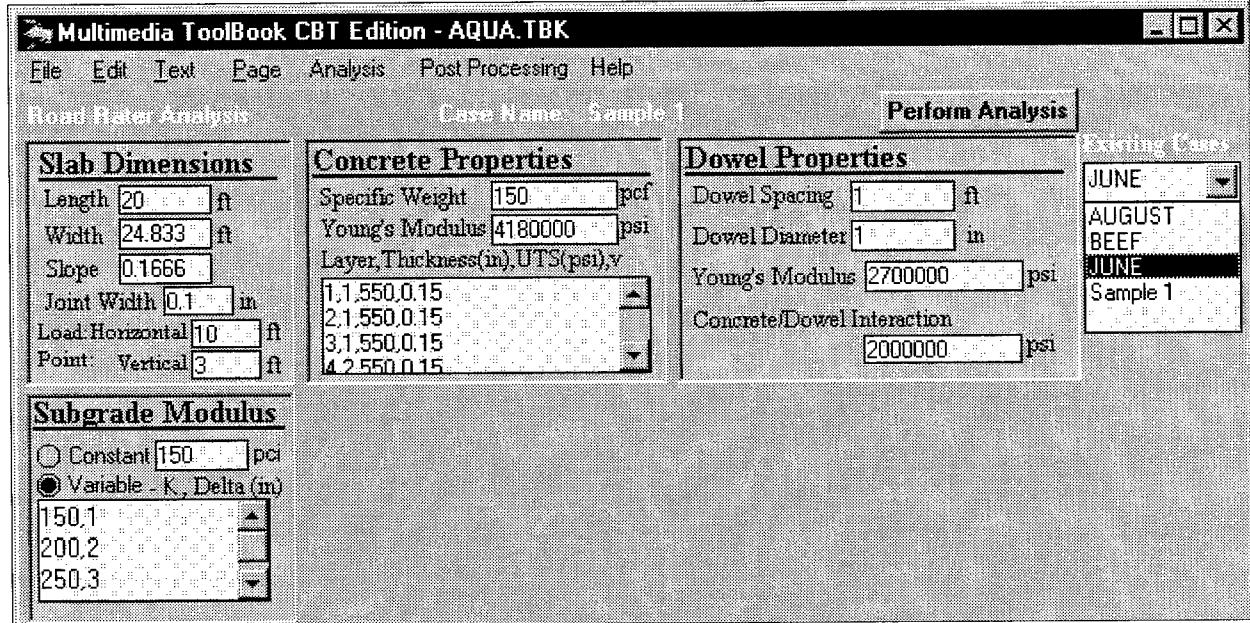
Figure 5–2. *Existing Cases* menu

To run Road Rater, select an input file using the *Existing Cases* menu on the right and click the [Perform Analysis] button located in the upper right corner of the screen.

During the analysis process (which should take 15–20 minutes), the user can shrink the Windows screen by clicking on the ☐ button in the upper right corner and then create new input data sets, review old data sets, or perform the same operations in other parts of PaveSim. If there is sufficient memory, the user will be able to begin another analysis; otherwise the second analysis will not be allowed to proceed.

There will be no signal when Road Rater has completed its analysis. One way to check on the progress is to click on *Rigid* at the bottom of the screen. This will return the Road Rater screen to full size. If *Rigid* no longer appears at the bottom of

the screen, the analysis is complete and the user can proceed to *Post Processing*. Click on *Post Processing* in the top menu bar and highlight *Road Rater Cases*. Figure 5–3 shows the post processing screen. Any data presently visible in the chart can be removed by clicking [Clear Data].
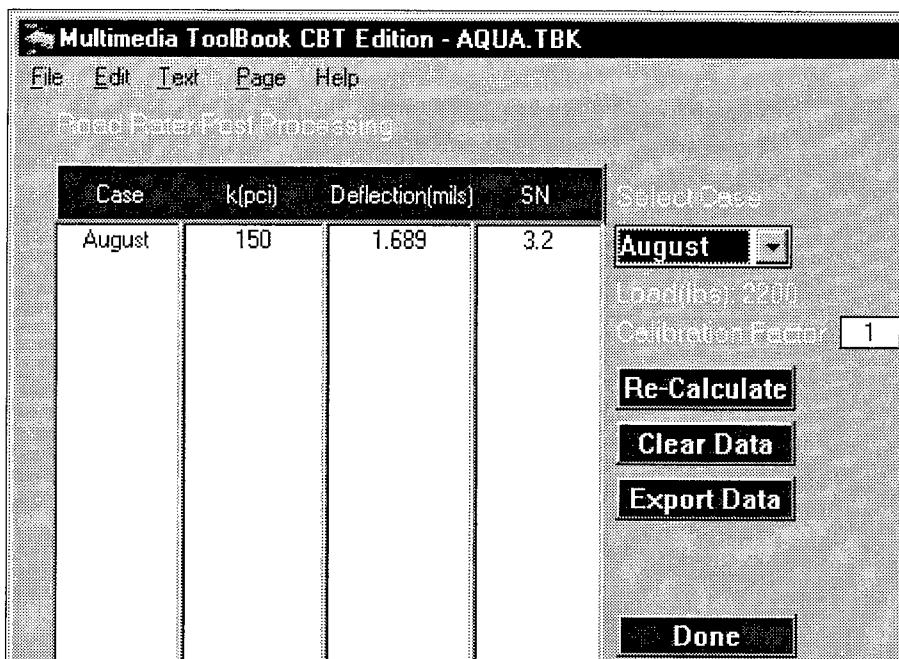

Figure 5–3. *Road Rater* post processing screen

To choose an existing case, click on the *Select Case* menu and highlight your choice. One line of data will be added to the chart. The data include an estimated structural number (SN) based on an equation derived from the charts in Potter and Dirks (1989).

A calibration factor has been offered. When set to "1", the structural number is calculated on the deflection offered by PaveSim's Road Rater component. Should this value vary from known empirical values, the calibration factor can be adjusted. To use this feature, enter the new *Calibration Factor* and click [Re-Calculate].

To transfer the data in the chart to Microsoft Excel for further analysis, click [Export Data]. When finished, return to PaveSim by clicking on the PaveSim screen or by closing Excel. Once back at the Post Processing screen for the Road Rater component, click [Done] to return to the *Road Rater input* screen.

PAVEMENT CONSUMPTION

PaveSim's Pavement Consumption component accepts input on pavement and truckloads, then applies finite element analysis to determine the effective pavement depth after a given number of passes of the truck. From the startup screen the user can move to Pavement Consumption by clicking on the picture labeled *Pavement Consumption*, or from any other screen by highlighting *Pavement Consumption* under the *Analysis* menu in the top menu bar. The Pavement Consumption screen is shown in Figure 5–4.
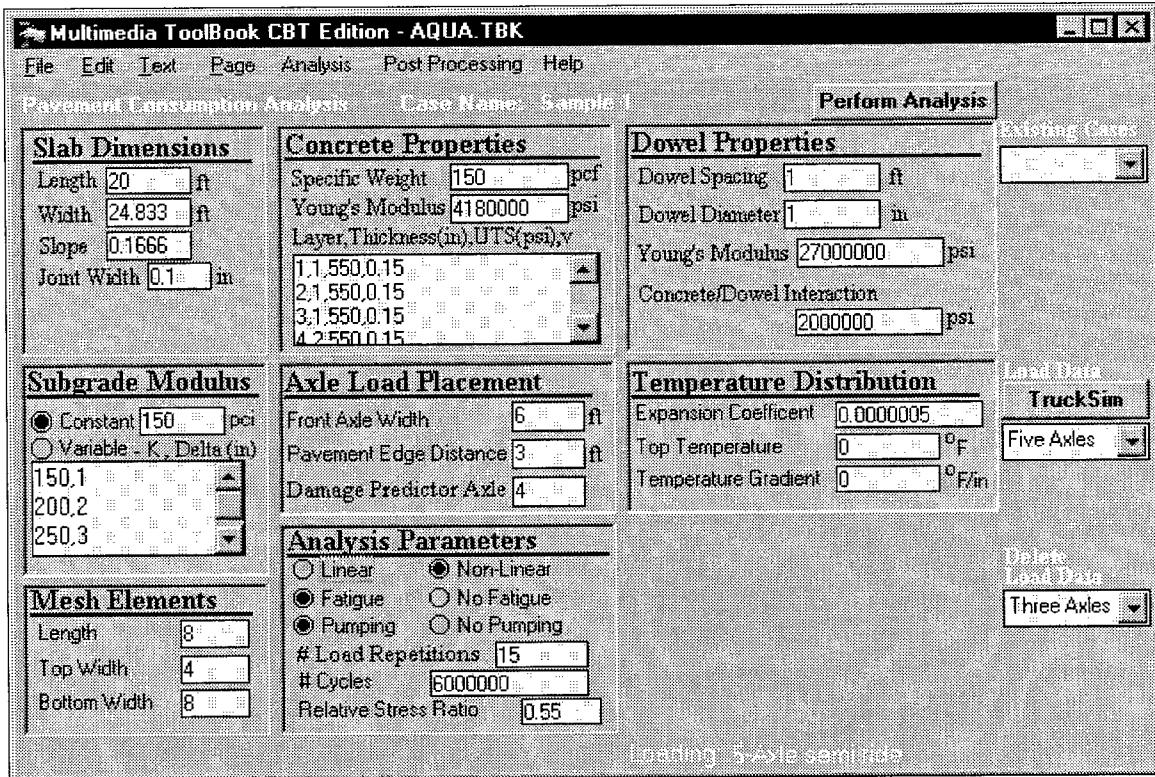
Figure 5—4. *Pavement Consumption* input screen

As in the Road Rater component, the values in the fields are the values that were last entered rather than default values. If left blank, Young's modulus will be calculated from the tensile strength of the concrete. Also, if left blank in the *Axle Load Placement*, the governing axle determined by the TruckSim simulation will be the *Damage Predictor Axle*.

The name of the TruckSim load case most recently selected is shown next to the word *Loading:* in reverse lettering at the bottom of the screen. To change this loading case, move the mouse to the pull-down menu beneath the | TruckSim | button and highlight the desired axle category (*Two Axles, Three Axles, Five Axles* or *Other*; see Figure 5—5). Next, select the specific case from among the menu items that appear. The case you have chosen will then be listed next to *Loading:* at the bottom of the page. New load data can be generated by entering TruckSim. To enter TruckSim from this screen, click | TruckSim | and follow the directions in Chapter 3 to create new load simulation cases.

Once the input data are correct, save the case using the *Save* or *Save As...* options under the *File* menu in the top menu bar. The analysis, which will take about two to three hours to complete, will begin after | Perform Analysis | has been clicked.

After the analysis is complete, the next phase is post processing. Select *Pavement Consumption Cases* from the *Post Processing* menu. The screen shown in Figure 5—6 will appear. Choose the desired case from the *Select Case* menu.

> **NOTE:** If a case that is still being analyzed is chosen from the *Select case* menu, a window will appear stating that the case does not exist.
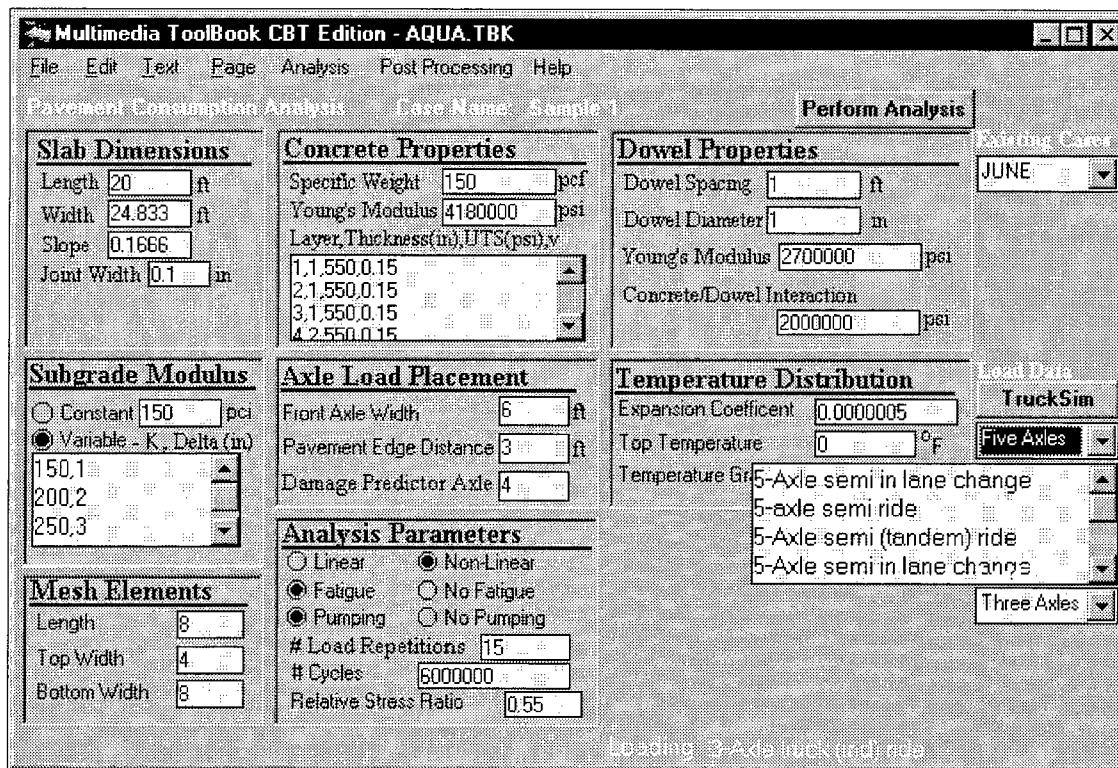
Figure 5–5. Menu to select loading data
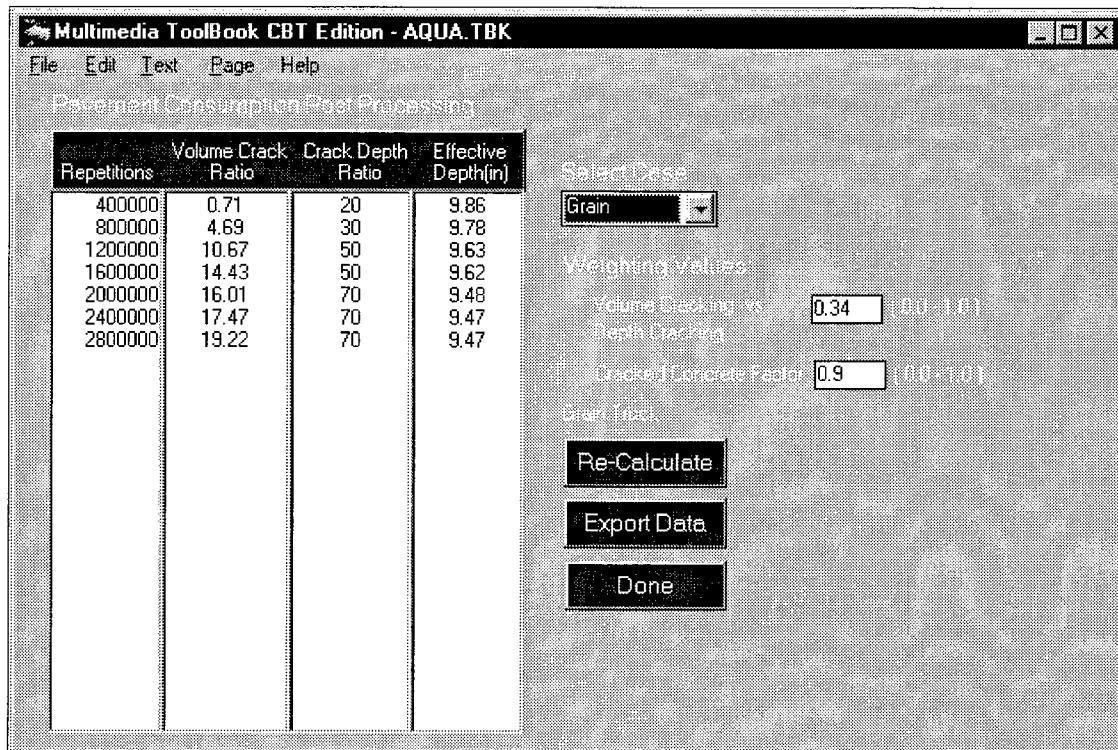
Figure 5–6. *Pavement Consumption* post processing screen

Select *Grain* from the *Select Case* menu. These data simulate the vertical loads created by a 3-axle semi truck loaded with 400 bushels of corn traveling over standard pavement. The *Load Data* file for this case is called *Grain Truck*. Figure 5–6 shows the values resulting from case *Grain*.

When an existing case is selected, the values will fill the chart. The effects of *Volume Crack Ratio* and *Depth Crack Ratio* on the *Effective Depth* can be controlled by the weighting factors in the windows on the right side of the screen. The field labeled *Weighting Factors* accepts values that will allow the user to adjust the contribution of the cracking types to the measure of effective pavement depth remaining at any number of repetitions.

The *Volume Cracking vs Depth Cracking* value ranges from zero to one. A value of zero indicates that the volume of cracking does not contribute to the calculation of effective depth, so crack depth is the only contributing factor to the loss of pavement depth. Alternatively, a value of one indicates that the volume of cracking will determine effective pavement depth and crack depth is to be ignored.

Similarly, *Cracked Concrete Factor* can vary from zero to one. A value of zero indicates that cracked concrete will not contribute to the effective depth of the pavement, whereas a value of one indicates that the maximum contribution of the cracked concrete will be expected.

After changing any of these values, click [**Re-Calculate**] to view the new effective depths.

Export Data will take the user to Excel and transfer the data in the post processing chart as well. The user can work with the data in this environment and return to PaveSim by closing the Excel window when the investigation is completed.

Click on [Done] to return to the Pavement Consumption input screen.

PERFORMANCE COMPARISON

Performance Comparison uses the same type of input and completes the same analysis as Pavement Consumption except that it considers only a single pass of the chosen truck (without fatigue or pumping) and compares the deflection caused by that truck to the deflection caused by a standard 18-wheel tractor-semitrailer or another chosen truck.

To access the Performance Comparison input screen, shown in Figure 5–7, click the picture labeled *Performance Comparison* at the startup screen or highlight *Performance Comparison* in the *Analysis* menu.

The input for Performance Comparison is the same as that for Pavement Consumption except that the field *Analysis Parameters* does not appear (these parameters are held constant at *linear analysis, no fatigue,* and *no pumping*). A truckload data set is chosen in the same manner as it was in Pavement Consumption and is indicated by the *Loading:* statement at the bottom right of the screen. To change the truckload data set, highlight the desired database using the [▼] menu beneath the [TruckSim] button. To generate a new load case, click on [TruckSim].
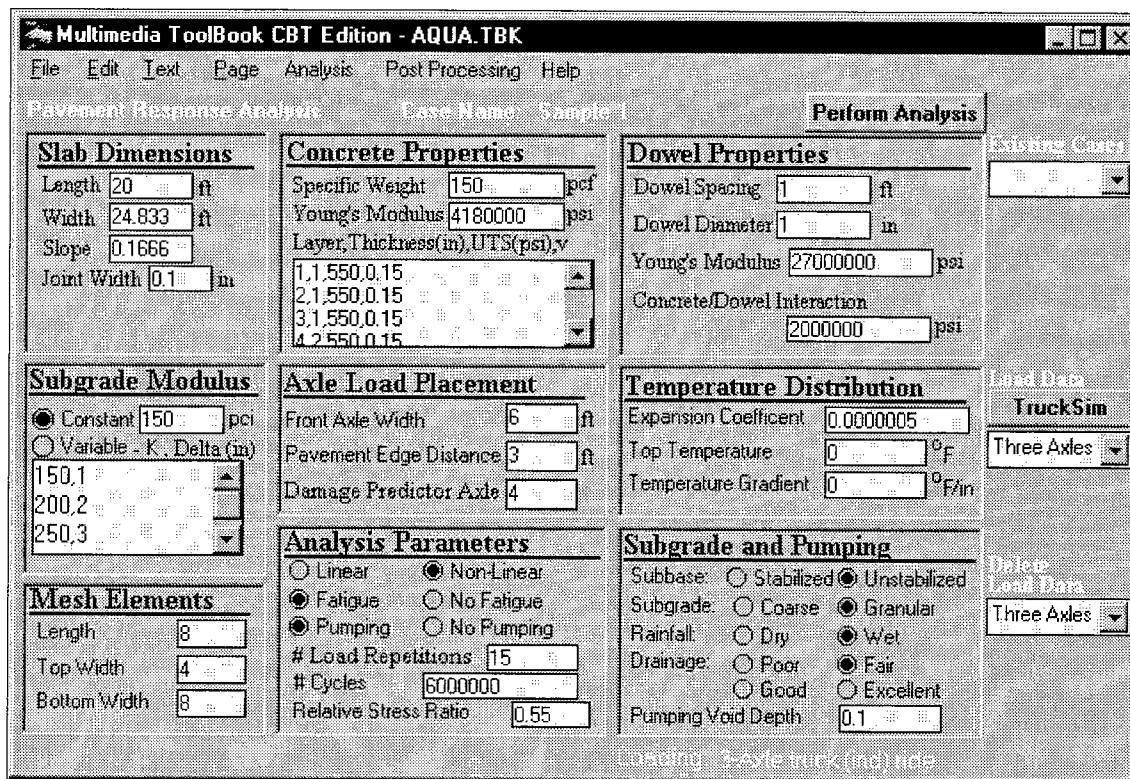
Figure 5-7. *Performance Comparison* **input screen**

As an example, a comparison can be made between the standard 18-wheel tractor-semitrailer and one with a walking beam suspension. To select the *S18W* Performance Comparison case, highlight *S18W* in the drop-down menu under *Existing Cases* near the upper right corner of the screen. The truckload is indicated next to *Loading:* at the bottom right of the screen and should now read *Standard 18 Wheel*. To change the load case to *Walking Beam* (created in Chapter 3), highlight the *Five Axles* database using the ▼ menu beneath the TruckSim button, then highlight *Walking Beam* in the next pop-up menu.

Now the concrete properties will be the same as those used for *S18W*, but the loads will be those generated by the semi with the walking beam suspension. *Save As...* "WBeam." To begin the finite element analysis, click Perform Analysis. The analysis will be completed in one to two hours.

From under the *Post Processing* menu in the top menu bar, select *Performance Comparison Cases*. The screen shown in Figure 5–8 will appear.

To compare the deflection resulting from one pass of each truck over the pavement, two cases must be selected. Click on the ▼ menus under *Case 1* and *Case 2* to highlight the appropriate cases. After both cases have been selected, a message will be printed: either *Case 1 is X% larger than Case 2* or *Case 1 is Y% smaller than Case 2*.

If you compare the deflection resulting from the 10 percent overload case *Over10* to that of the Standard 18-wheel case *S18W*, you will find that the 10 percent overload case is 8 percent larger than the Standard 18-wheel deflection case (see Figure 5–8).

After *Wbeam* has been analyzed, it will be listed in the *Case* fields and can be selected to compare with *S18W* or any other *Performance Comparison* case. Click [Done] to return to the *Performance Comparison* input screen.

PAVEMENT RESPONSE

As with the other three PaveSim components, the Pavement Response input screen (Figure 5–9) can be reached by clicking the picture at the startup screen or by *selecting Pavement Response* from the *Analysis* menu. Pavement Response is the research component of PaveSim. It allows the user complete control of the computational parameters, including those related to subgrade and pumping damage. In the Pavement Consumption and Performance Comparison components, the parameters listed in the *Subgrade and Pumping* field were held

Figure 5–8. *Performance Comparison* **post processing screen**

constant at *stabilized subbase, granular subgrade, fair drainage, wet climate,* and *void depth at 0.2 inches.* In the Pavement Response component, the user can vary those values.

As with the other components, the input screen has a menu of *Existing Cases* from which pavement data can be selected, and a menu from which to select truckload data or access TruckSim to create a new loading case. The *Help* menu in the top

Figure 5–9. *Pavement Response* **input screen**

menu bar, which provides descriptions and diagrams for each input field, is available in all components of PaveSim (including the Pavement Response component). When pavement and loading cases have been selected (and saved if necessary), click on Perform Analysis . Allow two to three hours to complete the finite element analysis.

PaveSim offers no direct post processing option for Pavement Response. The research nature of the option is better served by allowing the user to choose the processing that will be most useful. The output file is located at *c:\PaveSim\casenameo* where *casename* is the name next to *Case Name:* near the top of the input screen when the analysis begins. For example, if the case name is *EINSTEIN*, the pathname will be *c:\PaveSim\einsteino*. This files contains all finite element analysis results, including deflections at the nodes and stresses in layers. This data can be exported to other applications, such as a spreadsheet, for further processing.

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APPENDIX A
SIMULATION OF ROAD RATER TEST

The Road Rater test, developed in 1979, is currently performed on most rehabilitation and resurfacing projects in Iowa. A Road Rater deflection dish measures the amplitude of movement (hereafter called deflection) of a pavement surface due to an applied load of known magnitude and location. The deflections are then correlated to the pavement's strength (which is used to quantify the pavement's condition).

An introduction to the Road Rater test is given in the next section. Subsequent sections briefly explain soil support values and the procedure used to perform the simulation, and discuss the results of the simulation. The fourth and final section shows the sensitivity of the simulation to different input parameters.

THE ROAD RATER TEST

The Road Rater estimates the structural capacity of pavements using dynamic deflection measurements. To create a loading force, a large mass is hydraulically lowered onto the pavement and oscillated through a servo valve. The applied force varies from 400 to 2,400 pounds for rigid pavements and the resulting deflection is measured by four velocity sensors. One sensor is positioned directly under the ram and the others are spaced at one-foot intervals from the ram (see Figures A–1 to A–3).
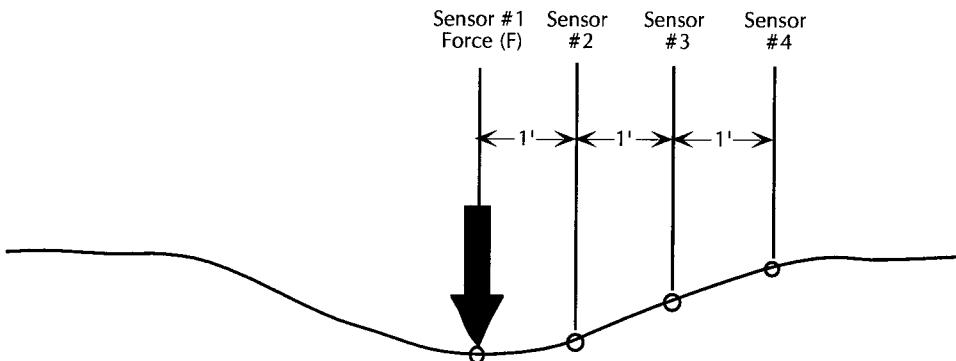
Figure A–1. Road Rater deflection dish

The force applied to the pavement is also measured by a velocity sensor mounted on top of the hydraulic two-way ram. The sensor measures peak-to-peak mass displacement which can be translated into a force with the following expression:

$$F = 32.70 f^2 D$$

Where F is the peak-to-peak force in pounds, f is the frequency of the loading in Hertz (Hz), and D is the peak-to-peak displacement of the mass in inches. For testing of rigid pavement, the manufacturer recommends a frequency of 30 Hz and a 0.068-inch mass displacement, which produces a force of:

$$F = 32.70 f^2 \quad D = 32.70(30)^2(0.068) = 2,000 \text{ lb.}$$

This represents the maximum force for the Model 400 Road Rater (used by the Iowa DOT).

The official Road Rater test procedure is Test Method No. Iowa 1009–B. Tests are conducted annually in the outside wheel track of a roadway during the Spring (April and May) because the roads are the most unstable during this time. The results are recorded on coding sheets which are processed by a computer that has been programmed with the relationships that convert the deflections into structural ratings and the deflection basin shapes into soil support (K) values (see section A.2 for details on soil support [K] values).

For rigid and composite pavements, tests are performed at the joints and mid-panels. The ram is placed one foot from the joint with all the sensors positioned on the same pavement panel. By conducting tests on the joints and comparing the Structural Ratings and soil support (K) values with those obtained at mid-panel, the condition of the joints can be determined. For the design of an asphaltic overlay, the 80th percentile Structural Rating is used.

Figure A–2. Road Rater test vehicle

For logistical reasons, only ten joints are tested for each test section longer than two miles; only 15 mid-panel locations and six joints are tested for test sections less than two miles long. Road Rater measurements are inventoried and used to quantify pavement conditions in the pavement management system. The information from the Road Rater test is then used to determine asphaltic overlay thickness.

The Road Rater-based design method for asphalt concrete overlays works well, but requires a great deal of field testing (a minimum of 30 tests per test section must be conducted to obtain statistically valid information). Because of the need for such a large amount of field testing during a limited time, a more efficient means of data collection would be advantageous. A computer model would provide more efficient data collection. By supplying the model with the necessary data (roadway characteristics and traffic history), deflection estimates could be obtained during all times of the year with minimal labor cost.

Figure A–3. Load ram and sensors

SOIL SUPPORT (K) VALUES

This section provides a brief explanation of the soil support (K) values measured by the Road Rater and used by PaveSim to simulate subgrade support. Soil support (K) values were developed to account for the variability of pavement strength due to different subgrade support capacities. Also, to normalize the effects of subgrade

moisture on Road Rater deflection readings, tests are conducted when the pavements are weakest (after the frost is out of the ground and the subgrade is saturated). In Iowa, pavements are weakest during April and May. Performing the Road Rater tests annually during these months makes it possible to identify the subgrade soil type or density. Without detailed soil information it is extremely difficult to adjust Road Rater deflection data taken during other times of the year when the subgrades are firm. Because detailed soil information is seldom available and soil types can vary within the same pavement section, all Road Rater testing is conducted in April or May. This limits the effects due to temperature (such as joint lockup and temperature deflections).

The base relationships for soil support (K) values were developed by first establishing a relationship for the subgrade strength (modulus of elasticity, E_s) using the spreadability or percent spread of the deflection basin versus the Sensor #1 deflection, where the spreadability or percent spread was the average of five sensor readings divided by the Sensor #1 deflection reading. The soil subgrade factors used by the Iowa DOT were developed by correlating Plate Load Test information to standard Proctor Density and AASHTO (American Association of State Highway and Transportation Officials) Soil Group Index. These values have provided a basis for design since the adaptation of the AASHTO Road Test Guides during the late 1950s. These historical subgrade values were used in the development of the Road Rater deflection-basin–derived (K) values. Initial testing was performed on new roadways that contained subgrades of known soil types and subbase treatments. Deflection basins were developed for typical soil types and combinations of various soil and granular subbases. Further improvements were made using load testing data for Illinois soils. From this improved soil subgrade model, Road Rater (K) values were developed to provide answers to deflection basin problems.

In 1983 extensive pavement and subgrade testing was done for a selected study group of Iowa Pavements (21 LTM Sections). Soil core samples were taken at individual Road Rater test points. The tests determined moisture and in-place density effects for soil types commonly used in Iowa. The results of the testing showed that reproducible, predictable Road Rater deflection-basin–derived (K) values could be obtained for specific materials and conditions. It was determined that the assigned values provide an acceptable range for design.

PAVESIM SIMULATION OF THE ROAD RATER TEST

As explained in Chapter 5, one of the components of PaveSim simulates the Road Rater test. The result of the Road Rater simulation, as in the actual test, is the deflection of the pavement at Sensor #2. Because field test data exhibit a certain amount of scatter (statistical spread), it can be difficult to compare them with simulation results. As Table A–1 indicates, on a given stretch of roadway with fairly consistent traffic characteristics, only the soil support (K) values change. Therefore, meaningful information can be obtained for such roadway stretches by plotting deflection as a function of the soil support (K) values.

Figures A–4 and A–5 plot the deflections computed by PaveSim and those collected by the Iowa DOT against corresponding soil support (K) values for two different roadways (U.S. Highway 52 and Iowa Highway 13).

Table A–1. Data needed by PaveSim

| Description	Where to find data	Default value
Type of reinforcement	Construction history	Doweled
Slab width	Construction history	24.83'
Slab length	Construction history	20'
Joint width	Construction history	0.1"
Skew slope (m)	Construction history	0.1666
Dowel spacing	Construction history	1'
Dowel diameter	DOT/construction standards	1"
Young's modulus for dowel material	Estimate	27,000,000 psi
Modulus of concrete/dowel interaction	Estimate	2,000,000 psi
Number of cycles	—	—
Number of repetitions	—	—
Relative stress ratio	—	—
Layer thickness	Construction history	Construction history
Ultimate tensile strength (of concrete)	Estimate	550 psi
Poisson's ratio	Estimate	0.15
Young's modulus of concrete	Estimate	3,000,000 psi
Subgrade modulus	Field data	Field data
Thermal expansion coefficient	Estimate	0.0000005
Temperature of top of slab	Estimate	0
Temperature gradient	Estimate	0
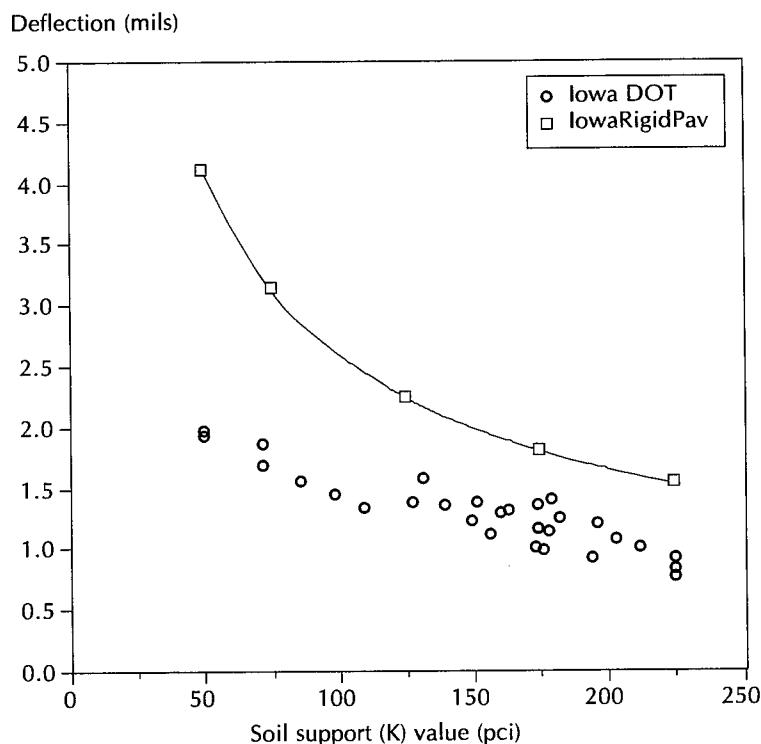
**Figure A–4. Deflections and soil support (K) values
for U.S. Highway 52, Milepost 36.00 to 43.00**
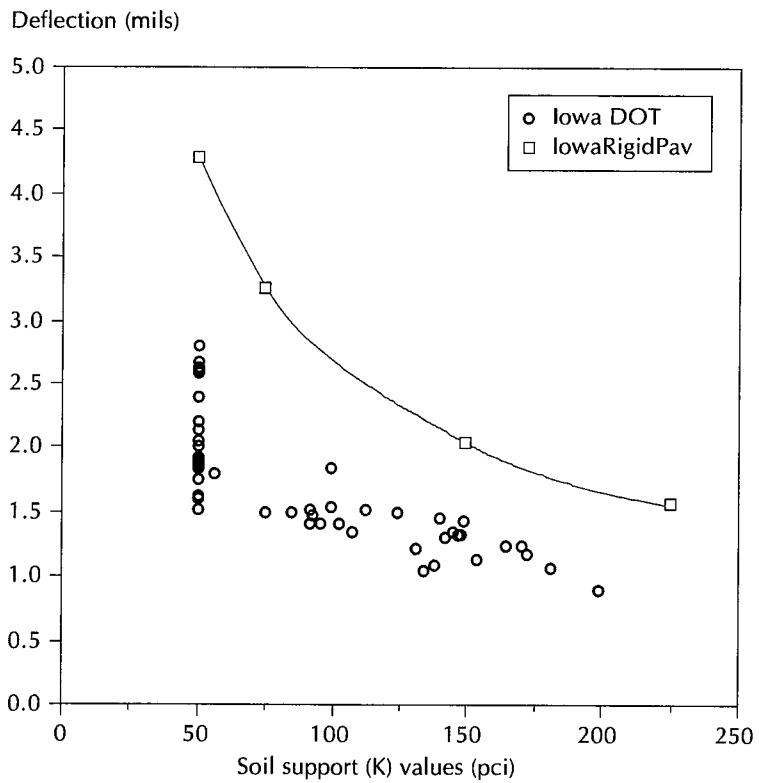
Deflection (mils)

**Figure A–5. Deflections and soil support (K) values
for Iowa Highway 13, Mileposts 60.50 to 72.50**

Results of the simulation and the Road Rater test data match well qualitatively:
deflections are high for low values of K, but then quickly decrease as K increases.
Quantitatively, however, PaveSim data values are about twice as large as those
collected from the Road Rater test. To address this substantial difference, a
sensitivity analysis of the PaveSim simulation was conducted and is presented in the
next section.

SENSITIVITY ANALYSIS OF THE PAVESIM SIMULATION

Some of the data used in the PaveSim simulation are only estimates, so errors in
computed deflections are expected. The amount of error that can be associated with
these estimates should therefore be investigated. Of the parameters listed in Table
A–1, the six parameters shown in italics should be estimated.

Since there is more uncertainty (e.g., dowel conditions, modulus of dowel concrete
interaction, and pumping) at the joints than at mid-panel, the research team decided
to perform the sensitivity analysis only on mid-panel tests. Parameters listed above
that do not play a critical role for mid-panel deflections or do not vary significantly
therefore do not warrant a sensitivity analysis. For example, because dowels are not
a critical factor in the determination of mid-panel deflections, the parameters
associated with dowels do not need to be very precise. Also, because the range of
dowel parameter values (Young's modulus of dowel material and Modulus of
concrete/dowel interaction) is relatively small, the amount of error associated with a
representative value is further reduced. Since the range of Poisson's ratio is also quite
small, the amount of error attributable to it was not investigated. Thus the sensitivity

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analysis of input parameters was reduced to three: ultimate tensile strength (of concrete), Young's modulus of concrete, and subgrade modulus. Ultimate tensile strength and Young's modulus of concrete are interdependent and can therefore be combined, leaving only two material parameters to investigate.

In addition to uncertainty in material properties, the location of the test load must be estimated. In the field test, the load is placed in the outer wheel track of the road. Because the PaveSim wheel track is assumed to be 3' from the pavement's edge (even though the actual distance varies), a sensitivity analysis of the location was also performed.

Sensitivity of PaveSim deflections to Young's modulus of concrete

To determine how much error in the computed deflections can be attributed to uncertainties in the Young's modulus of concrete, the Road Rater simulation was performed for a range of values from 2E6 psi up to 6E6 psi, in 1E6 psi increments. This range includes concrete that has both extremely low strength (e.g., a highly fatigued inferior grade concrete) and well-seasoned high-strength concrete. Also, to determine whether the sensitivity of Young's modulus varies with different soil support (K) values, deflections for each value of Young's modulus were computed for a range of soil support (K) values (see Figure A–6).

The analysis shows that within the usual range of Young's modulus (3–4E6 psi), the computed deflection does not vary substantially (nine percent difference between curves). The analysis also indicates that the deflection decrease attained by increasing the grade of concrete becomes progressively smaller between neighboring curves. It is interesting to note that the incremental change in deflection attained by increasing concrete strength is roughly the same for the range of soil support (K) values tested.

Deflection (mils)

Figure A–6. Sensitivity to Young's Modulus of concrete for a range of soil support (K) values

Sensitivity of PaveSim deflections to soil support (K) values

To determine the amount of error that might be associated with uncertainties in the soil support (K) values, the Road Rater simulation was performed for a wide range of values (from 50 to 500 pci) for a given roadway (IA 13; MP 60.50–72.50). The results of the simulation were then plotted on the same grid as Iowa Department of Transportation data (see Figure A–7).

As Figure A–7 shows, the two data sets follow similar trends, but the simulation data are somewhat larger. Two possible explanations were considered:

1) Due to the very small quantity being measured, the Road Rater field test deflection measurements cannot be exact. Also, due to the approximations inherent in the finite element analysis, simulated measurements cannot match

Deflection (mils)

Figure A-7. Road Rater simulation deflections and soil support (K) values for Iowa Highway 13, Mileposts 60.50 to 72.50

physical conditions exactly. Considering these two difficulties, the two data sets match quite well, especially for design considerations.

2) Figure A-7 suggests that a soil support axis shift may be at least partly responsible for differences between the two data sets. Because soil support (K) values used in the simulation are taken directly from the Road Rater field test, the amount of error associated with their use is not known. Thus, if the Road Rater field test underestimates soil support (K), the Iowa DOT deflections would be incorrectly shifted to the left. For example, if the Road Rater field test measures a deflection of 1.5 mils and a corresponding soil support (K) value of 100 pci but the actual soil support (K) value is closer to 250 pci, that point would actually correspond to the K=250 pci point on the simulation curve. Figure A-8 reflects such an axis shift, accomplished by multiplying the soil support (K) values of the Iowa DOT data by a factor of three.

Although this "axis shift" makes the two data sets match quite well, without justification it is meaningless. Ideally, we would identify another source independent of the Road Rater test for soil support (K) values. With such data, the differences in the two data sets could be more adequately explained. Regardless, the simulation results are clearly very dependent upon soil support (K) values and thus caution must be exercised in the choice of input values.

Sensitivity of PaveSim deflections to test load location

In the field test, the location of the test load is in the outer wheel track, which varies from roadway to roadway. An investigation into the sensitivity of the deflections due to the load location was therefore performed. In the PaveSim model the location of the wheel track is assumed to be 3 feet from the edge of the pavement. For comparison purposes, the simulation was performed with the load located a distance

Deflection (mils)
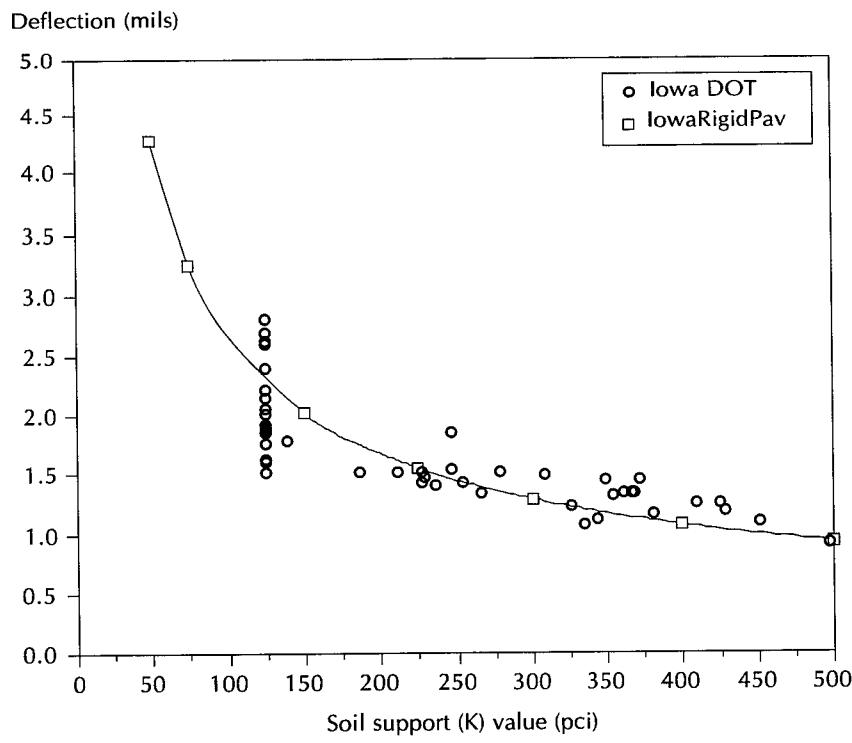
Figure A–8. Iowa RigidPav simulated data andto Road Rater field test
data with shifted axis, for Iowa Highway 13, Mileposts 60.50 to 72.50

of 4.5 feet from the pavement edge. Figure A–9 shows the results of the two
simulations. As the figure illustrates, the computed deflection is reduced 10–20
percent by moving the load 1.5 feet toward the center.

Deflection (mils)
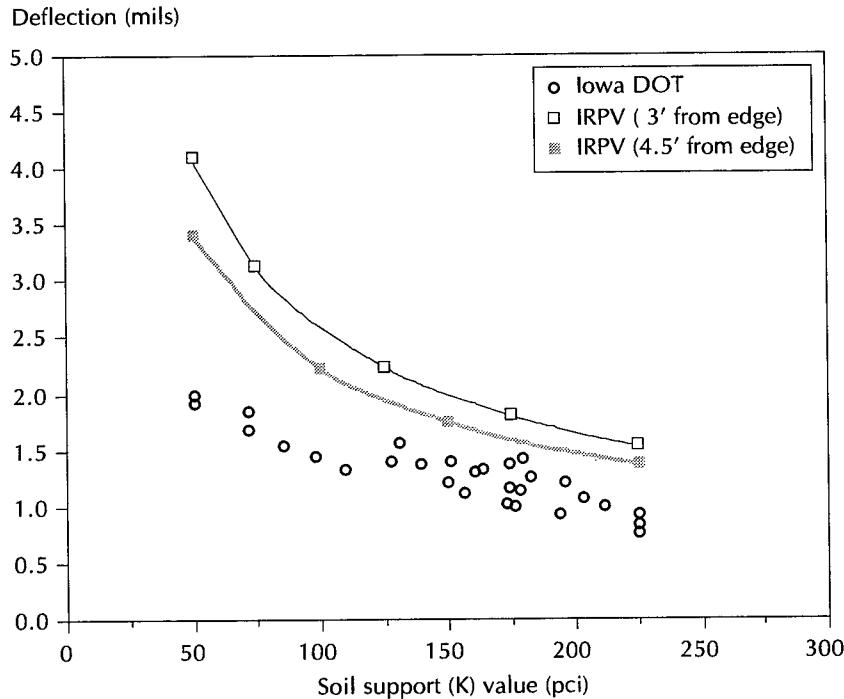
Figure A–9. Iowa RigidPav simulated data (loads 3 feet and 4.5 feet from pavement edge)
and Road Rater field test data, U.S. Highway 52, Mileposts 36.00 to 43.00

PaveSim: Simulation of Pavement Damage Due to Heavy Vehicles

APPENDIX B
IMPORTING ROAD PROFILE DATA

This appendix gives detailed instructions for importing road profile data into TruckSim. First, go to the Road Profile Input screen in TruckSim. While in this screen, create a temporary road profile by clicking [New], naming the profile, and inputting a couple of data points in the *Profile Input* field. Once this is done, select the *Export* command from the *File* menu. The temporary road profile will be exported to the c:*TruckSim\Input\Prof_Tab* directory and assigned the same name as the ID number in the upper right corner of the Road Profile Input screen.

Next, the exported temporary road profile must be modified to be imported with the new road profile data. To do this, open the exported road profile with a text editor (an example of an exported file is shown below). Delete all the data between the *RField "PlotData"* and *~endRField* lines and paste the new road profile data between these lines in the same format as the old data. The format consists of the horizontal distance in feet followed by the vertical distance in inches (separated by a comma).

NOTE: The amount of data TruckSim can handle is limited. Any data exceeding TruckSim's limit will not be included in the new road profile.

The name and category of the new road profile data also should be changed. To change the name, replace the name in quotes in the line that starts with the word *page* and the new name of the profile data. In the example below, the current name of the data is *Temporary*.

  page "Temporary"

The category is changed by putting the category name in the line following the RField "subdir" line. The category name in the current example is 'IRI25.0'.

  RField "subdir"
  IRI25.0

Once these modifications have been made, close the file and go back to TruckSim's Road Profile Input screen. Select *Import* from the *File* menu and import the file with the appropriate ID number. The new road profile data will be in TruckSim with the specified name and category. An example of an edited export file ready for importing is shown below. In this example the new name is *I80* and the category is *Interstates*.

Exported file

  exportSGUIFile v1.0

  book "INPUT\PROF_TAB\PROFILE.TBK"
  category "input,Profile"
  page "Temporary"
  RField "startend"

```
1,3,1,9
~endRField
RField "x1000"

~endRField
RField "PlotData"
1,1
2,4
3,9
~endRField
RField "notes"
Data for no tabular profile input.
~endRField
RField "subdir"
IRI25.0
~endRField
endBook
```

Modified file for importing

```
exportSGUIFile v1.0

book "INPUT\PROF_TAB\PROFILE.TBK"
category "input,Profile"
page "I80"
RField "startend"
1,3,1,9
~endRField
RField "x1000"

~endRField
RField "PlotData"
1,2
2,4
3,6
4,8
5,10
6,12
7,14
8,16
9,18
10,20
11,22
12,24
~endRField
RField "notes"
Data for no tabular profile input.
~endRField
RField "subdir"
Interstates
~endRField
endBook
```

APPENDIX C
TRUCKSIM KEYWORDS FOR OVERRIDING PARAMETERS

Keyword	Description
BD(n)	axle n linear shock absorber damping rate (lb-s/in)
BT(n)	axle n tire damping rate (lb-s/in)
HCGA(n)	height of axle n center of gravity (CG) above ground (in)
HCGTU(1)	height of total tractor CG (in)
HCGTU(2)	height of total unladen trailer CG (in)
HH(1)	height of hitch above ground (in)
HLLB(1)	height of bottom of rectangular load above top of trailer load bed (in)
HRP1(1)	height of reference point RPSM1_1 above ground (in)
HRP1(2)	height of reference point RPSM1_2 above ground (in)
HTLB(2)	height of top of trailer load bed above ground (in)
iaxle n	in reference to axle n (used with Spring menu)
IYYTU(1)	total tractor pitch moment of inertia (in-lb-s2)
IYYTU(2)	total unladen trailer pitch moment of inertia (in-lb-s2)
KHY(1)	hitch 1 pitch torsional stiffness (in-lb/deg)
KT(n)	axle n tire spring rate
LDUAL(n)	axle n dual tire spacing (use 0 for singles) (in)
LTAND(t)	tandem suspension t axle spacing (in)
LTNDLLL(t)	tandem t load-leveler link length (in)
LWB(1)	tractor wheelbase (in)
LWB(2)	trailer wheelbase (in)
LXRL(1)	X dimension of rectangular load (in)
LXRP1(1)	X distance from tractor front axle to RPSM1_1 (positive to rear) (in)
LXRP1(2)	X distance from hitch 1 (fifth wheel) to RPSM1_2 (positive to rear) (in)
LYRL(1)	Y dimension of rectangular load (in)
LZRL(1)	Z dimension of rectangular load (in)
M(n)	total mass supported by ground below axle n of laden vehicle (lbm)
MTNDLL(t)	tandem t peak-to-peak load-leveler coulomb-friction moment (lbm)
MTRAILU	total mass of unladen trailer (lbm)
MUL(n)	total mass supported by ground below axle n of unladen vehicle (lbm)
MUS(n)	(scaled) mass of An (lbm)
PROFILE FIRST	short name of the channel in the ERD file with road profile data
RSLOPE_X	longitudinal road slope (positive slope gives a positive vehicle pitch) (–)
RSLOPE_Y	lateral road slope (positive slope gives a positive vehicle roll) (–)
SF_ERD	scale factor to be applied to input ERD road profile data (–)
SPEED	forward vehicle speed (mph)

NOTE: Refer also to the View All Parameters screen accessible from the Runs screen in TruckSim.