THE FLORIDA COMPREHENSIVE PAVEMENT ANALYSIS SYSTEM (COMPAS) -
VOL. 1: DEVELOPMENT OF ANALYTICAL MODELS

FLORIDA DOT STATE PROJECT 99000-1712

by

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ABSTRACT

The Florida Comprehensive Pavement Analysis System (COMPAS) was developed to assist the Florida Department of Transportation (FDOT) in evaluating the effects of different forecasted truck characteristics and truck use on flexible pavement performance and life cycle costs. This is accomplished through a comprehensive approach involving the combined application of the following analytical models:

1. a load shift algorithm;
2. a vehicle simulation model;
3. a program for evaluating load equivalencies;
4. a program for evaluating cumulative 18-kip ESAL's;
5. a performance evaluation and overlay design procedure; and
6. a cost evaluation program.

An overview of Florida COMPAS is initially provided to explain the general structure of the microcomputer-based pavement analysis package, and the basic functions of the different analytical models given previously. This is followed by separate chapters detailing the development of the various analysis programs.

Florida COMPAS is expected to be used as a tool for FDOT in developing rational policies governing truck use of the State's highway network, and to permit the Department to be responsive to changes in truck and tire technology for the years to come.
DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Florida Department of Transportation. This report does not constitute a standard, specification, or regulation.
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CHAPTER 1. INTRODUCTION

Premature failures of flexible pavements can occur for a variety of reasons among which are: 1) increased vehicle loads; 2) changes in tire construction and recommended tire inflation pressures; 3) dynamic load amplification due to road roughness and differences in vehicle suspension characteristics; and 4) inadequate structural design. In view of the many possible causes of premature failures, a comprehensive understanding of why they occur can only be obtained with a system capable of handling the many different factors that affect pavement performance.

The objective of State Project 99000-1712 is to provide the Florida Department of Transportation (FDOT) with a system for assessing the impact of different forecasted truck characteristics and use on flexible pavement performance. Truck suspension, tire inflation pressure, axle load, and axle configuration are vehicle-related factors that influence the rate of pavement deterioration with time. The system developed in this study, aptly called Florida COMPAS for reasons that will later become apparent, is intended to be a project level analysis tool for estimating not only the effects of heavy-vehicle characteristics on pavement performance, but also the economic and energy impact that changes in truck characteristics and use can bring about. Florida COMPAS is particularly useful for developing rational policies to regulate freight carriers on the State’s highway network, for assessment of pavement damage responsibility and road user fees, and as a tool to the Department for formulating recommendations to the State Legislature concerning truck weight regulations. The system is even more relevant in view of the changes that have occurred in truck and tire technology over
the years, the effects of which may no longer be evaluated using current empirical pavement performance relationships. These changes include: 1) the observed increase in recommended tire inflation pressures compared to those used during the time of the AASHO Road Test; 2) the predominant use of conventional radial tires in lieu of bias-ply tires; 3) the emerging acceptance of wide base radial tires, also known as "super-singles", in the United States; 4) the growing use of air bag and other recent suspension designs; and 5) the potential introduction of new vehicle configurations such as tractor-tanker combinations with triple axles on the trailing tanker. Only through a comprehensive approach that combines procedures for: 1) simulating the effects of vehicle characteristics on vehicle loadings; 2) evaluating pavement performance as a function of pavement material properties, layer thicknesses, axle loads, axle configuration, tire type, tire inflation pressure, and tire configuration; and 3) estimating user and pavement costs associated with different forecasted vehicle characteristics and truck use can the Department be truly responsive to the changes that have taken place in truck and tire technology and to those that will still occur in the future. The system developed for Florida on this research project was developed based on this approach. It is an integrated package that combines all of the aforementioned analysis procedures and is aptly named Florida COMPAS for Florida COMprehensive Pavement Analysis System.

A simplified framework of this comprehensive pavement analysis tool is shown in Figure 1. The purpose of the present Chapter is to provide an overview of Florida COMPAS by explaining the general structure of the package and the basic functions of each element of the framework. This
Figure 1. Simplified Framework of Florida COMPAS
overview will then be followed by Chapters detailing the development of the different framework elements. Only a brief background on Florida COMPAS is provided here. A more detailed framework of the analysis package is presented in the accompanying User’s Guide to Florida COMPAS.

OVERVIEW OF FLORIDA COMPAS

The evaluation of the effects of heavy vehicle characteristics on pavement performance and life-cycle costs proceeds in a stepwise manner through the following basic elements of the framework:

1. a load-shift algorithm;
2. a vehicle simulation model;
3. a program for evaluating load equivalencies;
4. a program for evaluating cumulative 18-kip ESALs;
5. a performance evaluation and overlay design procedure; and
6. a cost evaluation program.

In the initial step, the load-shift algorithm is applied to predict the shift in gross vehicle and axle weight distributions resulting from a user-specified increase in legal load limits. Current and alternate scenarios are initially defined by the user that establishes, among other things: 1) the different vehicle categories in the traffic stream; 2) the current and proposed legal load limits; 3) estimates of the current and expected usage of the different tire types; 4) current and expected tire inflation pressures for the different tire types; and 5) the existing gross vehicle weight (GVW) distribution for each vehicle type. Default values for many of these variables are provided within Florida COMPAS to facilitate user input.
To perform the load shift, a simple function is used that relates existing upper GVW intervals for different truck types to a ratio of future to present practical maximum gross vehicle weights. The upper GVW limit in each specified GVW distribution is multiplied by the load shift factor derived from this function and the number of vehicles in each GVW category is re-distributed accordingly. In addition, the gross vehicle weight is distributed among the different axles of the vehicle to arrive at estimates of the axle loads for each GVW category. These axle loads are subsequently used with the vehicle simulation program for predicting vehicle dynamic loads. This program is executed for every vehicle in the current and alternate scenarios.

Input menu screens are used to facilitate user entry of vehicle simulation parameters. For each vehicle type, the user has the option of specifying which GVW categories to run with the simulation model and of specifying the types of suspensions that are used with a given vehicle type. In addition, for a divided highway, the user has the option of specifying whether two separate analyses will be made for each traffic direction. In this case, the user can specify individual analysis sections for the two traffic directions that may differ in terms of pavement surface profile, layer thicknesses, material properties, and initial distress conditions. Separate performance evaluations, overlay designs, and cost evaluations are then made on the prescribed analysis sections.

The number of simulation runs to be executed for any given vehicle category and scenario will depend on the number of GVW categories selected for the simulation, the number of prescribed suspension types
and tire types, and whether the project to be analyzed is on a divided or an undivided highway. Default values for the different simulation parameters, such as suspension properties by suspension type, tire spring rates by tire type and tire inflation pressure, wheelbases, vehicle inertial properties, and pavement surface profiles by values of the Present Serviceability Index (PSI), are provided within Florida COMPAS to assist the user in generating the required number of vehicle simulation files. The effects of heavy vehicle characteristics and initial pavement surface profile on flexible pavement performance and life-cycle costs are thus estimated through the effects of these factors on the predicted vehicle dynamic load profile. For each vehicle that is simulated, the predicted dynamic load profiles are used to evaluate load equivalency factors for the different axles of the vehicle. This particular function is performed by the load equivalency program that is part of the framework shown in Figure 1.

The load equivalency program uses damage equations based on PSI, fatigue cracking, and rutting for calculating load equivalencies as a function of: 1) axle load; 2) axle configuration (i.e., single, tandem, and triple axle assemblies); 3) tire configuration (i.e., single or dual tires); 4) tire type (i.e., conventional radial, bias-ply, and wide base radial tires); 5) tire inflation pressure; 6) asphalt layer thickness; and 7) subgrade stiffness. These damage equations were developed using predicted performance data generated from computer runs of the finite element pavement analysis program FLEXPASS (1) developed at Texas A&M for FDOT in a previous research study.
In generating the performance data base, a finite element tire model developed by Tielking at Texas A&M University (2) was used to predict tire contact pressure distributions for the various tire inflation pressures, tire loads, and tire types considered. This finite element model utilizes axisymmetric shell elements to represent the tire carcass. A comprehensive description of tire construction details is input to the model, thereby permitting study of the influence of tire characteristics on the pressure distribution at the tire-pavement interface. The predicted contact pressure distributions for different tire loads, tire inflation pressures, and tire types were then used to establish the nodal forces that were input to the FLEXPASS computer program. In this way, the effects of tire inflation pressure and tire type were included in the development of the damage equations. In addition, a prediction equation for tire spring rate as a function of these two variables was developed in the process, and is used in Florida COMPAS to calculate default values for this vehicle simulation parameter.

The calculated load equivalency factors are adjusted for dynamic load effects through one of two possible approaches built into the load equivalency program. In one approach, the distribution of predicted dynamic axle loads are sampled using uniform random numbers, and the load equivalency factor for each sampled load is calculated from the damage equations. A distribution of sampled load equivalency factors is thus obtained and the expected value of this distribution is calculated and used as an adjusted load equivalency factor. In the other approach discussed in Reference (3), a dynamic load coefficient is used to adjust the load equivalency factor calculated from the damage equations. This
load coefficient is a function of the standard deviation of the coefficient of impact, defined as the ratio of dynamic load to static load, and determined from the predicted dynamic load profile.

Upon completion of all required vehicle simulation runs and load equivalency calculations, a program to calculate cumulative 18-kip ESALs/day for both current and alternate scenarios is executed. The predicted traffic rates are for the initial year of the analysis period for each scenario. The possible increase in traffic rate from the initial value is accounted for through a user-specified traffic growth rate.

The 18-kip ESAL program shown in Figure 1 uses the adjusted load equivalency factors calculated by the previous program, in conjunction with the predicted number of applications of a given vehicle, to calculate the cumulative 18-kip ESALs/day. In addition, for vehicles associated with GVW categories that were not selected by the user for the vehicle simulation, the 18-kip ESAL program uses ratios of adjusted to static load equivalency factors (LEF's) calculated by the load equivalency program to estimate adjusted LEF's for these vehicles. Herein, adjusted LEF's are used to refer to load equivalencies that have been adjusted for dynamic load effects, using one of the approaches described previously. Static LEF's, on the other hand, are those which are based solely on static axle loads.

For all vehicles for which the simulation model was executed, the load equivalency program calculates ratios of adjusted to static LEF's corresponding to the different scenarios, traffic directions, vehicle categories, tire types, and suspension types considered. For a given
axle assembly of a particular vehicle category, the 18-kip ESAL program uses an average of the load equivalency ratios determined for the various GVW categories included in the vehicle simulation to estimate an adjusted load equivalency factor for the given axle assembly. A bookkeeping feature is built into the program so that it uses LEF ratios appropriate for the particular scenario, traffic direction, vehicle category, tire category, suspension category, and axle assembly being considered. For vehicle categories in which no simulation runs were made, such as in cases where the user decided to skip certain vehicle categories from the simulation, the 18-kip ESAL program then calculates the appropriate static LEFs to evaluate the contributions of vehicles in these categories to the cumulative daily 18-kip ESAL’s for the initial year of the analysis period. The traffic rates calculated are subsequently used in evaluating pavement performance for the current and alternate scenarios, and as necessary, for each traffic direction of the project being analyzed.

For the performance evaluation, the user has the option of using the damage equations for PSI, rutting, and fatigue cracking developed in this study, or the finite element program FLEXPASS developed by Texas A&M for FDOT in an earlier study. In the former case, the damage equations are used throughout the analysis period to predict serviceability loss, rutting, and fatigue cracking with cumulative load applications. This is a simplified option for evaluating pavement performance and is applicable for problems involving policy formulations.

In the other option, the FLEXPASS program is used to predict pavement performance up to the time of the initial overlay. From that
point onwards, the damage equations are used to predict the performance of overlays. This latter option permits the user to more carefully address questions related to material requirements for pavements to be able to sustain forecasted changes in heavy vehicle characteristics and truck use.

The thickness design of overlays is accomplished using the Overlay Design Equations developed in a previous FHWA study (4). These equations were developed assuming that overlay life is governed by reflection cracking. The overlay design procedure was modified in this study to predict crack growth with time or cumulative 18-kip load applications.

In the implementation of the overlay design procedure, the user has the option of specifying a minimum and a maximum overlay thickness. The program then designs as many overlays as necessary to last the analysis period for the given range of permissible overlay thicknesses. The timing of the initial overlay is governed by the earliest occurrence of one or more failure levels specified for PSI, rutting, and fatigue cracking. For subsequent overlays, the time it takes for a crack to propagate through the previous overlay is also considered, in addition to the preceding distress modes, in establishing the schedule of subsequent overlays.

After execution of the performance evaluation and overlay design programs, the predicted PSI histories for the different scenarios and traffic directions are used in the cost evaluation program to estimate user costs, and pavement costs throughout the analysis period. In this program, user costs attributed to vehicle depreciation, oil consumption, tire wear, vehicle maintenance, and user travel time are adjusted for the
effects of PSI using relationships developed from data compiled by Zaniewski (5). Future costs are converted to equivalent present worth costs using the discount rate specified by the user. For each scenario, traffic direction, and vehicle category considered, the cost evaluation program provides estimates of user costs for each year of the analysis period. These include the user cost components mentioned previously plus fuel consumption cost. In addition, for each scenario and traffic direction, the program estimates the costs associated with routine maintenance, level-ups, millings, and overlays. Maintenance costs are calculated based on the user-specified unit cost for routine maintenance during the initial year of the analysis period and the prescribed annual increment in maintenance cost. The level-up cost is calculated using the estimated volume of level-up required at the time of an overlay. This is calculated in the overlay design program using the predicted value for rut depth at the time of the overlay and assuming that the transverse pavement profile is shaped like a parabola and that the rut depth is based on a 4-foot straight edge. In addition, if the user has specified a depth of milling, the cost of milling is calculated from its prescribed unit cost. In this instance, the level-up cost will be zero unless the prescribed milling will not totally eliminate the predicted rut depth at the time of the overlay. Finally, the overlay cost is calculated from the required thickness of the overlay and its unit in-place cost.

A summary is provided at the end that shows the cost impact of forecasted changes in heavy vehicle characteristics and truck use. For each scenario, the total pavement cost and total user cost are summarized, thus showing clearly the trade-offs that forecasted changes
in truck characteristics and truck use may bring about. For example, the results may indicate that increased agency expenditures for maintenance and rehabilitation may be more than offset by the potential benefits to the user of reduced vehicle operating costs. This type of information would be extremely useful to the Department in formulating rational and defensible guidelines covering truck use of the State's highways.

SUMMARY

This Chapter has presented an overview of Florida COMPAS by explaining the basic functions of the different programs comprising the system and how these programs are linked together into a logical framework. As should be by now evident, the system is robust in terms of its capabilities for analyzing the effects of a wide-range of vehicle-related, and materials-related variables on pavement performance and life-cycle costs. The remaining Chapters of this report will discuss the development of the different programs comprising this Comprehensive Pavement Analysis System, developed to permit the Florida DOT to be responsive to changes in truck and tire technology for the years to come.
CHAPTER 2. THE LOAD SHIFT ALGORITHM IN FLORIDA COMPAS

One of the important steps in estimating the effects on pavements and vehicle user costs of changes in the vehicle fleet and characteristics, is the estimation of the weight carried by each vehicle. The process of making these estimates is accomplished in two main steps. First, the weight, by axle, is calculated for the existing vehicle fleet, by vehicle type, and weight category. Second, the effects of a change in the vehicle fleet is estimated, as when a change in the legal load limits is implemented, for example. To estimate the effects of higher limits, the existing truck's Gross Vehicle Weight (GVW) is distributed to higher weight categories. The total payload carried is assumed to remain constant, resulting in fewer vehicles carrying heavier loads. This in turn affects pavement condition and deterioration, and vehicle user costs.

In this study, the estimation of the loads carried by each axle of the vehicles using a particular highway, and the change in those loads resulting from a change in the legal load limits, are based upon a joint Texas Transportation Institute and Center for Transportation Research Study, documented in Research Report 298/312-1, Volume 5F (5). This research was sponsored by the Texas State Department of Highways and Public Transportation, and resulted in the development of a computerized procedure to estimate pavement rehabilitation costs called RENU. The RENU procedure was modified in this study to include in the analysis a vehicle category that is not in the current scenario, but is expected to be used in the alternate scenario which may be characterized, for example, by higher legal load limits.
CALCULATION OF LOAD SHIFTS

Previous research has found that when the legal load limits are increased, not all vehicle weights are increased. Some vehicles are empty or carrying loads which do not approach the previous load limits. As weights approach the legal limits, the effect becomes much greater. In this study, following the RENU procedure, the total truck payload is assumed to remain constant when load limits are changed. A portion of the payload is shifted into higher GVW categories. This shift is calculated using equations developed from empirical data. The shift is simulated by increasing the upper weight limit for every GVW category by vehicle type. The equations of the procedure are given below. The shift is shown graphically in Figure 2.

The upper limit of each GVW category in the alternate scenario is given by:

If $UIN_c < SGVW$ then

$$UIN_A = UIN_c$$

If $SGVW < UIN_c < CWHT_A$ then

$$UIN_A = UIN_c \cdot \left[ 1 + \frac{CWHT_c}{CWHT_A - SGVW} \cdot (UIN_c - SGVW) \right]$$

If $UIN_c > CWHT_A$ then
Figure 2. Load Shifting Procedure.
\[ UIN_A = UIN_C \times \left( \frac{CWHT_A}{CWHT_c} \right) \]

Where:

- \( UIN_C \) = Upper Weight Limit of GVW Category, Current Scenario
- \( UIN_A \) = Upper Weight Limit of GVW Category, Alternate Scenario
- \( SGVW \) = GVW at which Load Shifting Occurs
- \( CWHT_c \) = Effective Maximum GVW, given Load Limits by Axle and GVW, Current Scenario
- \( CWHT_A \) = Effective Maximum GVW, given Load Limits by Axle and GVW, Alternate Scenario

The higher payload and lower number of vehicles in each GVW category is calculated by:

\[ WMID_A = \left( \frac{UIN_{A,I} + UIN_{A,J}}{2} \right) \]

\[ PA_A = WMID_A - EGVW \]

\[ VEH_A = VEH_C \times \left( \frac{PA_C}{PA_A} \right) \]

Where:
The proportion of vehicles shifted to a new vehicle type can either be input directly or the program will calculate the shift. The adjustment within the program to calculate the number of vehicles for vehicle categories not in the current scenario is given below:

\[
PCOF = \frac{PA_{A,N} - PA_{A,E}}{PA_{A,E}}
\]

\[
VEH_{A,N} = \left( \frac{PA_{C,E} \times VEH_{C,E}}{PA_{A,N}} \right) \times (PCOF)
\]

\[
VEH'_{A,E} = (VEH_{A,E}) \times (1 - PCOF)
\]

Where:
PCOF = Proportion of payload to be shifted to New Vehicle Type

VEH\_AN = Number of Vehicles in GVW Category for New Vehicle Type, Alternate Scenario

VEH\_CE = Number of Vehicles in GVW Category of Existing Vehicle Type that Vehicles for New Type will be taken from, Current Scenario

VEH\_AE = Number of Vehicles in GVW Category of Existing Vehicle Type that Vehicles for New Type will be taken from, Alternate Scenario before adjustment

VEH\_AE\_A = Number of Vehicles in GVW Category of Existing Vehicle Type that Vehicles for New Type will be taken from, Alternate Scenario after adjustment

PA\_AN = Payload of GVW Category for New Vehicle Type, Alternate Scenario

PA\_CE = Payload of GVW Category of Existing Vehicle Type that Vehicles for New Type will be taken from, Current Scenario

PA\_AE = Payload of GVW Category of Existing Vehicle Type that Vehicles for New Type will be taken from, Alternate Scenario

**CALCULATION OF AXLE LOADS**

After the GVW for each vehicle, weight category, and scenario are calculated, then the weight carried by each axle must be calculated. This is accomplished by first calculating the weight carried on the front
axle (FA) or steering axle. The following equations from RENU are used for making these calculations.

<table>
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<th>TRUCK TYPE</th>
<th>EQUATION</th>
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<td>2D (2 single axles)</td>
<td>FA = 2.0 + 0.27 GVW</td>
</tr>
<tr>
<td>3A (1 single &amp; 1 tandem axle)</td>
<td>FA = 2.9 + 0.20 GVW</td>
</tr>
<tr>
<td>3-S2 (2 or more tandem axles)</td>
<td>FA = 6.0 + 0.05 GVW</td>
</tr>
<tr>
<td>2-S1-2 (3 or more single axles)</td>
<td>FA = 7.5 + 0.03 GVW</td>
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The remaining load, after subtracting the front axle load, is distributed evenly to the rear axles.
CHAPTER 3. VEHICLE SIMULATION PROGRAM

One of the major factors contributing to the deterioration of highways is the excessive wear on the road surface due to heavy-duty truck traffic. One of the goals of the highway engineer is to minimize the forces applied to the road by trucks travelling over them. This can be done by combining optimal design of the truck suspension and payload, with careful construction and maintenance of the roadway surface, and implementation of rational policies governing truck use of highways. Reducing the tire forces applied by trucks to roadway surfaces will reduce damage to the road and increase pavement life expectancy.

An important and useful tool for establishing rational truck weight regulations is a method of quantifying tire forces for a given vehicle as it travels down a stretch of road. Currently, experimental methods provide the most reliable way of predicting tire forces. Also in application are analytical simulation programs which are able to simulate the dynamic behavior of vehicles, and in this way predict the tire forces. These programs are particularly applicable to the problem of developing rational policies governing truck use of highways, and a simple, accurate, and validated simulation program can be a valuable asset to the highway engineer. This chapter describes the Tire Force Prediction (TFP) program written to predict tire forces on heavy-duty articulated vehicles as they travel down a road.

CAPABILITIES OF THE TFP PROGRAM

The TFP program is designed to enable the highway engineer to predict tire forces that occur as a vehicle travels down a road. There
are four basic vehicle configurations that the TFP program can simulate:

1. A straight truck
2. A tractor/semitrailer combination
3. A tractor/semitrailer combination with one full trailer
4. A tractor/semitrailer combination with two full trailers

The straight truck or the tractor in the tractor semitrailer combination can have from one to three rear drive axles, i.e., single, tandem, and triple axle assemblies. The semitrailer can also have one to three axles, while a full trailer can have one or two front axles and one or two rear axles. Each unit in the vehicle train can carry a payload.

The road is defined by a data file of points representing the elevation of the road at constant intervals for the two wheel paths. The elevation data should be in units of thousandths of an inch. This is described later in detail.

The tire forces predicted by the TFP program are for a straight road traversed by a vehicle at constant velocity, a typical scenario of highway travel. No turning or braking maneuvers can be simulated, nor are the effects of roll considered in the simulation. While these capabilities may be desirable to include in a vehicle simulation program, the expected applications of Florida COMPAS, especially those related to the formulation of policy governing truck use of the State's highways, will normally involve vehicles moving at a constant speed along a straight section of roadway. Consequently, the additional capabilities for analyzing turning or braking maneuvers, and vehicle roll, were not modeled for simplicity in program development and use.
VEHICLE MODEL

The model of the tractor/semitrailer/full trailer used in developing the program is shown in Figure 3.

Figure 3. TFP Tractor/Semitrailer/Full Trailer Model.

The model used consists of two planar rigid-body inertial masses representing the tractor sprung mass and the semitrailer sprung mass. The fifth wheel connection between the tractor and the semitrailer is modelled as a very stiff spring. Each full trailer is modelled as a planar rigid-body inertial mass uncoupled from the vehicle train. Each vehicle mass is constrained to move in the vertical (heave) direction and to rotate (pitch) in the x-y plane. A small angle assumption has been made for rotation of the rigid bodies in the x-y plane. If a payload is included on a vehicle, the inertial properties (mass, pitch moment of inertia) of the vehicle are combined with the inertial properties of the payload to obtain the total mass and total pitch moment of inertia.
Each axle is modelled as a planar rigid-body inertial mass representing the weight of the tires, the axle, and the axle support hardware for each axle. These unsprung masses are constrained to move in the vertical direction only. Connecting the unsprung masses to the ground input is a spring representing the spring rate of each tire. The tire is modelled as a linear spring. The input to the program requires the spring rate for one tire on the axle; however, the program multiplies the spring rate by the number of tires on the axle to represent the total tire spring rate for the whole axle. It is important to note that the tire spring rate becomes zero during the simulation if the tire leaves the ground.

The vehicle suspension is represented by a parallel combination of a spring, a viscous damper and a coulomb damper at each axle. Again, the input to the program requires the values of the suspension parameters for one side of the suspension only; however, the values are doubled in the program to represent the total for the whole axle assembly. The springs are modelled as linear springs. The viscous dampers represent shock absorbers, and exert a force proportional to the relative velocity between the tire mass and the vehicle mass. In practice, shock absorbers usually only appear on the front suspensions of tractors in order to increase the ride comfort of the driver. The coulomb dampers exert a constant force against the direction of relative motion between the tire mass and the vehicle mass. This is due mostly to dry friction between the leaves in the leaf springs. There is a slight dead zone in the coulomb damping around zero relative velocity, so that the damper is not contributing a force for very small relative velocities.
The model described above is simulated numerically within the TFP program. A flowchart outlining the execution of the program is given in Figure 4. The input to the model is a velocity input determined as the slope of the road between two elevation points multiplied by the forward velocity of the vehicle. The input to the drive axles of the tractor and all trailer axles is simply the input to the steering axle of the tractor delayed in time. The time delay is equivalent to the distance between the tractor steering axle and the trailing axle in question divided by the speed of the vehicle.

The differential equations of motion describing the system of masses, springs, viscous dampers and coulomb dampers are integrated numerically using a fourth-order Runger-Kutta integration routine with an integration step size of approximately .0025 seconds. This step size was determined by iteratively reducing the integration step size until further reduction showed no variation in the forces predicted.

If the vehicle to be simulated does not contain as many axles as the program model, the program parameterizes the extra axles such that they appear invisible to the truck model; hence, no contributions are made by these axles.

PROGRAM INPUT

Two input files are required to run the TFP program. The first file, referred to as the model file, contains the parameters of the vehicle to be simulated. The other file, known as the road file, contains the elevation profile of the road. By default, the TFP program refers to these files as TRKMOD.DAT and TERRAIN.DAT respectively.
Figure 4. Flowchart of TFP Program.
In order to facilitate the generation of the required model files, a data entry program has been written that prompts the user for the various simulation parameters. Default values for many of these parameters have also been established to facilitate user input.

The road file should contain two columns of profile data. The data represent roadway surface elevations measured at constant intervals. Each column of data is the elevation profile, in thousandths of an inch (mils), of the road surface under one wheel path. Since TFP does not consider roll characteristics of the vehicle, the program uses the average of the two elevations at each distance. The program uses a list-directed format, so the data need only be in two columns separated by at least one space or a comma.

The program automatically generates a 50-foot runway leading up to the first elevation point. The runway is flat for the first 25 feet and becomes a linear ramp for the next 25 feet up to the first data point. Since the initial conditions of the vehicle at the start of the road profile are unknown for any simulation, the lead-in runway provides a method of starting the vehicle model with zero initial conditions and gradually making the transition to the start of the given road profile without exciting excessive dynamics in the vehicle. In order to compare a simulation using the TFP to a real-life scenario, sufficient lead-in road profile data should be included to minimize the effect of unknown initial conditions prior to the beginning of the road profile for the pavement section of interest. The lead-in road profile data should exceed the distance the vehicle will travel in the three to five seconds necessary for the initial response of the vehicle to die out.
PROGRAM OUTPUT

The output of the TFP program is a list of the tire forces that are generated between each tire and the road surface as a function of distance. This distance output begins at -50 feet. This is due to the 50-foot runway preceding the first elevation data point. Since the model does not consider the roll of the vehicle, the forces generated on the right side of a vehicle are equivalent to the forces generated on the left side. Therefore, the data is output for only one side. Also, the force output is the force under one tire if the axle has single tires at each end, or the total force under both tires, if the axle has dual tires at each end. This results in only one tire force output per axle.

The first column of each output file is the distance in feet. The rest of the columns in each output file are the tire forces that occur on each axle at particular points along the road. The tire forces are output in order, from the front to the rearmost axle of a vehicle unit, in the following files:

1. TRACTOR.DAT contains the predicted tire forces for a straight truck or a tractor;
2. TRAILER1.DAT has the predicted tire forces for a semi-trailer;
3. TRAILER2.DAT has the predicted tire forces for the first full trailer; and
4. TRAILER3.DAT contains the predicted tire forces for the second full trailer.

The output data for each axle is recorded with respect to its absolute distance along the road. For example, at 75 feet, the force that occurs due to the first axle passing that point is listed, followed
by the force that occurs at some later time due to the second axle
passing that point. Since all the axles are not at the same distance at
the same time, one line of output data does not represent one instant in
time.

The output from the simulation program are used in Florida COMPAS to
adjust load equivalency factors for considering dynamic load effects in
the calculation of the daily 18-kip equivalent single axle loads (ESAL’s)
during the first year of the analysis period. This is explained in a
subsequent chapter of this report.

MODEL VERIFICATION

In order to verify the results of this program with respect to its
ability to reasonably model the dynamic response of a vehicle, and
predict tire forces, the output from the program were compared to the
output from a more sophisticated model for an identically parameterized
vehicle. The program used for comparison is the directional response
program, Phase 4, from the University of Michigan Highway Safety Research
Institute (7). This program is fairly general in nature and can be used
to study vehicle trains with as many as three trailers. Phase 4
incorporates nonlinear spring/damping characteristics, tire braking and
cornering properties, and anti-lock braking mechanisms. It can model
load transferring suspensions, such as walking beam suspensions, as well
as independently acting tandem axles. Further, Phase 4 can simulate
vehicle roll, and incorporates a truck frame torsional degree of freedom
not found in most vehicle simulation models. About the only limitations
of the program are the inability to model a triple axle assembly, the
greater complexity, relative to the TFP program, of required simulation
parameters, and the significantly longer execution time as compared to TFP.

Two different vehicles were used in the comparisons. The first vehicle is a straight truck with one rear axle, and the second vehicle is a tractor-semitrailer (3S2). These vehicles are illustrated in Figure 5 which also show the static axle loads. The speeds at which the vehicles were simulated were 30 and 60 miles/hour. Simulation parameters for each vehicle are given in Figure 6, which show the TFP input data files.

The road profiles used in the simulation are shown in Figures 7 to 9. Site 4 is a smooth flexible pavement section with a Present Serviceability Index, PSI, of 4.01. Site 8 is a medium-smooth section with a PSI of 3.06, and Site 6 is a rough section with a PSI of 1.30. The predicted tire forces for the following axles were used in the comparisons:

1. The drive axle of the single-unit truck;
2. The lead drive axle of the tractor of the 3S2 combination; and
3. The lead axle of the semi-trailer tandem assembly.

Results of the simulations for Site 8, the medium-smooth section, are shown in Figures 10 to 12.

It is observed that for the straight-truck simulations (Figure 10), the predicted tire forces from the two programs are quite similar. For the tractor-semitrailer, the predicted tire forces at the simulation speed of 30 miles/hour (Figure 11) are also quite comparable. However, at a speed of 60 miles/hour, it is observed from Figure 12 that the Phase 4 predictions are generally somewhat higher than the TFP predictions. The trends in the predicted wheel load profiles are, however, similar.
Figure 5. Vehicles Simulated in TFP Versus Phase 4 Comparisons
### Straight Truck 30 MPH

<table>
<thead>
<tr>
<th>Configuration [1,2,3 or 4]</th>
<th>Velocity [0-200 FT/SEC]</th>
<th>Simulation Distance [Feet]</th>
<th>Tractor Wheelbase [Inches]</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.00</td>
<td></td>
<td>500.00</td>
<td>207.00</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>300000.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

# of Rear Tractor Axles [1,2, or 3] | # of Rear Tractor Tires [1-SINGLE 2-DUAL] |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Tractor-Semitrailer 30 MPH

<table>
<thead>
<tr>
<th>Configuration [1,2,3 or 4]</th>
<th>Velocity [0-200 FT/SEC]</th>
<th>Simulation Distance [Feet]</th>
<th>Tractor Wheelbase [Inches]</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td>44.00</td>
<td>500.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tractor Axle #1 Static Load [LBS]</th>
<th>Tractor Axle #1 Susp Spring Rate [LB/IN/SIDE]</th>
<th>Tractor Axle #1 Visc Damp Rate [LB/(IN/S)/SIDE]</th>
</tr>
</thead>
</table>
Figure 7. Measured Wheelpath Profiles for Site 4, the Smooth Pavement Section.
Figure 8. Measured Wheelpath Profiles for Site 8, the Medium-Smooth Section.
Figure 9. Measured Wheelpath Profiles for Site 6, the Rough Pavement Section.
Figure 10. Comparison of Predicted Tire Forces from TFP and Phase 4 (Straight Truck).
Figure 11. Comparison of Predicted Tire Forces from TFP and Phase 4 (Tractor-Semitrailer at 30 mph).
Figure 12. Comparison of Predicted Tire Forces from TFP and Phase 4 (Tractor-Semitrailer at 60 mph).
Comparisons of predicted tire forces for the other two pavement sections are given in Appendix A. In most cases, the observations associated with the tire force predictions for Site 8 also apply for the simulations made on Sites 4 and 6. It is noted that the Phase 4 program is more complicated, and simulates more truck dynamics than the TFP program which may account for the observed discrepancies in the tire forces predicted.

As a second method of verification, the results of simulations using the TFP program were compared to experimental data. Vehicle dynamic load measurements were obtained from flexible pavement sections instrumented with piezoelectric film strips. Figure 13 is a picture showing the typical layout of the sensors used.

Piezoelectric materials have the characteristics of generating an electrical charge when subjected to load. Since the electrical charge is proportional to the applied load, piezoelectric materials have recently found application as weigh-in-motion devices. For the dynamic load measurements that were made, pavement sections of differing roughness levels were selected, and each section was instrumented with 14 piezoelectric film strips prior to the measurements. The first 10 film strips, in the direction of vehicle travel, were spaced 2 feet apart while the last 4 were spaced at 10 feet. The piezoelectric film strips were located a sufficient distance from the start of the test section so as to have sufficient lead-in profile for the simulation. In most cases, the first film strip was located 300 feet from the start of the test section. All sections were 0.2 miles in length.
Figure 13. Layout of Piezoelectric Film Strips for Measurement of Vehicle Dynamic Loads.
As shown in Figure 14, two test vehicles were used in the dynamic load measurements. One vehicle was a single unit truck with measured static axle loads of 6,940 lbs., and 11,020 lbs. on the steering and drive axles respectively. The other vehicle was a 3S2 combination with measured static axle loads of 9,400 lbs. on the steering axle; 24,100 lbs. on the tractor drive axle; and 23,700 lbs. on the semitrailer axle. The test vehicles were driven at speeds of 10, 40, and 60 miles/hour, with three replicate measurements made at each vehicle speed. Only dynamic load measurements at the outer wheelpath were obtained.

Figure 15 shows the input data used in the TFP simulations. It is noted that the values of some simulation parameters, i.e., suspension spring rates, Coulomb damping, viscous damping, tire spring rates, and pitch moments of inertia, had to be estimated since these were not measured. For these parameters, input values were obtained from data compiled by Fancher et al., and reported in Reference (8). It is noted that the primary aim of the exercise was to check if reasonable predictions of tire forces can be obtained when values of mechanical properties, within the range of those reported in the literature, are used in the simulation. This approach to model verification is believed to be consistent with the intended application of the simulation program within Florida COMPAS.

For the comparisons of predicted and measured dynamic tire forces, the data collected from Sites 4, 6, and 8 were used. The road profiles for the simulation are the same as those shown in Figures 7 to 9 with the exception that the thickness of the piezoelectric film strip (1/8-inch) was added to each road profile at the appropriate locations.
Figure 14. Test Vehicles Used in Vehicle Dynamic Load Measurements.
Figure 15. TFP Input Files Used in Comparing Tire Force Predictions with Experimental Data: (a) Input Data for Straight Truck; (b) Input Data for Tractor-Semitrailer.
Sample results from the comparisons are presented in Figures 16 to 18. In these figures, the average of the three tire force measurements made at the given vehicle speed, are plotted as dots, and are overlaid against a plot of the predicted load profile from the simulation program. Figure 16 shows a comparison of predicted versus observed tire forces for Site 4, the smooth section; Figure 17 shows a comparison using data from Site 6, the rough section; and Figure 18 shows a comparison using data from Site 8, the medium-smooth section. Further comparisons are given in Appendix B. In general, it is observed that the TFP predictions bound the range of the experimental data. Discrete peaks are observed in the predicted tire force profile at distances corresponding to the location of the sensor strips. This is due to the fact that the sensor strip thickness has been included in the road profile data, and the strips appear as sudden bumps in the road profile.

MEASUREMENT OF SURFACE PROFILES FOR EVALUATION OF VEHICLE DYNAMIC LOADS

Application of the vehicle simulation program within Florida COMPAS requires measurements of pavement surface profile. Various devices and procedures have been developed for accomplishing these measurements. Examples include the Profilometer and the South Dakota Profiler. Of practical necessity, devices for measuring pavement roughness must be capable of providing repeatable measurements at normal highway speeds. In addition, devices which do not require difficult calibration procedures, possess the capability for field processing of the data collected, and are relatively inexpensive to own, operate and maintain.
Figure 16. Comparison of TFP Predictions with Experimental Data from Site 4 Measured at 40 mph: (a) Lead Drive Axle of Tractor; (b) Lead Axle of Semitrailer.
Figure 17. Comparison of TFP Predictions with Experimental Data from Site 6 Measured at 40 mph: (a) Lead Drive Axle of Tractor; (b) Lead Axle of Semitrailer.
Figure 18. Comparison of TFP Predictions with Experimental Data from Site 8 Measured at 40 mph:
(a) Lead Drive Axle of Tractor; (b) Lead Axle of Semitrailer.
are most desirable. One device which holds promise as an instrument for the routine collection of profile data on a network wide scale is the Siometer, currently used by the Texas State Department of Highways and Public Transportation (SDHPT) for evaluation of pavement riding quality. A unique feature of this device is the statistical modeling procedure for characterizing the vehicle on which it is installed. This feature lends portability to the Siometer. The parameters of the statistical model are determined in a self-calibration procedure that is run before profile data are collected.

The applicability of the Siometer as a device for profile measurements was also evaluated during the course of the study to identify a method which the Florida DOT may want to consider for collecting the profile measurements necessary to conduct applications of Florida COMPAS. In this evaluation, profile measurements with the Siometer were compared with those from a Surface Dynamics Profilometer. The findings obtained are presented in Appendix C of this report.
CHAPTER 4. DEVELOPMENT OF DAMAGE EQUATIONS FOR EVALUATING PAVEMENT PERFORMANCE AND LOAD EQUIVALENCY FACTORS

The AASHO Road Test continues to be the basis for many pavement design procedures and truck weight regulations currently being implemented. In that field experiment, the flexible pavement sections in the different test loops were subjected to axle loadings from vehicles equipped with single or tandem axles and fitted with bias-ply tires inflated to 75 or 80 psi tire inflation pressure. The applicability of the empirical relationships developed from the AASHO Road Test are therefore limited to the loading conditions that were established for the experiment.

However, since completion of the Road Test, changes in truck and tire technology have occurred for which the empirical relationships may no longer be valid. In recent years, for example, highway engineers have observed an increase in truck tire inflation pressures that are significantly higher than those used in the AASHO Road Test. Today, radial tires are predominantly used by commercial trucking fleets, and recommended cold inflation pressures of 100 psi or more are not uncommon. New tire designs, such as the wide base radial (WBR) tires, are also beginning to gain acceptance. These tires, also known as "super singles" since they replace conventional dual tires, are popular in Europe and are reported to offer savings in fuel consumption due to reduced rolling resistance.

Theoretical and experimental investigations (9, 10) have shown that the contact pressure distribution at the tire-pavement interface is non-uniform and is sensitive to the tire construction. These findings imply
that pavement performance may be influenced, not only by tire inflation pressure, but by differences in tire construction or tire type as well.

With the changes that have taken place since the AASHO Road Test, new relationships have to be developed for predicting the likely effects of tire inflation pressure and tire type on pavement performance. Fortunately, over the years, rational models for evaluating pavement performance have been developed that permit the analysis of the effects of a wide range of factors on pavement performance. These factors include pavement material characteristics, environmental factors, and traffic loading conditions.

The approach therefore followed in this study is to take advantage of the developments that have been made in pavement analysis techniques through application of existing models to predict the effects of tire pressure, tire type, axle load, and axle configuration on flexible pavement performance. Damage equations for predicting fatigue cracking, rutting, and serviceability loss with cumulative load applications were developed for Florida and are discussed in this chapter. The study variables included, among other factors, three different tire types (e.g., bias-ply, conventional radial, and wide base radial tires), and three axle configurations (e.g., single, tandem, and triple axle assemblies). Thus, a wide range of variables was considered to develop relationships that are robust and are applicable for a wider range of loading conditions than those found at the AASHO Road Test. The damage equations developed are expected to be of use to highway engineers concerned with truck weight regulations and the assessment of damage responsibility for establishment of road user fees.
ANALYTICAL MODELS USED IN THE STUDY

Although much research has been done in modeling the effects of load on predicted pavement performance, relatively little research has been made to investigate the effects of tire construction on predicted pavement distress. The main reason for this is the previous lack of models for predicting the effects of different tire construction characteristics on the pressures at the tire footprint. Thus, tire contact pressure has almost always been modeled as a uniform circular pressure distribution equal to the tire inflation pressure, a simplification that ignores the bending stiffness of the tire.

In recent years however, research studies conducted by Tielking at Texas A&M University have led to the development of a finite element tire model for predicting tire contact pressure distributions as a function of tire inflation pressure, tire load, and tire type. This model utilizes axisymmetric shell elements to represent the tire carcass. A comprehensive description of tire construction details is input to the model, thereby permitting study of the influence of tire characteristics on the contact pressure distribution. A discussion of the finite element tire model is given in Reference (10). This model was used in the present study to predict tire contact pressure distributions for the various tire inflation pressures, tire loads, and tire types considered. The predicted tire contact pressure distributions were used to establish the nodal forces that were input to a finite element model for predicting pavement performance. This finite element model, known as FLEXPASS, was developed by Tseng and Lytton at Texas A&M University (1).
FLEXPASS, an acronym for FLEXible Pavement Analysis Structural System, is based on modifications made to the ILLI-PAVE program developed at the University of Illinois. Within this program are models for predicting the progression of fatigue cracking, rutting, and serviceability loss with increasing axle load applications. The program offers the capability of modeling the non-uniformity in tire contact pressure distributions, and of modeling single, tandem, and triple axles on single or dual tires. In addition, the program permits the seasonal evaluation of pavement performance.

The algorithm for predicting fatigue cracking in FLEXPASS is based on the phenomenological model:

\[ N_f = K_1 (1/\varepsilon_t)^{K_2} \]  

(1)

where,

- \( N_f \) = number of load applications prior to failure,
- \( \varepsilon_t \) = tensile strain at the bottom of the asphalt surface layer,
- and
- \( K_1, K_2 \) = fatigue constants.

Explicit equations for determining the fatigue constants \( K_1 \) and \( K_2 \) in the above equation were developed by Tseng and Lytton using fracture mechanics theory (11). Derivations made show that the fatigue constant \( K_1 \) is dependent on asphalt mixture and pavement properties such as the parameters of the Paris and Erdogan equation (12), the elastic stiffness, and the asphalt surface layer thickness, and that the constant \( K_2 \) varies with asphalt cement properties such as asphalt content, viscosity, penetration, and temperature. The interested reader is referred to
Reference (11) for a more detailed discussion of the prediction methodology.

The algorithm for predicting permanent deformation is based on a three-parameter model relating permanent strain to repeated load applications. Specifically, the following model is used to evaluate permanent deformation in each pavement layer:

\[ \epsilon_a = \epsilon_o e^{-(p/N)^\beta} \]  \hspace{1cm} (2)

where,

- \( \epsilon_a \) = permanent vertical strain,
- \( N \) = cumulative load applications, and
- \( \epsilon_o, \rho, \beta \) = permanent deformation parameters.

Permanent deformation is evaluated in the program by accumulating the permanent strains produced in each layer by repeated traffic load applications. The algorithm for rutting is based on an evaluation of the vertical resilient strain in each layer and on the fractional increase of permanent strain determined from Eq. (2) above. A more detailed discussion of the permanent deformation algorithm is given in Reference (13).

Finally, serviceability loss is evaluated using the AASHO PSI equation with the predicted values of rut depth, cracked area, and slope variance. In the program, the slope variance is predicted from rut depth variance using the VESYS equation relating these parameters (14).

**STUDY PARAMETERS**

The following variables were included as factors in the experimental design used in this study:
(1) Three asphalt concrete thicknesses
   2 inches
   4 inches
   6 inches

(2) One base course thickness
   10 inches

(3) Three subgrade moduli
   5000 psi
   15000 psi
   25000 psi

(4) Three types of tire construction
   conventional radial
   bias-ply
   wide base radial

(5) Different loading configurations including:
   single, tandem, and triple axles
   single and dual tires
   6 tire load levels
   3 inflation pressures.

For each combination of variables included in the experimental design, the FLEXPASS program was used to predict fatigue cracking, rutting, and serviceability loss with increasing load applications. A total of 630 separate runs were made.

The Florida (Wet-No Freeze) zone was characterized by the seasonal temperatures and layer moduli used in the development of pavement damage functions for the 1982 Federal Highway Cost Allocation Study (15). The
values of these variables are given in Tables 1, 2, and 3.

Table 1. Effective temperatures & asphalt concrete stiffnesses.

<table>
<thead>
<tr>
<th>SEASON</th>
<th>Temperature ('F)</th>
<th>Stiffness (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall</td>
<td>75</td>
<td>580000.0</td>
</tr>
<tr>
<td>Winter</td>
<td>57</td>
<td>1190000.0</td>
</tr>
<tr>
<td>Spring</td>
<td>78</td>
<td>530000.0</td>
</tr>
<tr>
<td>Summer</td>
<td>97</td>
<td>350000.0</td>
</tr>
</tbody>
</table>

Table 2. Coefficient $k_1$ for base stiffness.

<table>
<thead>
<tr>
<th>SEASON</th>
<th>$k_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall</td>
<td>5000.0</td>
</tr>
<tr>
<td>Winter</td>
<td>4750.0</td>
</tr>
<tr>
<td>Spring</td>
<td>5000.0</td>
</tr>
<tr>
<td>Summer</td>
<td>5250.0</td>
</tr>
</tbody>
</table>

Note: Base Stiffness is given by $E_{base} = k_1(\theta)^{k_2}$, where $k_2 = 0.6$, and $\theta = $Bulk Stress.

Table 3. Subgrade moduli & thickness used in the study.

<table>
<thead>
<tr>
<th>SEASON</th>
<th>Subgrade Modulus (psi)</th>
<th>Subgrade Thickness (inches)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Fall</td>
<td>4250.0</td>
<td>13,500.0</td>
</tr>
<tr>
<td>Winter</td>
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<tr>
<td>Spring</td>
<td>4250.0</td>
<td>13,500.0</td>
</tr>
<tr>
<td>Summer</td>
<td>4250.0</td>
<td>13,500.0</td>
</tr>
</tbody>
</table>
The moisture contents used to characterize the base and subgrade layers for the different environmental zones were established using the Integrated Climatic Effects Model developed for the Federal Highway Administration by Lytton, et al. (16). The predictions from this model were checked against the measured values of moisture contents reported in the 1982 FHWA Cost Allocation Study (15).

The effects of base modulus and base thickness on predicted pavement performance have been found to be relatively small compared to the effects of the other design variables (17). Therefore, for this study, the base course thickness was kept at only one level.

DEVELOPMENT OF DAMAGE EQUATIONS

Load equivalency factors are determined from a damage equation which relates the level of damage, \( g \), to the number of repetitions, \( N \), of any given load. This relation is stated functionally as:

\[
g = f(N_i)
\]  

(3)

The above relationship may be used to predict the number of allowable load repetitions prior to a given damage level. A ratio may then be formed between the number of load repetitions of a standard load, \( N_0 \), to cause a given level of damage, \( g \), and the number of repetitions of some other load, \( N_i \), to cause the same level of damage. The ratio thus formed is the load equivalency factor, \( LEF_i \), for axle load \( i \). In equation form, the load equivalency factor is given by:

\[
LEF_i = \frac{N_0}{N_i}
\]  

(4)

For this study, the standard load level was defined as follows:

Axle load \( = 18 \) kips
Tire type = Bias-Ply
No. of tires = 2 (dual)
No. of axles = 1 (single)
Tire pressure = 75 psi

In addition, a sigmoidal (S-shaped) curve was chosen as the form of the damage equation. A typical sigmoidal curve is shown in Figure 19. The S-shaped feature of the curve requires an equation of the form:

\[ g = c \cdot e^{-(\rho/N)^\beta} \]  \hspace{1cm} (5)

where,

- \( \rho \) = the number of load repetitions when \( g/c \) reaches a value of \( 1/e \),
- \( \beta \) = an exponent which dictates the degree of curvature of the sigmoidal curve, and
- \( g \) and \( c \) depend on the type of distress.

Nonlinear regression analysis was used to fit the S-shaped curve to the performance data generated from the FLEXPASS runs, and therefore find the parameters \( \rho \), \( \beta \), and \( c \) of the sigmoidal curve. Multiple regression analyses were then conducted to get equations for these parameters that were functions of the following primary variables:

- \( Ld \) = gross axle load (kips)
- \( Ax \) = number of axles
  - 1 for single axle
  - 2 for tandem axle
  - 3 for triple axle
Figure 19. A Typical Sigmoidal Curve.

Sigmoidal (S-shaped) Curve

\[ g = c \cdot \exp\left(-\frac{\rho}{N}\right)^{\beta} \]

\( \rho = 10000.0 \)

\( \beta = 0.2 \)

\( \beta = 0.5 \)
Tire = number of tires
   = 1 for single tire
   = 2 for dual tires

Es = subgrade modulus (psi)

\( t \) = asphalt concrete thickness (inches)

\( P \) = tire inflation pressure (psi)

Once the parameters \( \rho \), \( \beta \), and \( c \) are determined, Eq. (5) can be used to predict the performance history of a given pavement section subjected to a particular set of loading conditions defined by the variables axle load, axle configuration, tire configuration, tire type, and tire inflation pressure. In addition, for the given loading conditions, the number of load applications, \( N_i \), of axle load \( i \), prior to the pavement section reaching a specified level of damage, \( g \), may be found from Eq. (5) as:

\[
N_i = \frac{\rho_i}{\left[ -\ln \frac{\sigma}{\sigma_i} \right]^{1/\beta}}
\]

(6)

Thus, Eq. (6) may be used, in conjunction with Eq. (4), to determine load equivalency factors for different loading conditions. The prediction equations for the model parameters \( \rho \), \( \beta \), and \( c \), for different types of pavement distress, are presented in the following.
(1) Serviceability loss

For loss of serviceability, \( g \) and \( c \) are defined as:

\[
g = \frac{P_0 - P}{P_0 - P_t}
\]

(7)

\[
c = \frac{P_0 - P_f}{P_0 - P_t}
\]

(8)

where,

\( P_0 \) = initial serviceability index (taken as 4.2 for this study),
\( P \) = present serviceability index at any given time,
\( P_t \) = terminal serviceability index (e.g. 2.5), and
\( P_f \) = final (minimum) serviceability index.

For this study \( P_f \) is taken as 0.0, therefore, \( c = P_0/(P_0 - P_f) \) from Eq. (8). For all three types of tires, \( \rho \) and \( \beta \) are given by the following expressions:

\[
\log(\rho) = a_0 + a_1 \cdot \log(Ld) + a_2 \cdot \log(Ax) + a_3 \cdot \log(Tire) + a_4 \cdot \log(Em) + a_5 \cdot \log(t+3) + a_6 \cdot \frac{\log(P)}{\sqrt{t+3}}
\]

(9)

\[
\log(\beta) = a_0 + a_1 \cdot \frac{\log(Ld)}{t+3} + a_2 \cdot \log(Ax) + a_3 \cdot \log(Tire) + a_4 \cdot \log(Em) + a_5 \cdot \log(t+3) + a_6 \cdot \log(P)
\]

(10)

The values of the coefficients in the above equations, and the coefficients of determination, \( R^2 \), are given in Tables 4 and 5.
Table 4. Coefficients for parameter "rho" based on PSI.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>-0.0333</td>
<td>-3.3600</td>
<td>2.7550</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-3.9500</td>
<td>-3.9300</td>
<td>-3.4800</td>
</tr>
<tr>
<td>$a_2$</td>
<td>3.5270</td>
<td>3.6840</td>
<td>3.1300</td>
</tr>
<tr>
<td>$a_3$</td>
<td>2.9010</td>
<td>3.1020</td>
<td>0.0000</td>
</tr>
<tr>
<td>$a_4$</td>
<td>2.0220</td>
<td>2.2940</td>
<td>1.6740</td>
</tr>
<tr>
<td>$a_5$</td>
<td>6.1200</td>
<td>7.0080</td>
<td>5.7500</td>
</tr>
<tr>
<td>$a_6$</td>
<td>-3.5800</td>
<td>-1.7400</td>
<td>-5.4300</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.932</td>
<td>0.845</td>
<td>0.930</td>
</tr>
</tbody>
</table>

Table 5. Coefficients for parameter "beta" based on PSI.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>-0.79200</td>
<td>-0.82300</td>
<td>-0.68900</td>
</tr>
<tr>
<td>$a_1$</td>
<td>2.90900</td>
<td>2.78200</td>
<td>2.27200</td>
</tr>
<tr>
<td>$a_2$</td>
<td>0.49010</td>
<td>0.32680</td>
<td>0.80620</td>
</tr>
<tr>
<td>$a_3$</td>
<td>0.03136</td>
<td>0.07801</td>
<td>0.00000</td>
</tr>
<tr>
<td>$a_4$</td>
<td>-0.16900</td>
<td>-0.19100</td>
<td>-0.15600</td>
</tr>
<tr>
<td>$a_5$</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>$a_6$</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.803</td>
<td>0.668</td>
<td>0.757</td>
</tr>
</tbody>
</table>

(2) Rutting

For rutting, $g$ and $c$ are defined as:

$$ g = \frac{r}{r_c} $$  \hspace{1cm} (11)

$$ c = \frac{r_f}{r_c} $$  \hspace{1cm} (12)

where,
r = present rut depth (measured in inches),

r_t = terminal rut depth (e.g. 0.5 inches), and

r_f = final (asymptotic) rut depth (measured in inches).

For all three types of tires, \( \rho, \beta, \) and c are given by the following expressions:

\[
\log(p) = a_0 + a_1 \log(Ld) + a_2 \log(Ax) + a_3 \log(Tire)
+ a_4 \log(Es) + a_5 \log(t+3) + a_6 \frac{\log(P)}{\sqrt{t+3}}
\]

(13)

\[
\log(\beta) = a_0 + a_1 \log(Ld) + a_2 \log(Ax) + a_3 \log(Tire)
+ a_4 \log(Es) + a_5 \log(t+3) + a_6 \log(P)
\]

(14)

\[
\log(c) = a_0 + a_1 \log(Ld) + a_2 \log(Ax) + a_3 \log(Tire)
+ a_4 \log(Es) + a_5 \log(t+3) + a_6 \log(P)
\]

(15)

The values of the coefficients in Eqs. (13) through (15), and the coefficients of determination, \( R^2 \), are given in Tables 6, 7, and 8.

Table 6. Coefficients for parameter "rho" based on rutting.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>-2.500</td>
<td>-4.170</td>
<td>7.450</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>-2.150</td>
<td>-1.180</td>
<td>-3.180</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>5.060</td>
<td>3.882</td>
<td>4.970</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>-0.630</td>
<td>-0.961</td>
<td>0.000</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>1.897</td>
<td>2.020</td>
<td>1.552</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>6.055</td>
<td>4.564</td>
<td>2.911</td>
</tr>
<tr>
<td>( a_6 )</td>
<td>-4.240</td>
<td>-3.140</td>
<td>-10.300</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.958</td>
<td>0.918</td>
<td>0.913</td>
</tr>
</tbody>
</table>
Table 7. Coefficients for parameter "beta" based on rutting.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>-0.0640</td>
<td>0.1274</td>
<td>-0.3020</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>-0.0411</td>
<td>-0.1750</td>
<td>0.1649</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>-0.1200</td>
<td>-0.1000</td>
<td>-0.2450</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>0.2759</td>
<td>0.5029</td>
<td>0.0000</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>-0.1540</td>
<td>-0.2370</td>
<td>-0.1140</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>-0.2320</td>
<td>0.1361</td>
<td>-0.4250</td>
</tr>
<tr>
<td>( a_6 )</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.631</td>
<td>0.832</td>
<td>0.716</td>
</tr>
</tbody>
</table>

Table 8. Coefficients for parameter "c" based on rutting.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>-0.2930</td>
<td>-0.374</td>
<td>-0.6260</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>0.8753</td>
<td>1.043</td>
<td>0.7483</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>-0.0850</td>
<td>-0.303</td>
<td>0.0000</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>-0.7100</td>
<td>-0.786</td>
<td>0.0000</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>0.0000</td>
<td>0.000</td>
<td>0.0000</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>-0.5720</td>
<td>-0.835</td>
<td>-0.1380</td>
</tr>
<tr>
<td>( a_6 )</td>
<td>0.0000</td>
<td>0.000</td>
<td>0.0000</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.960</td>
<td>0.950</td>
<td>0.845</td>
</tr>
</tbody>
</table>

(3) Fatigue Cracking

For fatigue cracking, \( g \) and \( c \) are defined as:

\[
g = \frac{\text{Cracked Area}}{1000.0} \tag{16}
\]

\[
c = \frac{\text{Cracked Area}_{(\text{max.})}}{1000.0} \tag{17}
\]
Cracked area is measured in square feet, per one thousand square feet of road surface area. Since the limit of this variable is 1,000 ft²/1,000 ft², c = 1 from Eq. (17).

For all three types of tires, ρ and β are given by the following expressions:

\[
\log(\rho) = a_0 + a_1 (1 - \frac{1}{c}) \log(Ld) + a_2 \log(Ax + 1) + a_3 \log(Tire) + a_4 \log(Es) + a_5 \log(t) + a_6 \frac{\log(P)}{t}
\]  

(18)

\[
\log(\beta) = a_0 + a_1 \log(Ld) + a_2 \log(Ax) + a_3 \log(Tire) + a_4 \log(Es) + a_5 \log(t + 3) + a_6 \log(P)
\]  

(19)

The values of the coefficients in the preceding equations, and the coefficients of determination, \( R^2 \), are given in Tables 9 and 10.

### Table 9. Coefficients for parameter "rho" based on fatigue cracking.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>2.98600</td>
<td>2.82100</td>
<td>3.12000</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>-1.97000</td>
<td>-2.08000</td>
<td>-1.89000</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>1.33500</td>
<td>1.32700</td>
<td>1.30100</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>0.79700</td>
<td>0.88830</td>
<td>0.00000</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>0.19810</td>
<td>0.21720</td>
<td>0.24270</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>0.62950</td>
<td>0.65260</td>
<td>0.54430</td>
</tr>
<tr>
<td>( a_6 )</td>
<td>-0.97400</td>
<td>-0.73300</td>
<td>-1.14000</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.994</td>
<td>0.991</td>
<td>0.995</td>
</tr>
</tbody>
</table>

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Table 10. Coefficients for parameter "beta" based on fatigue cracking.

<table>
<thead>
<tr>
<th></th>
<th>Conv. Rad.</th>
<th>Bias-Ply</th>
<th>Wide Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>-0.3760</td>
<td>-0.3640</td>
<td>-0.6550</td>
</tr>
<tr>
<td>$a_1$</td>
<td>0.3803</td>
<td>0.3648</td>
<td>0.1868</td>
</tr>
<tr>
<td>$a_2$</td>
<td>-0.1790</td>
<td>-0.2150</td>
<td>0.0000</td>
</tr>
<tr>
<td>$a_3$</td>
<td>-0.3390</td>
<td>-0.3200</td>
<td>0.0000</td>
</tr>
<tr>
<td>$a_4$</td>
<td>-0.0751</td>
<td>-0.0708</td>
<td>-0.0650</td>
</tr>
<tr>
<td>$a_5$</td>
<td>0.0160</td>
<td>-0.0386</td>
<td>0.2360</td>
</tr>
<tr>
<td>$a_6$</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.1546</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.706</td>
<td>0.480</td>
<td>0.874</td>
</tr>
</tbody>
</table>

STUDY RESULTS

In this study, the effects of different tire types, tire pressure, tire load, and axle configuration were evaluated using equivalency factors determined from the damage equations that were developed. The effects of these different variables on pavement performance are presented in the following.

(1) Tire Pressure Effect

Higher inflation pressure increases the radial tensile strain at the bottom of the asphalt layer, resulting in the reduction of pavement fatigue life. This pressure effect is more pronounced for pavements with thin asphalt concrete layers than for pavements with thick asphalt layers. Based on fatigue cracking, application of the damage equations developed in this study shows that the load equivalency factors for a wide base radial tire are more sensitive to tire inflation pressure than those determined for bias-ply or conventional radial tires. The
predicted changes in LEF with increasing inflation pressure, for the three types of tires, are illustrated in Figures 20, 21, and 22. The predicted increase in LEF with increase in tire inflation pressure is given in Table 11 for each tire type.

Table 11. Effect of Tire Inflation Pressure on Predicted LEF based on Fatigue Cracking.*

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Load Equivalency Factor</th>
<th>Asphalt Concrete Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75 psi</td>
<td>125 psi</td>
</tr>
<tr>
<td>Bias-ply</td>
<td>1.00</td>
<td>1.21</td>
</tr>
<tr>
<td>Conv. Radial</td>
<td>1.32</td>
<td>1.69</td>
</tr>
<tr>
<td>Wide Base Radial</td>
<td>1.55</td>
<td>2.45</td>
</tr>
<tr>
<td>Bias-ply</td>
<td>1.00</td>
<td>1.06</td>
</tr>
<tr>
<td>Conv. Radial</td>
<td>1.04</td>
<td>1.13</td>
</tr>
<tr>
<td>Wide Base Radial</td>
<td>2.00</td>
<td>2.51</td>
</tr>
</tbody>
</table>

* 18 kips, Single Axle, Es=15000 psi, Cracking=700 ft^2/1000 ft^2

Based on serviceability loss, the load equivalency factors determined in this study show that predicted pavement performance is also affected by tire inflation pressure and the effect is more for thinner pavements. The predicted changes in LEF with inflation pressure, for the three types of tires, are shown in Figures 23, 24, and 25. The predicted increase in LEF with increase in tire inflation pressure is given in Table 12 for each tire type.
LEF Based on Cracking (700 Sft/1000 Sft)
Bias-Ply Tire (Florida)
Axle = 1, Tire = 2, Es = 15000

Figure 20. The Change in LEF with Inflation Pressure, Based on Fatigue Cracking, for Bias-Ply Radial Tire.
LEF Based on Cracking (700 SFt/1000 SFt)
Conv. Radial Tire (Florida)
Axle = 1, Tire = 2, Es = 15000

Figure 21. The Change in LEF with Inflation Pressure, Based on Cracking, for Conventional Radial Tire.
LEF Based on Cracking (700 Sft/1000 Sft)
Wide Base Rad. Tire (Florida)
Axle = 1, Tire = 1, Es = 15000

Figure 22. The Change in LEF with Inflation Pressure, Based on Cracking, for Wide Base Radial Tire.
LEF Based on PSI (2.50) Bias-Ply Tire (Florida) Axle = 1, Tire = 2, Es = 15000

Figure 23. The Change in LEF with Inflation Pressure, Based on PSI, for Bias-Ply Tire.
Figure 24. The Change in LEF with Inflation Pressure, Based on PSI, for Conventional Radial Tire.
Figure 25. The Change in LEF with Inflation Pressure, Based on PSI, for Wide Base Radial Tire.
Table 12. Effect of Tire Inflation Pressure on Predicted LEF based on PSI.*

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Load Equivalency Factor</th>
<th>Asphalt Concrete Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75 psi</td>
<td>125 psi</td>
</tr>
<tr>
<td>Bias-ply</td>
<td>1.00</td>
<td>1.49</td>
</tr>
<tr>
<td>Conv. Radial</td>
<td>1.44</td>
<td>3.26</td>
</tr>
<tr>
<td>Wide Base Radial</td>
<td>8.17</td>
<td>28.26</td>
</tr>
<tr>
<td>Bias-ply</td>
<td>1.00</td>
<td>1.34</td>
</tr>
<tr>
<td>Conv. Radial</td>
<td>1.18</td>
<td>2.18</td>
</tr>
<tr>
<td>Wide Base Radial</td>
<td>3.98</td>
<td>10.04</td>
</tr>
</tbody>
</table>

* 18 kips, Single Axle, Es=15000 psi, TSI=2.5

Based on rutting, the load equivalency factors determined in the study show an increase in LEF with increase in tire inflation pressure. In general, increased inflation pressure causes increased vertical compressive strain in the top few inches of the pavement only. Therefore, with increase in pressure, the increase in rutting is primarily associated with the additional rutting in the asphalt layer and some rutting in the base layer, while the contribution from the subgrade is negligible. Computer runs made in this study show that the increase in vertical compressive strain at the top of the subgrade is very small with increase in tire inflation pressure. Similar results were also reported by Marshek in Reference (18), where he states that "Tire inflation pressure has almost no effect on the rutting parameter $\varepsilon_0\), with $\varepsilon_0$ being the vertical compressive strain at the top of the subgrade."
The variations in LEF with inflation pressure, for the three tire types, are shown in Figures 26, 27, and 28 and summarized below in Table 13.

Table 13. Effect of Tire Inflation Pressure on Predicted LEF based on Rutting.*

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Load Equivalency Factor</th>
<th>Asphalt Concrete Thickness (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75 psi</td>
<td>125 psi</td>
</tr>
<tr>
<td>Bias-ply</td>
<td>1.00</td>
<td>2.05</td>
</tr>
<tr>
<td>Conv. Radial</td>
<td>2.24</td>
<td>5.91</td>
</tr>
<tr>
<td>Wide Base Radial</td>
<td>2.54</td>
<td>26.74</td>
</tr>
<tr>
<td>Bias-ply</td>
<td>1.00</td>
<td>1.71</td>
</tr>
<tr>
<td>Conv. Radial</td>
<td>3.57</td>
<td>7.35</td>
</tr>
<tr>
<td>Wide Base Radial</td>
<td>13.64</td>
<td>78.79</td>
</tr>
</tbody>
</table>

* 18 kips, Single Axle, Es=15000 psi, Rutting=0.5 inches

(2) Load Effect

Computer runs made in the study show that, with an increase in load, the vertical compressive strain at the top of the subgrade increases significantly. The axle load was found to be the most significant factor with respect to rutting and serviceability loss.

The increase in radial tensile strain at the bottom of the asphalt layer with increase in load was found to depend upon the thickness of the asphalt layer. In general, thinner pavements showed lesser increases in radial strain with load than thicker pavements.

The predicted changes in LEF with axle load, for the three types of distress, are shown in Figures 29, 30, and 31 and summarized below in Table 14.
Figure 26. The Change in LEF with Inflation Pressure, Based on Rutting, for Bias-Ply Tire.
Figure 27. The Change in LEF with Inflation Pressure, Based on Rutting, for Conventional Radial Tire.
LEF Based on Rutting (0.50")
Wide Base Rad. Tire (Florida)
Axle = 1, Tire = 1, Es = 15000

Figure 28. The Change in LEF with Inflation Pressure, Based on Rutting, for Wide Base Radial Tire.
Figure 29. The Change in LEF with Axle Load, Based on Fatigue Cracking, for Bias-Ply Tire.
Figure 30. The Change in LEF with Axle Load, Based on PSI, for Bias-Ply Tire.
LEF Based on Rutting (0.50")
Bias-Ply Tire (Florida)
Axle = 1, t = 4, P = 75, Es = 15000

Figure 31. The Change in LEF with Axle Load, Based on Rutting, for Bias-Ply Tire.
Table 14. Effect of Axle Load on Pavement Distress.*

<table>
<thead>
<tr>
<th>Distress Type</th>
<th>Load Equivalency Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.0 kips</td>
</tr>
<tr>
<td>PSI</td>
<td>0.45</td>
</tr>
<tr>
<td>Rutting</td>
<td>0.11</td>
</tr>
<tr>
<td>Fatigue Cracking</td>
<td>0.65</td>
</tr>
</tbody>
</table>

* Bias-ply tire, Single Axle, Dual Tire, P=75 psi, t=4", Es=15000 psi

(3) Asphalt Concrete Thickness

LEF plots based on fatigue cracking show that for thin pavements, the increase in LEF is relatively small with increase in axle load. For a 2-inch asphalt layer for example, increasing the axle load from 18 kips to 24 kips increases the LEF by about 66%, as may be observed from Figure 20. For a 6-inch asphalt layer however, the same increase in axle load is predicted to result in a 105% increase in LEF.

Runs made of the Tielking tire model showed that if the pressure is kept constant, then an increase in tire load shifts the peak pressure distribution towards the tire shoulders. Research conducted by Marshek (18) also showed a similar finding. He reports that "low inflation pressures resulted in large contact areas and high pressures near the tire shoulder region". For thinner pavements, shifting of the peak pressure towards the tire shoulder causes a smaller increase in tensile strain at the bottom of the asphalt layer than for thicker pavements.

The effect of increased tire pressure depends on the asphalt concrete thickness. LEF equations developed for the three types of distress show that the pressure effect is more pronounced for pavements with thin
asphalt concrete layers than for pavements with thick asphalt concrete layers. These results are shown in Tables 11, 12, and 13.

(4) Axle Configuration

According to the AASHTO performance equations (19), a 33-kip tandem, and a 46-kip triple axle load are about as damaging as an 18-kip single axle load. At these loading conditions, the AASHTO load equivalency factors are approximately unity. For this study however, the load equivalency factors determined on the basis of serviceability loss show that the load levels at which tandem and triple axles become as equally damaging as an 18-kip single axle load, are lower than those predicted from the AASHTO equations. As may be observed from Figure 32, the load levels at which the load equivalency factor is unity are approximately 31 and 42 kips for tandem and triple axles respectively. This indicates that the PSI damage equations developed herein are more conservative than those developed from the AASHO Road Test.

Similarly, on the basis of fatigue cracking, the predicted load equivalency factors show that a 26-kip tandem, and a 33-kip triple axle load are about as damaging as an 18-kip single axle load. On the basis of rutting, the predicted load equivalency factors show that a 28-kip tandem, and a 37-kip triple axle load are about as damaging as an 18-kip single axle load. Load equivalency factors calculated on the basis of fatigue cracking and rutting are illustrated in Figures 33 and 34.

(5) Tire Construction

LEF plots based on cracking, rutting and serviceability index show that, in general, the bias-ply tire is the least damaging of the tire
LEF Based on PSI (2.50)
Bias-Ply Tire (Florida)
Tire = 2, t = 4, P = 75, Es = 15000

Figure 32. Plots of LEF for Different Axle Configurations, Based on PSI, for Bias-Ply Tire.
Figure 33. Plots of LEF for Different Axle Configurations, Based on Fatigue Cracking, for Bias-Ply Tire.
Figure 34. Plots of LEF for Different Axle Configurations, Based on Rutting, for Bias-Ply Tire.
types evaluated. The wide base radial tire is more damaging than the conventional radial tire, however this difference reduces at higher loads. This trend is somewhat consistent with that obtained in another study done by Southgate (20) where he reports that "there is a larger difference in damage factors between flotation tires and dual tires at lesser loads, and the damage factors approach equality at the higher loads".

SUMMARY

On the basis of the results presented, the following findings are noted:

(1) Performance predictions using predicted tire contact pressure distributions show that the effects of tire inflation pressure on fatigue cracking, rutting, and loss of serviceability are significant.

(2) The effect of tire inflation pressure, on all three types of distress considered in this study, depends on the asphalt concrete thickness. An increase in tire inflation pressure causes more damage in thin pavements as compared to thick pavements.

(3) The effect of increased tire load on fatigue cracking depends on the asphalt layer thickness. Pavements with thicker asphalt layers are affected more by increases in tire load than pavements with thin asphalt layers. For the latter case, the radial strain at the bottom of the asphalt layer approaches compression, and the increase in radial tensile strain, with increase in load, is relatively small.

(4) Based on loss of serviceability, a 31-kip tandem axle load and a 42-kip triple axle load are about as damaging as an 18-kip single axle load.
load. At these load levels, the load equivalency factor is approximately unity.

(5) In general, of all the tire types studied, the bias-ply tire was found to be the least damaging, while the wide base radial tire was found to be the most damaging.

The damage equations presented herein are used in Florida COMPAS to determine load equivalency factors for calculating the daily 18-kip equivalent single axle loads (ESAL's) during the initial year of the analysis period. This is explained more in the next chapter. In addition, the damage equations are used for evaluating pavement performance. For the period prior to the placement of the initial overlay, the user has the option of using FLEXPASS or the damage equations for predicting serviceability loss, fatigue cracking, and rutting with increasing load applications. Thereafter, the damage equations presented are used in evaluating the performance of the overlaid pavement. The evaluation of pavement performance after an overlay is discussed in more detail in a subsequent chapter.
As discussed previously, the damage equations developed for Florida may be used to determine load equivalencies as a function of axle load, axle configuration, tire configuration, tire type, tire inflation pressure, asphalt concrete thickness, and subgrade modulus. The load equivalencies determined are for static loading conditions. In order to consider dynamic load effects in the evaluation of pavement performance under different forecasted truck characteristics and truck use, a procedure was developed for adjusting load equivalency factors using the dynamic load profile predicted from the vehicle simulation. This procedure for adjusting load equivalency factors is illustrated in Figure 35.

As shown in the figure, two options are available for considering vehicle dynamic loads in the determination of load equivalencies. In the first approach, a dynamic load coefficient is calculated from the predicted dynamic load profile following the procedure given in Reference (3). In this procedure, the standard deviation of the coefficient of impact, defined as the ratio of dynamic to static axle load, is used to calculate a dynamic load coefficient from the formula:

\[ \alpha = 1.0 + 6(SD_{ic})^2 \]  \hspace{1cm} (20)

where,

\[ \alpha = \text{dynamic load coefficient} \]

\[ SD_{ic} = \text{standard deviation of the coefficient of impact} \]
Figure 35. Flow Chart of Program to Calculate Load Equivalency Factors and Adjust for Dynamic Load Effects.
Figure 35. Flow Chart of Program to Calculate Load Equivalency Factors and Adjust for Dynamic Load Effects (continued).
The static load equivalency factor calculated for a particular set of loading conditions is then multiplied by the coefficient, $\alpha$, determined from the above equation to get an adjusted load equivalency factor. Static load equivalencies are determined herein using the damage equation based on PSI. The adjusted LEF, obtained from multiplying the static LEF with the dynamic load coefficient, is then used to calculate the cumulative 18-kip ESAL's/day for the initial year of the analysis period.

For a perfectly smooth road, the dynamic wheel load will be equal, theoretically, to the static wheel load. Thus, the standard deviation of the coefficient of impact, $\text{SD}_{ic}$, in Eq. (20) will be zero, $\alpha$ will be unity, and the adjusted load equivalency factor will be equal to the static load equivalency. However, as the road surface gets rougher, $\text{SD}_{ic}$ will increase, and the coefficient $\alpha$ will also increase. Thus, it is evident that the adjusted LEF will get larger as the road gets rougher, which would imply an increase in the damaging potential associated with a given wheel load as the initial surface roughness is increased.

The other approach for adjusting load equivalencies involves calculating the expected value of load equivalency factors associated with axle loads sampled from the cumulative distribution of the predicted dynamic loads. In this approach, 1000 uniform random numbers are initially generated, for sampling the cumulative distribution of dynamic axle loads corresponding to a given axle assembly of a particular vehicle. For each sampled point, a load equivalency factor is determined using the damage equations developed. Thus, a distribution of load equivalency factors is obtained, and an adjusted LEF is determined by taking the expected value of the distribution of load equivalency factors.
In the program, load equivalencies are determined for each of three distress modes, i.e., serviceability loss, fatigue cracking, and rutting. In this way, predictions of pavement performance with time, using the damage equations developed, can be made using a traffic rate consistent with a given distress mode. In addition, adjusted load equivalencies are determined for two different asphalt concrete thicknesses, i.e., the existing asphalt thickness, $T_1$, and the sum of $T_1$ and the maximum overlay thickness. This is done to allow for adjusting the calculated traffic rates, in terms of cumulative 18-kip ESALs/day, whenever overlays are placed to account for the effect of the increased asphalt concrete thickness.

The program for calculating load equivalencies is executed after each run of the vehicle simulation model. From the predicted dynamic load profiles, the program computes adjusted load equivalency factors for the different axle assemblies of the given vehicle, using one of the two procedures described previously. As may be observed from Figure 35, the user has the option of including the steering axle in the calculation of the traffic rates for the initial year of the analysis period.

The calculated load equivalency factors are written to a disk file after each run of the load equivalency program. In addition, ratios of adjusted to static LEF are written to the file for adjusting load equivalency factors associated with vehicles for which no simulation runs were conducted. It is noted that for any given vehicle category, the user has the option of selecting GVW categories for which vehicle simulation runs are to be made.

The file generated by the load equivalency program is used as an input
file for a subsequent program that calculates the cumulative 18-kip ESAL/day for the initial year of the analysis period. This program, referred to in COMPAS as ESAL18, is executed after all required runs of the vehicle simulation and load equivalency programs have been completed. A flowchart of the ESAL18 program is shown in Figure 36.

Initially, the program determines if any vehicle simulation runs were conducted. If so, ESAL18 reads the output file from the load equivalency program, and calculates the contributions of the different vehicles simulated to the cumulative 18-kip ESAL/day for the initial year. In addition, for a given scenario, traffic direction, vehicle category, tire type, suspension type, and axle assembly, the program computes the average of the ratios of adjusted to static load equivalency factors determined for the different GVW categories selected for the vehicle simulation. These ratios are subsequently used to estimate an adjusted LEF for those cases where no simulation runs were conducted. This is done by multiplying the static load equivalency factor by the average ratio of adjusted to static LEF appropriate for the scenario, traffic direction, vehicle category, tire type, suspension type, and axle assembly being considered. Thus, as long as vehicle simulation runs were made for a given vehicle category, adjusted load equivalency factors will be estimated for that particular vehicle. Otherwise, if no simulation runs were made, then the contribution of the given vehicle category to the predicted initial traffic rate is calculated from the static load equivalency factors.

In addition to the option of selecting specific GVW categories, the user has the option of specifying a certain percentile of the GVW distribution for conducting the vehicle simulation. If this option is
Figure 36. Flow Chart of the Program to Calculate Daily 18-kip ESAL's.
Figure 36. Flow Chart of the Program to Calculate Daily 18-kip ESAL's (continued).
Figure 36. Flow Chart of the Program to Calculate Daily 18-kip ESAL's (continued).
prescribed, the simulation is conducted using static axle loads representative of the percentile specified by the user. In effect, this implies that a vehicle, with static axle loads corresponding to the specified percentile, is used to represent all vehicles within the given category. Thus, the contribution of the given vehicle category to the initial traffic rate is calculated using the adjusted load equivalency factors determined for this "representative" vehicle, and the total number of vehicles per day specified for the given vehicle category.

The output from the ESAL18 program consists of the cumulative 18-kip ESAL/day for each scenario and traffic direction, and for each distress mode and asphalt concrete thickness considered. The program always calculates initial traffic rates for the current and alternate scenarios defined by the user, as well as for the three different distress modes and two asphalt concrete thicknesses. In addition, a traffic rate per traffic direction is determined for the case of a divided highway where the user has decided to have separate performance evaluations conducted using specified analysis sections for the two traffic directions. The initial traffic rates, in conjunction with the growth rate of 18-kip ESAL's, are used in Florida COMPAS to predict the cumulative number of 18-kip equivalent single axle load applications at any time during the analysis period for the purpose of determining the PSI, fatigue cracking, and rutting at that particular time using the damage equations developed.
CHAPTER 6. DEVELOPMENT OF THE OVERLAY DESIGN PROCEDURE

Asphalt concrete overlays are commonly used for pavement rehabilitation. Within Florida COMPAS, a mechanistic-empirical overlay design procedure based on reflection cracking is used, in conjunction with the damage equations discussed earlier, to establish the timing of overlays and the required overlay thicknesses. The overlay design procedure based on reflection cracking was developed by Jayawickrama, Smith, Lytton, and Tirado in a study conducted for the Federal Highway Administration (4). This overlay design procedure was modified in the current study to provide the capability of predicting reflection crack growth with time or cumulative load applications. A brief background on the theoretical development of this procedure is given in the following. This background information is then followed by a discussion of how the overlay design and damage equations fit into a framework for predicting the timing and thicknesses of overlays, as well as the overlay performance, that are input to the life-cycle cost analysis of Florida COMPAS.

OVERLAY DESIGN BASED ON REFLECTION CRACKING

A form of distress that significantly affects the service life of an overlay is reflection cracking, so named because it mirrors the crack and joint pattern of the original pavement. The mechanisms which are generally recognized as causing reflection cracking are the horizontal and vertical movements of the original pavement layers. These movements occur as a result of changes in temperature, traffic loading, or a combination of both. At lower temperatures, the pavement surface
contracts resulting in movement at the already existing cracks or joints in the original pavement layers. These movements create tensile stresses in the overlay causing a crack to open which will then continue to grow with repeated expansion and contraction of the underlying pavement. Another important mechanism that contributes to reflection crack growth occurs due to the influence of traffic loading. As shown in Figure 37, every time a wheel load passes over a crack in the old pavement, the overlay will be subjected to shear and bending stresses that induce a crack to propagate into the overlay.

A mechanistic-empirical procedure for predicting the service life of bituminous overlays based on the thermal, shear, and bending mechanisms noted previously was developed by Jayawickrama and Lytton at Texas A&M University (21). In this procedure, reflection crack growth is modeled using the Paris and Erdogan equation (12):

\[
\frac{dc}{dN} = A(\Delta K)^n
\]  

(21)

where,

- \( c \) = crack length
- \( N \) = number of load repetitions
- \( \Delta K \) = change in stress intensity factor
- \( A, n \) = fracture parameters

Integration of Eq. (21) leads to the following expression for the number of load applications to failure:

\[
N_f = \int_0^h \frac{dc}{A(\Delta K)^n}
\]  

(22)
Figure 37. Stresses Induced at the Cracked Section Due to a Moving Wheel Load.
where,

\[ N_f = \text{number of load applications to failure} \]

\[ h = \text{thickness of the overlay} \]

Equation (22) requires a knowledge of the stress intensity factors within the overlay for predicting service life. Expressions for evaluating stress intensity factors under thermal, shear, and bending modes of crack growth were developed using beam-on-elastic foundation theory and finite element analysis. Beam-on-elastic foundation theory was used to establish the form of the expressions for stress intensity factors of the three different modes of crack growth. In this analysis, the original surface layer and the overlay are modeled as a beam resting on top of a homogeneous elastic medium representing the base and the subgrade. Mathematical expressions were determined that reflected the influence of layer stiffnesses, layer thicknesses, wheel load, and subgrade support on the stress intensity factors.

The finite element technique was subsequently used to calculate stress intensity factors for different crack tip positions and levels of aggregate interlock. The results of this analysis are summarized in Table 15. In addition, the calculated stress intensity factors were non-dimensionalized using equations derived from the beam-on-elastic foundation analysis.

Figure 38 shows the non-dimensionalized stress intensity factors for the bending and shear modes of crack growth while Figure 39 shows the non-dimensionalized thermal stress intensity factors. An interesting observation that can be made from the results is that the failure mechanism due to bending is effective only up to a certain c/d ratio.
Table 15. Results of Finite Element Computation of Stress Intensity Factors (psi√ft).

<table>
<thead>
<tr>
<th>c/d</th>
<th>Bending Aggregate Interlock Ratio</th>
<th>Shearing Aggregate Interlock Ratio</th>
<th>Thermal Contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>0.05</td>
<td>120.6</td>
<td>117.6</td>
<td>114.9</td>
</tr>
<tr>
<td>0.15</td>
<td>157.2</td>
<td>147.9</td>
<td>129.4</td>
</tr>
<tr>
<td>0.25</td>
<td>163.7</td>
<td>146.3</td>
<td>111.1</td>
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<td>0.35</td>
<td>149.5</td>
<td>124.1</td>
<td>76.2</td>
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<tr>
<td>0.45</td>
<td>118.6</td>
<td>87.7</td>
<td>33.6</td>
</tr>
<tr>
<td>0.55</td>
<td>72.5</td>
<td>38.5</td>
<td>--</td>
</tr>
<tr>
<td>0.65</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>0.75</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>0.85</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>0.95</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure 38. Non-dimensionalized Bending and Shearing Stress Intensity Factors vs. Non-dimensionalized Crack Length.
Figure 39. Non-dimensionalized Thermal Stress Intensity Factors vs. Non-dimensionalized Crack Length.
where \( c \) and \( d \) represent the crack length and the total pavement thickness respectively. Beyond this limiting \( c/d \) ratio, only the shear and thermal mechanisms remain effective in propagating the crack through the overlay. In addition, comparison of the relative magnitudes of the stress intensity factors shown in Table 15 indicates that the shear and thermal modes are the predominant mechanisms of crack growth.

In addition to the stress intensity factor, the use of the Paris and Erdogan equation requires a knowledge of the fracture parameters \( A \) and \( n \). In the overlay design procedure, the fracture parameter, \( n \), is determined from the slope, \( m \), of the log of the mix stiffness versus the log of the loading time curve. Specifically, the following relationship, based on derivations made by Schapery (22), is used for determining the fracture parameter, \( n \):

\[
\frac{2}{n} = m
\]  

(23)

The above relationship has been verified in laboratory investigations conducted by Germann and Lytton (23), and by Molenaar (24). Examination of the laboratory data from these studies has shown that Eq. (23) leads to reasonably accurate estimates of the measured values of \( n \).

In predicting the fracture parameter, \( n \), from Eq. (23), a computerized version of McLeod's nomograph (25) is used to construct the log stiffness versus the log loading time curve using the following properties of a given mix:

1. Penetration at 77° F,
2. Viscosity at 275°F in centistokes or viscosity at 140°F in poises, 
3. Asphalt content (%),
4. Air voids content (%), and
5. Service temperature, °F.

The slope, m, of the curve is determined and the fracture parameter, n, is subsequently predicted using Eq. (23). From the predicted n-value, the fracture parameter, A, is then determined using the following laboratory-derived relationships (26):

For the shear and bending modes of crack growth,
\[ n = -2.2 - 0.5 \log_{10} A \tag{24} \]

For the thermal mode of crack growth,
\[ n = -0.92 - 0.42 \log_{10} A \tag{25} \]

Using the relationships established for predicting stress intensity factors and fracture parameters, the service life of an overlay for each of the three different mechanisms of crack growth can be predicted by integration of the Paris and Erdogan equation. In the formulation of the overlay design procedure, the mechanistic predictions were calibrated to field performance data to arrive at mechanistic-empirical equations for predicting service life corresponding to different levels of reflection cracking. The form of the regression model was selected to reflect the combined influence of the three different mechanisms of crack growth. Specifically, the following regression model was used in the empirical calibration:
\[ N_{\text{obs}} = (N_{\text{dt}})_1 \left\{ \frac{\alpha_1 - \alpha_2}{(N_{\text{db}})_1} - \frac{\alpha_3}{(N_{\text{db}})_1} \right\} + (N_{\text{dt}})_2 \left\{ \frac{\alpha_4 - \alpha_5}{(N_{\text{ds}})_2} \right\} \]  (26)

where,

- \( N_{\text{obs}} \) = observed reflection cracking life
- \( (N_{\text{dt}})_i \) = mechanistically predicted reflection cracking life for stage \( i \) (\( i = 1, 2 \)) based on the thermal mechanism of crack growth
- \( (N_{\text{ds}})_i \) = mechanistically predicted reflection cracking life for stage \( i \) (\( i = 1, 2 \)) based on the shear mechanism of crack growth
- \( (N_{\text{db}})_i \) = mechanistically predicted reflection cracking life for the bending mechanism of crack growth
- \( \alpha_i \) = regression coefficients

In the calibration of the mechanistic predictions, two different stages of crack growth were considered. In the first stage, it is assumed that all three different mechanisms of crack growth are effective in propagating the crack through the overlay. In the second stage, only the shear and thermal mechanisms remain effective. Based on the results of the finite element analysis presented previously, a value of 0.181 for the non-dimensionalized bending stress intensity factor was selected as the limiting value below which the bending mechanism ceases to be effective in propagating the crack through the overlay.

A set of overlay design equations were then formulated by regressing the service life predictions obtained from separate integrations of the Paris and Erdogan equation with estimates of the field service life corresponding to different levels of reflection cracking. In the regression analysis, design equations were established for damage levels of 0.33, 0.40, and 0.50 corresponding, respectively, to low, intermediate, and high levels of reflection cracking. A damage level of
0.33 corresponds to the case where the crack spacing is approximately 15 feet. Similarly, damage levels of 0.40 and 0.50 are associated with crack spacings of 12.5 and 10 feet respectively.

Using distress data on reflection cracking collected during the FHWA study reported in Reference (4), regression runs were made to establish overlay design equations appropriate for Florida conditions. It was found that the most reasonable predictions were obtained using a regression model that considered only the contributions of the thermal and shear mechanisms of crack growth, i.e., \( a_1 = a_2 = a_3 = 0.0 \) in Eq. (26). Consequently, in the overlay design procedure of Florida COMPAS, the integration of the Paris and Erdogan equation is carried out only for these two mechanisms of crack growth. The theoretical predictions of service life are then used in one of the following regression equations to predict the overlay field service life based on the damage level specified by the user:

For a damage level of 0.33:

\[
N_{obs} = N_{dt} \left\{ 0.358810 - 0.000062270 \frac{N_{dt}}{N_{ds}} \right\}
\]  
(27)

For a damage level of 0.40:

\[
N_{obs} = N_{dt} \left\{ 0.409394 - 0.000054431 \frac{N_{dt}}{N_{ds}} \right\}
\]  
(28)

For a damage level of 0.50:

\[
N_{obs} = N_{dt} \left\{ 0.496584 - 0.000025794 \frac{N_{dt}}{N_{ds}} \right\}
\]  
(29)
where,

\[ N_{obs} = \text{predicted field service life in years} \]

\[ N_{dt} = \text{theoretical service life based on thermal mode of crack growth} \]

\[ N_{ds} = \text{theoretical service life based on shear mode of crack growth} \]

Consequently, for a given crack length, \( c \), the values of \( N_{dt} \) and \( N_{ds} \) are calculated through integration of the Paris and Erdogan equation using the appropriate values for the stress intensity factor and the fracture parameters, \( A \) and \( n \). Depending on the damage level specified by the user, the theoretical predictions for service life are then used in Eqs. (27), (28), or (29), to predict the field service life corresponding to the given crack length, \( c \).

**FRAMEWORK FOR OVERLAY DESIGN AND PERFORMANCE EVALUATION**

The preceding overlay design algorithm based on reflection cracking was incorporated into a framework for determining overlay thicknesses and for evaluating the performance of the overlaid pavement. Figure 40 shows the framework of the overlay design and performance evaluation program developed for Florida COMPAS. Initially, the user enters the required input data shown in the figure. Once the input data have been read, a support modulus is calculated that represents the combined stiffness of the pavement layers beneath the original asphalt layer. This calculation is necessary since the overlay design algorithm was developed using beam-on-elastic foundation theory.

The calculation of an equivalent support modulus is carried out in two steps as illustrated in Figure 41. In the first step, the surface
Figure 40. Framework of the Performance Evaluation and Overlay Design Procedure.
Figure 40. Framework of the Performance Evaluation and Overlay Design Procedure (continued).
Figure 40. Framework of the Performance Evaluation and Overlay Design Procedure (continued).
Figure 40. Framework of the Performance Evaluation and Overlay Design Procedure (continued).
Figure 41. Calculation of the Equivalent Support Modulus in the Overlay Program.

\[ w = w' \] - surface deflection

\( E_1 \) - stiffness of layer 1, 1-1, 2, 3

\( t_1 \) - thickness of layer 1, 1-1, 2, 3

\( E_{sg} \) - subgrade stiffness

\( E_s \) - equivalent support modulus
deflection, $w$, due to an 18-kip single axle load is calculated using the actual layer thicknesses and moduli specified by the user. In the second step, the pavement is represented as a two-layer system consisting of the asphalt surface layer and a homogeneous elastic medium of modulus $E_s$. The value of this equivalent support modulus $E_s$ is then obtained by requiring that the surface deflection, $w'$, for this two layer system be the same as the surface deflection, $w$, calculated in the previous step.

The surface deflection is computed using the following regression equation developed by Uzan (27) that is applicable for pavements consisting of up to four different layers:

$$\log_{10}(\frac{wE_{sg}}{pa}) = a_0 + \sum_{i=1}^{6} a_i \log_{10} X_i + \sum_{i=1}^{6} \sum_{j=1}^{6} b_{ij} \log_{10} X_i \log_{10} X_j$$  \hspace{1cm} (30)

where,

- $w$ = surface deflection under one wheel of the dual wheel load
- $E_{sg}$ = subgrade modulus, psi
- $a$ = radius of the loaded area = 4.501 inches
- $p$ = applied pressure = 70.7 psi for an 18-kip single axle load
- $X_1 = \frac{t_1}{a}$
- $X_2 = \frac{t_2}{a}$
- $X_3 = \frac{t_3}{a}$
- $X_4 = \frac{E_1}{E_{sg}}$
- $X_5 = \frac{E_2}{E_{sg}}$
- $X_6 = \frac{E_3}{E_{sg}}$
- $t_i$ = thickness of layer $i$, inches
- $E_i$ = modulus of layer $i$, psi
\[ a_0, a_i, b_i = \text{regression coefficients} \]

The coefficients of Eq. (30) are summarized in Table 16. This same equation is used in back-calculating a value for the support modulus of a two-layer system that will result in the same surface deflection calculated for the actual layered system. The support modulus is calculated for one or two traffic directions as necessary.

For each scenario and traffic direction established by the user, an overlay design and performance evaluation is conducted. The initial condition is first established wherein the initial amounts of fatigue cracking and rutting are predicted using the specified value of initial PSI, and the damage equations developed for Florida. In this step, the cumulative number of 18-kip load applications to reach the prescribed level of initial PSI is first evaluated using the damage equations for serviceability loss. Then, the amounts of fatigue cracking and rutting at this cumulative number of 18-kip load applications are predicted using the damage equations for these distress modes.

The time to initial failure is then evaluated using the specified failure criteria for PSI, fatigue cracking, and rutting, and is the time of the earliest occurrence of one or more of the user specified failure criteria. This evaluation is made using either the damage equations developed for Florida, or the performance predictions from the FLEXPASS program, executed prior to the overlay design and performance evaluation, if the user has opted to use FLEXPASS in lieu of the damage equations for predicting pavement performance during the initial design period. The performance predictions are written to a file for the subsequent
Table 16. Coefficients of the regression equation for surface deflection.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>0.29444803</td>
</tr>
<tr>
<td>$b_{23}$</td>
<td>0.11456876</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-0.23612042</td>
</tr>
<tr>
<td>$b_{24}$</td>
<td>0.01177786</td>
</tr>
<tr>
<td>$a_2$</td>
<td>-0.08992132</td>
</tr>
<tr>
<td>$b_{25}$</td>
<td>-0.19185640</td>
</tr>
<tr>
<td>$a_3$</td>
<td>-0.03402367</td>
</tr>
<tr>
<td>$b_{26}$</td>
<td>0.09645430</td>
</tr>
<tr>
<td>$a_4$</td>
<td>-0.24918090</td>
</tr>
<tr>
<td>$b_{33}$</td>
<td>-0.04005662</td>
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<td>$a_5$</td>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>$b_{35}$</td>
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</tr>
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<td>$b_{11}$</td>
<td>-0.20749072</td>
</tr>
<tr>
<td>$b_{36}$</td>
<td>-0.33473429</td>
</tr>
<tr>
<td>$b_{12}$</td>
<td>0.20149230</td>
</tr>
<tr>
<td>$b_{44}$</td>
<td>0.01450629</td>
</tr>
<tr>
<td>$b_{13}$</td>
<td>0.09854459</td>
</tr>
<tr>
<td>$b_{45}$</td>
<td>0.00952190</td>
</tr>
<tr>
<td>$b_{14}$</td>
<td>-0.21911926</td>
</tr>
<tr>
<td>$b_{48}$</td>
<td>0.01702288</td>
</tr>
<tr>
<td>$b_{15}$</td>
<td>0.12462257</td>
</tr>
<tr>
<td>$b_{55}$</td>
<td>0.00739489</td>
</tr>
<tr>
<td>$b_{16}$</td>
<td>0.10200553</td>
</tr>
<tr>
<td>$b_{68}$</td>
<td>0.02980141</td>
</tr>
<tr>
<td>$b_{22}$</td>
<td>-0.17199369</td>
</tr>
<tr>
<td>$b_{68}$</td>
<td>0.00000000</td>
</tr>
</tbody>
</table>
evaluation of life-cycle costs once the overlay design and performance evaluation has been completed.

The predicted time to initial failure is then compared with the length of the analysis period. If the predicted time to failure is greater than or equal to the length of the analysis period, no overlays are required, and the analysis then proceeds to the next traffic direction, as necessary, or to the next scenario. However, if the predicted time to failure is less than the length of the analysis period, then an overlay design and performance evaluation needs to be conducted.

The design of the initial overlay requires a knowledge of the spacing of transverse cracks at the time of the overlay in order to compute the stress intensity factor associated with the thermal mechanism of crack propagation. In order to estimate the crack spacing, regression equations developed by Lytton, Shanmugham, and Garrett (28) are used, which relate the crack spacing to original asphalt mixture properties, pavement age, average annual amplitude of solar radiation, and minimum monthly temperature. These regression equations are given as follows:

\[
I = -2.66 + 3.06\times\text{CMDG1} 
\]  
(31)

\[
\text{CMDG1} = 0.519(\text{PI})^{0.287} (\text{SP})^{0.122} (C_v)^{24.5} (D)^{-0.410} \times (T)^{1.66} (\text{SA})^{1.87} (\text{MT})^{-7.43} 
\]  
(32)

where,

- \(I\) = a crack index, defined as the sum of full transverse plus 1/2 of the number of half transverse cracks per 500 feet of roadway
- \(\text{CMDG1}\) = a cumulative damage index associated with thermal cracking
- \(\text{PI}\) = a normalized penetration index
  - \(= 0.25(\text{original penetration index} + 2)\) where the original penetration index is computed from user specified values for original
penetration at 77°F and viscosity at 140°F for the existing asphalt surface layer.

\[ SP = \frac{\text{original ring and ball softening point temperature (°F)}}{125.6} \]

\[ C_v = \frac{\text{volumetric concentration of the aggregate estimated from the asphalt content (%) specified by the user for the existing asphalt surface layer.}}{\text{depth of original asphalt layer/8.0}} \]

\[ D = \frac{\text{depth of original asphalt layer}}{8.0} \]

\[ T = \frac{\text{age of the existing pavement in years}}{10.0} \]

\[ SA = \frac{\text{average annual amplitude of solar radiation (langleyes/day)}}{240.0} \]

\[ MT = \frac{\text{[minimum monthly temperature (°F) + 20.0]}}{55.7} \]

From the above equations, the crack spacing at the time of the initial overlay is estimated as 500.0/I where I is obtained from Eq. (31) using the value for CMDGI computed from Eq. (32). For each Florida District, default values for the amplitude of solar radiation and the minimum monthly temperature are built into the program, should site-specific values be not readily available.

After prediction of the crack spacing, the counter, \( N_w \), for the number of required overlays is initialized, and the required life for the initial overlay is calculated. The modulus, and the slope, \( m \), of the creep compliance curve for the overlay are evaluated using a computerized version of McLeod's nomograph and the specified mixture properties for the overlay. The modulus of the overlay is required for evaluating overlay performance, while the slope, \( m \), is used for estimating the fracture parameter, \( n \), of the Paris and Erdogan equation for each mechanism of crack growth.

The overlay thickness is then initialized to the minimum thickness specified by the user, and the existing surface thickness is reduced by an
amount equal to the prescribed depth of milling. The overlay performance corresponding to the initial thickness is then evaluated for each of the following distress modes: reflection cracking, serviceability loss, fatigue cracking, and rutting. Overlay performance based on reflection cracking is evaluated using the procedure discussed in the previous section of this chapter. The performance based on serviceability loss, fatigue cracking, and rutting, is evaluated using the damage equations developed for Florida.

In order to incorporate the influence of the moduli of the existing asphalt layer and the overlay material in the evaluation of overlay performance using the damage equations, the following procedure is applied:

1. The surface deflection, \( u \), due to an 18-kip single axle load is calculated using Eq. (30) for a three-layer pavement system consisting of the overlay material, the existing asphalt surface layer, and the homogeneous elastic medium of modulus \( E_0 \) computed previously.

2. The overlay material and the existing asphalt layer is then combined into one layer of thickness equal to the sum of the thicknesses of the overlay and the existing surface layer, and characterized by a composite modulus calculated using the following equation attributed to Odemark (29):

\[
E_{\text{comp}} = \frac{E_0 (h_0)^3 + E'_1 (h'_1)^3}{(h_0)^3 + (h'_1)^3}
\]  

(33)

where,

\( E_{\text{comp}} \) = composite modulus
\[ E_o = \text{overlay modulus} \]
\[ E_{1'} = \text{modulus of existing asphalt surface layer} \]
\[ h_o = \text{thickness of the overlay} \]
\[ h_{1'} = \text{thickness of the existing asphalt surface layer} \]

3. For a pavement system consisting of an asphalt layer of modulus \( E_{\text{comp}} \) and thickness \((h_o + h_{1'})\) resting on top of a homogeneous elastic medium representing the subgrade, a value for subgrade modulus is calculated such that the surface deflection, \( u' \), due to an 18-kip single axle load is the same as the surface deflection, \( u \), calculated from step 1.

4. The value of subgrade modulus obtained from Step 3 is then used in calculating the performance of the overlaid pavement using the damage equations developed for Florida.

The life of the overlay is taken to be the minimum of the service lives calculated for all of the distress types noted previously. If this predicted overlay life is less than the required life, and the current overlay thickness is less than the maximum specified (Condition 1), the overlay thickness is incremented and the performance of the overlaid pavement for this new thickness of overlay is evaluated as before. The overlay increment is currently set at 0.5 inches within the program. Also, except as noted below, the incremented value for overlay thickness is not allowed to exceed the maximum thickness specified by the user.

If Condition 1 above is false, then a check is made as to whether the predicted life of the overlay is less than the required life, and whether the current overlay thickness is greater than or equal to the maximum specified (Condition 2). If Condition 2 is true, then the difference
between the overlay life and the required life is calculated, and the absolute value of the difference compared to a control variable denoted by $\Delta_{\text{limit}}$ in Figure 40. This variable allows the program to override the maximum thickness specified by the user. Specifically, if the absolute difference between the service life associated with the current overlay thickness, and the required life is less than or equal to $\Delta_{\text{limit}}$, the program will continue incrementing the overlay thickness until the required service life is achieved or exceeded. The value of $\Delta_{\text{limit}}$ is currently set to 5 years within the program.

Once an overlay thickness is obtained that provides a service life greater than or equal to the required life, or if Condition 2 above is false, the overlay thickness is adjusted so that the end of the overlay life is as close as possible to the end of the analysis period. This is accomplished by requiring the overlay life to be within some tolerance of the required life. Currently, the program will keep adjusting the overlay thickness until the predicted service life is within $-0.05$ years of the required life, or until the number of iterations exceed 200, whichever comes first. Once an adjusted thickness for the final overlay is determined, the performance of the overlaid pavement is evaluated, and the level-up volume is estimated using the rut depth predicted at the time of the overlay, and assuming that the transverse surface profile is shaped like a parabola. In the event that a depth of milling has been specified by the user, the level up volume will be zero if the prescribed depth of milling is such that the predicted rut depth at the time of the overlay is eliminated. The analysis then proceeds to the next traffic direction, as
necessary, or to the next scenario, until all scenarios and traffic directions have been analyzed.

If, earlier, the absolute difference between the predicted overlay life, and the required life was greater than $\Delta_{\text{limit}}$, the maximum specified overlay thickness is not overridden, and becomes the thickness for the $n^{th}$ overlay as determined by the counter, $N_{ov}$. The performance of the overlaid pavement is evaluated as before, and the required life for the succeeding overlay is determined. In addition, a composite modulus representative of the asphalt layers in the overlaid pavement is calculated using Odemark's theory. In effect, the original asphalt surface layer and all existing overlays are transformed into one bituminous layer of thickness equal to the sum of the individual thicknesses of the bituminous materials, and characterized by a composite modulus given by:

$$E'_1 = \frac{E_1(h_1)^3 + E_0 \sum_{i=1}^{N_{ov}} (h_{ov_i})^3}{(h_1)^3 + \sum_{i=1}^{N_{ov}} (h_{ov_i})^3}$$

(34)

where,

$E'_1$ = composite surface modulus

$E_1$ = modulus of the original asphalt surface layer

$h_1$ = thickness of the original asphalt surface layer

$E_0$ = overlay modulus

$h_{ov_i}$ = thickness of the $i^{th}$ overlay
The composite modulus from Eq. (34) above is then used as the asphalt surface modulus for the next overlay design. In addition, the crack spacing is set to the appropriate value associated with the damage level specified by the user. Thus, the crack spacing at the time of the next overlay is made consistent with the specified damage level for design purposes.

The overlay thickness is again initialized to the minimum specified thickness, and the calculations proceed as before. For each scenario and relevant traffic direction, as many overlays are designed as necessary for the pavement to sustain traffic through the end of the analysis period.
CHAPTER 7. THE COST ANALYSIS PROGRAM, FLAGCAP

The FLAGCAP (for Fla. General Cost Analysis for Pavements) computer program includes procedures for calculating two general types of costs: user (or motorist) costs, and pavement costs, during an analysis period. The costs are discounted over the analysis period using the specified discount rate. For purposes of discounting, all costs are discounted from the midpoint of the year they occur to the beginning of the analysis period. The program uses input provided by the user, and other input generated by the pavement analysis programs in COMPAS, such as time and depth of overlays during the analysis period, and the PSI history, to evaluate pavement life-cycle costs.

Analysis routines in FLAGCAP estimate the effect of pavement roughness on vehicle speeds, and these speeds are used, together with information on vehicle characteristics, to calculate vehicle operating costs. Time costs are also calculated using average vehicle speeds and values of time for passenger cars and trucks. FLAGCAP is designed for calculating user and pavement costs in present worth terms for two scenarios on each run of the computer program: the base scenario and an alternate scenario that has different input data. The vehicle weight distributions for the alternate scenario are estimated automatically from the base scenario using the load shifting routine discussed in Chapter 2. FLAGCAP is the last program to be executed in Florida COMPAS.
CALCULATION OF ADJUSTMENT FOR EFFECT OF PAVEMENT CONDITION ON AVERAGE SPEED

One of the factors affecting average travel speed is pavement condition. Vehicles tend to slow down on rougher pavements. The Highway Performance Monitoring System (HPMS), developed by the Federal Highway Administration (30), gives an equation relating average travel speed to pavement condition. A simplified version of that equation is used in this study for adjusting travel speed based on pavement conditions as quantified by PSI. The equation used is given by:

\[ \text{ASPD} = \text{SPD} \times (0.8613 \times \text{YPSI}^{0.828}) \]

Where:

\[ \text{ASPD} \] = Adjusted Average Travel Speed (mph), adjusted for pavement condition

\[ \text{SPD} \] = Average Travel Speed (mph), with very good pavement condition (PSI=5.0)

\[ \text{YPSI} \] = Yearly Pavement Present Serviceability Index

The Average Travel Speed (SPD) is an input item by vehicle type. It should be noted that the speed refers to ideal pavement conditions. When the average travel speed is not known, either the program default of 60 mph or values from the following table can be used. These values were calculated from the average PSI and speed for Florida reported in the 1988 Highway Statistics (31), and adjusted for ideal pavement conditions.
When the average travel speed is known for less than ideal conditions, the speed should be adjusted before it is used as input in the computer program. The following table of adjustments can be used. The average travel speed should be multiplied by the appropriate factor in the table.

<table>
<thead>
<tr>
<th>Present Serviceability Index</th>
<th>Adjustment Factor for Average Travel Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.1610</td>
</tr>
<tr>
<td>1.5</td>
<td>1.1182</td>
</tr>
<tr>
<td>2.0</td>
<td>1.0887</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0664</td>
</tr>
<tr>
<td>3.0</td>
<td>1.0485</td>
</tr>
<tr>
<td>3.5</td>
<td>1.0336</td>
</tr>
<tr>
<td>4.0</td>
<td>1.0209</td>
</tr>
<tr>
<td>4.5</td>
<td>1.0098</td>
</tr>
<tr>
<td>5.0</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

USE OF AVERAGE SPEED IN COMPUTER PROGRAM AND TIME COSTS

The average speed is used in two ways in the cost analysis program, FLAGCAP. First, extra time costs of driving at a lower speed on inferior
pavements are calculated and used directly in benefit estimates. Time costs are calculated using a value of time for passenger cars of $11.15 per vehicle hour and for trucks of $20.39 per vehicle hour. These are default values, and the user may input his or her own unit costs for value of time. The second way in which the average speed is used is in calculating vehicle operating costs, as described in the next section of this chapter.

CALCULATION OF VEHICLE OPERATING COSTS

In the computer program, each of the vehicle operating cost equations includes average vehicle speed as a variable in the equation. The cost analysis program uses the predicted present serviceability index history, from the pavement performance models in Florida COMPAS, to adjust certain components of vehicle operating cost. The average vehicle speed is calculated as outlined in the preceding section, and the vehicle operating costs are calculated as a function of vehicle type, gross vehicle weight (for trucks), and average vehicle speed. These costs are adjusted for the present serviceability index, except for fuel use. Following Zaniewski (5), no adjustment is made in fuel consumption by serviceability index. Adjustments are made in fuel consumption for tire type and tire pressure. An adjustment is also made in tire cost for tire type. Although there is some indication that tire wear also is a function of tire pressure, detailed estimates of tire wear by tire pressure were not available from the literature. In summary, the variables used in estimating each vehicle operating cost component are
summarized below, with an "x" indicating that the variable is used in the estimation procedure.

<table>
<thead>
<tr>
<th></th>
<th>GVW</th>
<th>Tire Type</th>
<th>Tire psi</th>
<th>Speed</th>
<th>Pavement SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Use</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Tire Wear</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Oil Use</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mnt. &amp; Rep.</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Depreciation</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

VEHICLE OPERATING COMPONENT COSTS

To obtain vehicle component costs, the consumption of each component category is first estimated as a function of vehicle speed and gross vehicle weight (GVW). The estimate of usage in physical terms is multiplied by the unit price of the component to obtain the corresponding cost estimate. Some of the usage estimates are adjusted for pavement roughness, tire type, and tire pressure as described in later sections of this chapter. For this study, several sources were investigated for estimating vehicle operating costs by vehicle type. Zaniewski's data were chosen because they were the most comprehensive available. Previous studies, including Zaniewski's, have not generally developed vehicle operating costs by GVW. It was determined that fairly good estimates could be made, by GVW, by taking Zaniewski's data for the four truck types with their range of GVW's, fitting equations to these GVW's, and using the resulting equations for all truck types, assuming that vehicle operating costs are simply a function of GVW. However, it was
necessary to make adjustments for the number of tires in the equations. The validity of this approach for estimating fuel consumption was checked by comparing the Zaniewski equation derived for four vehicle types (and their respective GVW's), with a fuel consumption function developed for 3-S2 vehicles by Cummins. These are plotted in Figure 42 (see Cunagin and Goff for a description of the Cummins model (32). It may be noted that the Zaniewski function derived from the four vehicle types matches the Cummins function for 3-S2 vehicles fairly well. The principal reasons the Cummins 3-S2 function shows more fuel efficiency is probably due to the fact that the Cummins vehicle used radial tires while the Zaniewski vehicle used bias-ply tires, and probably because the Cummins engine is more fuel efficient. Based on this comparison, it was decided that the Zaniewski functions would be used and that it would be assumed that they apply to all truck types with bias-ply tires. Adjustments for tire type are made as discussed later in the chapter. Zaniewski's data are used for all of the basic component equations and also for the unit prices. Table 17 shows Zaniewski's component unit prices. Future updating can be performed directly by changing these unit prices unless there is evidence in changes in consumption rates of the components due to technological improvements. Under such circumstances, re-estimation of consumptions should be carried out. Consumption data for each of the components (with the exception of the fuel consumption of trucks) were used to estimate the relationships of each component consumption with speed by vehicle type at zero grade and constant speed (no
Figure 42. Comparison of Cummins Engine Fuel Consumption for 3-S2 Vehicle as Compared to Function Based on Zaniewski's Four Truck Types.
Table 17. Vehicle Component Cost Unit Prices (September 1989)

<table>
<thead>
<tr>
<th>Component</th>
<th>Passanger</th>
<th>Trucks</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car</td>
<td></td>
<td>Single Unit</td>
<td></td>
<td>Semi’s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 axle</td>
<td>3 axle</td>
<td>4 axle</td>
<td>5 axle</td>
<td></td>
</tr>
<tr>
<td>Fuel*</td>
<td>1.00</td>
<td>1.00</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>$/gal</td>
</tr>
<tr>
<td>Oil</td>
<td>3.19</td>
<td>1.52</td>
<td>1.52</td>
<td>1.52</td>
<td>1.52</td>
<td>1.52</td>
<td>$/quart</td>
</tr>
<tr>
<td>Tires**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Tire</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biased</td>
<td>67</td>
<td>137</td>
<td>268</td>
<td>268</td>
<td>268</td>
<td>268</td>
<td></td>
</tr>
<tr>
<td>Radial</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Wide Based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sgle</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
<td>500</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Retreads</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biased</td>
<td>30</td>
<td>46</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Radial</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Wide Based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sgle</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
<td>250</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Maintenance and Repair</td>
<td>69.94</td>
<td>153.25</td>
<td>216.72</td>
<td>224.46</td>
<td>224.46</td>
<td></td>
<td>$/1000 mi</td>
</tr>
<tr>
<td>Depreciation Value</td>
<td>10057</td>
<td>13010</td>
<td>68025</td>
<td>73051</td>
<td>77445</td>
<td></td>
<td>$/vehicle</td>
</tr>
</tbody>
</table>

* Fuel Price represents after-tax cost.
** Cost are based on Zaniewski's assumption on truck tire cost which includes recaps; 2.5 recaps per tire for all trucks, except 2 axle unit which has 1.5 recaps.
acceleration or deceleration). The vehicle types in Zaniewski's data included four passenger car types, small, medium, large, and pickup, and four truck types, 2-axle single unit, 3-axle single unit, 4-axle semi's, and 5-axle semi's. In the current study, only two vehicle types are considered in estimating the vehicle operating component costs and they are the passenger cars and the trucks. However, truck gross vehicle weight is included as a variable in the truck equations and the equations are fitted to GVW for all truck types. Zaniewski's data on the four passenger car types are weighted evenly to arrive at the component costs for passenger cars while Zaniewski's data on the four truck types are consolidated into one truck type with their individual gross vehicle weights used directly in the component equations. The gross vehicle weights for single-unit trucks (2A and 3A) and truck semi-trailer combinations (2-S2 and 3-S2) are 12, 35, 40, and 62.5 kips, respectively.

Each of the five component costs for passenger cars is regressed against speed, and for trucks, against speed and GVW. The estimated equations are as follows:

\[
\begin{align*}
\text{Log}(\text{OIL}_{\text{PS}}) &= 1.34929 - 0.04913 s + 0.00051 s^2, \\
\text{Log}(\text{OIL}_{\text{TR}}) &= 0.56464 - 0.04868 s + 0.000516 s^2 + 0.51809 \text{Log}(\text{GVW}), \\
\text{Log}(\text{TIR}_{\text{PS}}) &= -2.64390 + 0.02657 s + 0.00017 s^2, \\
\text{Log}(\text{TIR}_{\text{TR}}) &= -5.46423 + 0.02756 s + 8.05 \times 10^{-5} s^2 + 0.67778 \text{Log}(\text{GVW}), \\
\text{Log}(\text{MRP}_{\text{PS}}) &= 3.79757 + 0.00748 s + 3.85 \times 10^{-5} s^2, \\
\text{Log}(\text{MRP}_{\text{TR}}) &= 3.78486 + 0.00462 s + 9.73 \times 10^{-5} s^2 - 0.005181 \text{Log}(\text{GVW}), \\
\text{Log}(\text{FUL}_{\text{PS}}) &= 4.37555 - 0.3680 s + 0.00049 s^2, \text{ and} \\
\text{Log}(\text{FUL}_{\text{TR}}) &= 5.54162 - 0.03898 s + 0.00042 s^2 + 0.01002 \text{GVW},
\end{align*}
\]
where,

\[
\begin{align*}
\text{DEP} &= \text{depreciation, in percent depreciable value per 1,000 miles,} \\
\text{OIL} &= \text{oil consumption, in quart per 1,000 miles,} \\
\text{TIR} &= \text{tire wear, in percent of wear per 1,000 miles,} \\
\text{MRP} &= \text{maintenance and repair, in percent of average cost per 1,000 miles,} \\
\text{FUL} &= \text{fuel consumption, in gallons per 1,000 miles,} \\
s &= \text{speed, in miles per hour, and} \\
\text{GVW} &= \text{gross vehicle weight, in kips.}
\end{align*}
\]

Subscript PS denotes passenger car, weighted average of large, medium, small, and pickup, and subscript TR denotes truck. The logarithms of the dependent variables in the above equations are evaluated using base e.

**PAVEMENT ADJUSTMENT FACTORS**

As discussed earlier, with the exception of fuel consumption, the vehicle operating component costs are sensitive to pavement condition, measured in terms of present serviceability index (PSI). Based on Zaniewski’s data, shown in Tables 18 through 21, adjustment factors for the effect of PSI on costs of depreciation, oil consumption, tire wear, and maintenance and repair, are developed for passenger vehicles and trucks. It appears that truck weights have little effect on pavement adjustments to depreciation, oil, and tire wear, but have some influence to maintenance and repair. The estimated equations for pavement adjustment to the components for both vehicle types are expressed as functions of PSI only, with the exception of the equation for maintenance and repair, in which truck weight (GVW) is included as an independent variable in addition to PSI.

**Passenger Vehicles:**

\[
\text{OIL}_{ps} = 2.18000 - 0.32000 \text{ PSI}
\]
Table 18. Oil Expense Adjustment Factors for Roadway Surface Condition

<table>
<thead>
<tr>
<th>Serviceability Index</th>
<th>Passenger Cars &amp; Pickup Trucks</th>
<th>Single Unit Trucks 2-S2 &amp; 3-S2 Semi's</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.86</td>
<td>1.16</td>
</tr>
<tr>
<td>1.5</td>
<td>1.70</td>
<td>1.13</td>
</tr>
<tr>
<td>2.0</td>
<td>1.54</td>
<td>1.10</td>
</tr>
<tr>
<td>2.5</td>
<td>1.38</td>
<td>1.07</td>
</tr>
<tr>
<td>3.0</td>
<td>1.22</td>
<td>1.04</td>
</tr>
<tr>
<td>3.5</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>4.0</td>
<td>0.90</td>
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</tr>
<tr>
<td>4.5</td>
<td>0.74</td>
<td>0.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Serviceability Index</th>
<th>Passenger Cars &amp; Pickup Trucks</th>
<th>Single Unit Trucks 2-S2 &amp; 3-S2 Semi's</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.40</td>
<td>1.67</td>
</tr>
<tr>
<td>1.5</td>
<td>1.97</td>
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</tr>
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<td>2.0</td>
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<tr>
<td>2.5</td>
<td>1.37</td>
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<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>4.0</td>
<td>0.86</td>
<td>0.95</td>
</tr>
<tr>
<td>4.5</td>
<td>0.76</td>
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</table>

<table>
<thead>
<tr>
<th>Serviceability Index</th>
<th>Passenger Cars &amp; Pickup Trucks</th>
<th>Single Unit Trucks</th>
<th>2-S2 &amp;3-S2 Semi-Trucks</th>
</tr>
</thead>
<tbody>
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<td>1.0</td>
<td>2.30</td>
<td>1.73</td>
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<td>1.5</td>
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<td>1.00</td>
</tr>
<tr>
<td>4.0</td>
<td>0.90</td>
<td>0.94</td>
<td>0.92</td>
</tr>
<tr>
<td>4.5</td>
<td>0.83</td>
<td>0.90</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 21. Use Related Depreciation Adjustment Factors for Roadway Surface Condition

<table>
<thead>
<tr>
<th>Serviceability Index</th>
<th>Passenger Cars &amp; Pickup Trucks</th>
<th>Single Unit Trucks</th>
<th>2-S2 &amp; 3-S2 Semi Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.14</td>
<td>1.33</td>
<td>1.32</td>
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<td>1.5</td>
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<td>1.15</td>
<td>1.14</td>
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<td>1.00</td>
</tr>
<tr>
<td>4.0</td>
<td>0.99</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>4.5</td>
<td>0.98</td>
<td>0.94</td>
<td>0.94</td>
</tr>
</tbody>
</table>

\[ TIR_{PS} = 2.64952 - .45619 \text{ PSI} \]
\[ MRP_{PS} = 2.58619 - .42952 \text{ PSI} \]
\[ DEP_{PS} = 1.15917 - .04333 \text{ PSI} \]

**Trucks:**

\[ OIL_{TR} = 1.22000 - .06000 \text{ PSI} \]
\[ TIR_{TR} = 1.74810 - .20476 \text{ PSI} \]
\[ MRP_{TR} = 2.31629 - .36129 \text{ PSI} \]
\[ DEP_{TR} = 1.39036 - .10786 \text{ PSI} \]

where all of the variables are defined as before.

### CALCULATION OF TIRE COSTS

The tire wear equations given above are used to calculate tire wear as a function of gross vehicle weight, vehicle speed, and present serviceability index. Two tire cost equations are given below, one for conventional tires and one for wide-base singles. These equations are used to adjust the equations based on Zaniewski's data for different numbers of tires and numbers of recaps per tire. The equation for tire cost for conventional tires, before adjusting for present serviceability index, is:

\[ TC = \frac{(Z \times T \times C)}{F} \]

where:

- \( TC \) = tire cost per 1,000 vehicle miles for a specific type of vehicle,
- \( Z \) = tire wear per 1,000 vehicle miles calculated using the equations developed in the preceding section, expressed
as a proportion of the total tire wear available from
the original tire and the standard number of recaps,

\[ T = \frac{[\text{original tire cost} + (\text{number of recaps per original}
    \text{ tire}) \times (\text{recap cost per tire})]}{\text{the number of conventional tires for this vehicle type,}} \]

\[ C = \frac{\text{an adjustment factor for adjusting the calculation when}
    \text{the number of recaps differs from the number of recaps}
    \text{assumed in Zaniewski.}}{1.8} \]

\[ F = \frac{[0.75 + 0.7 \times (\text{No. of Recaps})]}{2.5}. \]

For single-unit trucks, \( F = \frac{[0.75 + 0.7 \times (\text{No. of Recaps})]}{1.8}. \)

For combination trucks, \( F = \frac{0.75 + 0.7 \times (\text{No. of Recaps})}{2.5}. \)

In Zaniewski's tire wear calculations, it is assumed that 75 percent of the

tread rubber on the original tire is useable and that 70 percent of the

rubber on the recaps are useable. It is further assumed that single-unit

truck tires are recapped 1.8 times on average and that combination truck

conventional tires are recapped 2.5 times on average. The F factor in

the equation adjusts the tire wear when the user inputs a different

number of recaps than the number used by Zaniewski.

A slightly different equation is used for wide-base singles. This

equation assumes that the tire wear for wide-base singles is similar to

conventional radials and is proportional to the tread rubber on a wide-

base single as compared to two conventional radials.

\[ TC = \frac{(Z \times T \times C)(1/W)}{F} \]

where:

\[ TC = \text{tire cost per 1,000 vehicle miles for a specific type}
    \text{of vehicle,} \]

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Z = tire wear per 1,000 vehicle miles calculated using the equations based on Zaniewski tire wear, expressed as a proportion of the total tire wear available from the original tire and the standard number of recaps,

T = the number of wide-base single tires for this vehicle type,

C = [original tire cost + (number of recaps per original tire) x (recap cost per tire)],

W = (T_w x D_w)/(T_o x D_o), where T_w denotes the width of one wide-base single and T_o denotes the width of two conventional radial tires and where D_w is the tread depth of a wide-base single and D_o is the tread depth of a conventional radial tire.

F = an adjustment factor for adjusting the calculation when the number of recaps differs from the number of recaps assumed in Zaniewski.

EFFECTS OF TIRE TYPE ON FUEL CONSUMPTION

The fuel consumption equations apply for bias ply tires, and are assumed to be applicable for a tire pressure of 85 psi. Adjustments for tire type and tire pressure were developed from data in the literature. Several studies (33, 34, 35, 36) have been made on the effects of tire type on fuel consumption. Because wide-base single tires have been used more extensively in Canada than in the United States, more comparisons of conventional radials with wide-base singles have been made there. Several of these studies were reviewed in developing the estimates used in the computer program. Different results have been reported for winter
and summer conditions and also for different types of operation. The summer tests were judged to be more applicable to Florida conditions and are used in this study. In general, experimental tests tend to show more savings for wide-base singles than do field trials. Factors indicating fuel consumption relative to bias ply tires were developed based on the literature, and are stated in terms of the ratio to fuel consumption for bias-ply tires. A factor of 0.89, for example, indicates that a truck with wide-base singles is assumed to consume 89 percent as much fuel as a truck with bias-ply tires, at comparable speeds and gross vehicle weights. These factors usually were developed for trucks with a gross vehicle weight of approximately 60,000 pounds operating at a speed of about 50 to 60 miles per hour. It is assumed that these adjustments apply for all truck types, gross vehicle weights, and average vehicle speeds. The factors are as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias ply</td>
<td>1.00</td>
</tr>
<tr>
<td>Conventional radials</td>
<td>0.96</td>
</tr>
<tr>
<td>Low-profile radials</td>
<td>0.94</td>
</tr>
<tr>
<td>Wide-base radials</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**EFFECTS OF TIRE PRESSURE ON ROLLING RESISTANCE AND FUEL CONSUMPTION**

No research was found that directly related fuel consumption to tire pressure. However, several studies (33, 34, 35, 36, 37) have developed relationships between rolling resistance and tire pressure and these were used to develop an estimate of changes in fuel consumption for a specific tire pressure, denoted as tire pressure x, relative to a reference tire pressure of 85 psi, in the following steps. This calculation is made for a vehicle of a specific gross vehicle weight traveling at a specific speed, which is assumed to be the average highway
speed. All of the truck fuel consumption rates are for a tire pressure of 85 psi, so the following steps develop an adjustment for fuel consumption relative to 85 psi.

1. The rolling resistance coefficient is calculated twice, for the tire pressure \( x \) and for the reference tire pressure of 85 psi. This equation was developed for radial tires and is assumed to apply also to bias-ply tires and wide-base singles. The equation for calculating rolling resistance, \( RR \), is:

\[
RR = 0.001 \left( f_0 + \frac{f_1}{V^2} \right)
\]

where:

\[
f_0 = 27.136274 - 4.6961394 \log x,
\]

\[
f_1 = 0.0044467 - 0.0000189 x,
\]

\( V \) = speed in meters per second (= speed in miles per hour divided by 2.25), and

\( x \) = cold tire pressure in pounds per square inch (which is assumed to equal the hot tire pressure minus 10 psi).

2. Calculate DRRF, the change in rolling resistance force, in pounds, for tire pressure \( x \) relative to the reference tire pressure of 85 psi, using the following formula:

\[
DRRF = DRR \times GVW
\]

where DRR is the rolling resistance for tire pressure \( x \) minus the rolling resistance for the reference tire pressure of 85 psi, both of which are calculated using the formula given in Step 1 above, and GVW is the gross vehicle weight for the vehicle under consideration. (DRR will be negative when \( x \) is greater than 85 psi; this indicates that
DRRF also will be negative and the calculations in the following steps will lead to a negative change in fuel consumption.

3. Calculate DELTA, the estimated change in total brake horsepower required for the change in rolling resistance force for tire pressure x, compared to the reference tire pressure of 85 psi, at the given average vehicle speed.

\[ \text{DELTA} = (0.081 + 0.0035 \times S) \times \text{DRRF} \]

where DRRF is the value calculated in Step 2 above, S is the speed in miles per hour, and the term in parentheses is the unit change in brake horsepower required (DBHP) per unit change in rolling resistance force, which is estimated as \((0.081 + 0.0035 \times S)\), and is based on an empirical relationship developed from data in the literature.

4. Estimate DFUEL, the percent change in fuel consumed per change of one Brake Horsepower (BHP) required. DFUEL is based on empirical relationships and is calculated as follows:

- If \( S \leq 42.5 \text{ mph} \), \( \text{DFUEL} = 0.10 \times \frac{S}{42.5} \)
- If \( S \geq 62.5 \text{ mph} \), \( \text{DFUEL} = 0.40 \)
- If \( 42.5 < S < 62.5 \text{ mph} \), \( \text{DFUEL} = 0.10 + 0.3 \times \frac{(S - 42.5)}{20} \)

5. Calculate AFUEL, the proportionate reduction in fuel required for the tire pressure x as compared to the reference tire pressure of 85 psi.

\[ \text{AFUEL} = \frac{\text{DELTA} \times \text{DFUEL}}{100} \]

For example, if DELTA is -30 brake horsepower required and DFUEL is 0.2 percent per brake horsepower required, AFUEL would be \(-6/100\) or \(-0.06\), indicating that increasing from the reference tire pressure of 85 psi to a tire pressure x decreases fuel consumption by 6 percent.

6. The multiplier for fuel savings, MS, is calculated as follows:
M = 1.0 + AFUEL

In the example in Step 6, M = 1.0 + (-.06) = .94, indicating that fuel consumption at tire pressure x is 94 percent of fuel consumption at 85 psi, the tire pressure assumed in the fuel consumption equations given previously.

Calculations with these formulas indicate that trucks can reduce their fuel consumption considerably by increasing tire pressure. However, there may be adverse tire wear and safety effects from increasing tire pressure, and there are indications that most trucking firms follow tire manufacturer's recommended tire pressures because of safety considerations. No good data were located for estimating the effect of tire pressure on tire wear, tire blowouts, or highway safety. Therefore, it is recommended that the comparison of scenarios involving different tire pressures be made with caution, and these limitations be taken into consideration. It also should be recognized that this model assumes that the effects of tire pressure on fuel consumption is the same for wide-based singles as for conventional radials, since no data were available for developing separate equations for wide-based singles. Therefore, these equations are most applicable to scenarios that compare different tire pressures for conventional radials, especially for hot tire pressures between 85 psi and 135 psi.

CALCULATION OF PAVEMENT COSTS

The pavement costs are calculated for three components, the cost of overlays, the cost of level-ups, and the cost of routine maintenance. The equations for these calculations are given below.
\[
CMAN_Y = \frac{(CMANT + AMNT \cdot JY) \cdot LNN \cdot HLNG}{[1 + \frac{IDCT}{100}]^{Y-.5} \cdot 1000}
\]

\[
COLY_Y = \frac{[\frac{TOVIKL}{36}] \cdot \frac{WLN}{3} + \frac{[TOVIKL-DMIL]}{36} \cdot \frac{WSH}{3}]}{1000}
\]

\[
CLVL_Y = \frac{VOLINL \cdot TONS \cdot COVL}{[1 + \frac{IDCT}{100}]^{Y-.5} \cdot 1000}
\]

\[
CMTLN_Y = \frac{\frac{WLN}{3}}{[1 + \frac{IDCT}{100}]^{Y-.6} \cdot 1000}
\]

Where:

- \(CMAN_Y\) = Cost of Routine Maintenance in Year Y, (thous. $)
- \(COLY_Y\) = Cost of Overlay in Year Y, (thous. $)
- \(CLVL_Y\) = Cost of Level-Up in Year Y, (thous. $)
- \(CMTLN_Y\) = Cost of Milling in Year Y, (thous. $)
- \(CMANT\) = Cost of Routine Maintenance, first year after overlay of beginning of analysis period, per lane mile
- \(AMNT\) = Annual Increment in Routine Maintenance Costs per lane mile
- \(JY\) = Number of Years for Annual Increment
- \(LNN\) = Number of Lanes
- \(HLNG\) = Length (miles)
- \(IDCT\) = Discount Rate in percent
- \(DMIL\) = Depth of Milling in inches
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOVIKL</td>
<td>Overlay thickness in inches</td>
</tr>
<tr>
<td>WLN</td>
<td>Width of Travel Lanes of Highway in feet</td>
</tr>
<tr>
<td>WSH</td>
<td>Width of Paved Shoulders of Highway in feet</td>
</tr>
<tr>
<td>TONS</td>
<td>Number of Tons of Compacted Asphaltic Concrete per Compacted Cubic Yard</td>
</tr>
<tr>
<td>COVL</td>
<td>Cost of Overlay per Ton of Asphaltic Concrete</td>
</tr>
<tr>
<td>VOLIKL</td>
<td>Volume of Level-Up in cubic yards</td>
</tr>
<tr>
<td>CMIL</td>
<td>Cost of Milling per square yard</td>
</tr>
</tbody>
</table>
CHAPTER 8. SUMMARY

The preceding chapters have presented the different analytical models comprising the Florida Comprehensive Pavement Analysis System. This project level analysis package was developed to assist the Florida DOT in evaluating the effects of different forecasted truck characteristics and truck use on flexible pavement performance and life-cycle costs. The essential features of this comprehensive pavement analysis system are summarized as follows:

1. A load shift algorithm is used to predict the shift in gross vehicle and axle weight distributions due to a change in legal load limits. The shift in axle weight distribution influences the predicted 18-kip ESAL's for the current and alternate scenarios defined by the user, and thus, the predicted performance and pavement costs, as well as the estimated user costs.

2. The effects of heavy vehicle characteristics and initial surface roughness on flexible pavement performance are evaluated through the vehicle dynamic loads predicted using the simulation model developed in this study. This model, which was also verified in the research project, is used in Florida COMPAS to predict vehicle dynamic load profiles for different vehicle characteristics such as suspension properties, tire spring rates, wheelbases, static axle loadings, and inertial properties, as well as for different levels of pavement surface roughness. The predicted dynamic
load profiles are in turn used by the load equivalency program in Florida COMPAS to adjust load equivalency factors for dynamic load effects.

3. The program for evaluating load equivalency factors uses damage equations developed for Florida that consider, among other factors, the effects of tire type and tire inflation pressure on pavement service life. These damage models were developed using the finite element program, FLEXPASS, developed for Florida in an earlier study. The effect of tire construction on predicted pavement performance was considered through application of a finite element tire model to predict contact pressure distributions for different tire inflation pressures, tire loads, and tire types. Conventional radial, bias-ply, and wide-base radial tires were considered in the study. The predicted contact pressure distributions from the tire model were then used to establish the nodal forces that were input to the FLEXPASS computer program. In this way, the effects of inflation pressure and tire type were included in the development of the damage equations for Florida.

4. The load equivalency factors calculated by the load equivalency program are used, in conjunction with information on average daily traffic provided by the user, to determine the daily 18-kip ESAL's for the first year of the analysis period. This is done during the execution of the ESAL18 program in Florida COMPAS. The possible increase in 18-kip
ESAL's during the analysis period is accounted for through a traffic growth rate specified by the user.

5. The performance of the pavement during the analysis period is evaluated using the damage equations developed for Florida, or through a combined application of the damage equations and the FLEXPASS computer program. The user has the option, in Florida COMPAS, of using FLEXPASS to evaluate pavement performance up to the time of the initial overlay. Thereafter, the damage equations are used to predict fatigue cracking, rutting, and serviceability loss for the overlaid pavement.

6. The overlay design procedure uses fatigue cracking, rutting, and serviceability loss as criteria for establishing the timing of the initial overlay. Thereafter, reflection cracking is also used in determining when succeeding overlays need to be placed. The thickness design of overlays based on reflection cracking is accomplished using the Overlay Design Equations developed in a previous FHWA study.

7. The predicted PSI histories, as well as the number and thicknesses of overlays that have to be placed, and the estimated quantities of level-up, are used by the cost analysis program to estimate pavement costs, and user costs throughout the analysis period. User costs attributed to vehicle depreciation, oil consumption, tire wear, vehicle maintenance, and user travel time are calculated and adjusted for the effects of PSI by the program. Future costs are
converted to equivalent present worth costs using the
discount rate specified by the user. For each scenario
analyzed, a summary of pavement and user costs is provided
that shows the potential cost impact of forecasted changes in
truck characteristics and truck use.

The system developed in this study is expected to be a useful tool
to the Department in developing rational policies to cope with
anticipated changes in truck and tire technology for the years to come.
REFERENCES


27. Uzan, J., "Documentation of Texas Flexible Pavement Design System," Texas Transportation Institute, Texas A&M University, College Station, Texas, 1987.


APPENDIX A

RESULTS OF COMPARISONS BETWEEN TFP AND PHASE 4
TPF vs. Phase 4
Tractor-Semitrailer, 30 mph, Site 4
Leading Drive Axle on Tractor Tire Forces

LEGEND
--- TFP
--- PHASE 4

TPF vs. Phase 4
Tractor-Semitrailer, 30 mph, Site 4
Leading Axle on Semitrailer Tire Forces

LEGEND
--- TFP
--- PHASE 4
TFP vs. Phase 4

Tractor-Semitrailer, 60 mph, Site 4
Leading Drive Axle on Tractor Tire Forces

Legend:
- TFP
- PHASE 4

TFP vs. Phase 4

Tractor-Semitrailer, 60 mph, Site 4
Leading Axle on Semitrailer Tire Forces

Legend:
- TFP
- PHASE 4
TFP vs. Phase 4
Tractor-Semitrailer, 30 mph, Site 6
Leading Drive Axle on Tractor Tire Forces

Legend:
- --- TFP
- --- PHASE 4

DISTANCE [FT]

TFP vs. Phase 4
Tractor-Semitrailer, 30 mph, Site 6
Leading Axle on Semitrailer Tire Forces

Legend:
- --- TFP
- --- PHASE 4

DISTANCE [FT]
TFP vs. Phase 4
Tractor-Semitrailer, 60 mph, Site 6
Leading Drive Axle on Tractor Tire Forces

LEGEND

- - TFP
----- PHASE 4

TFP vs. Phase 4
Tractor-Semitrailer, 60 mph, Site 6
Leading Axle on Semitrailer Tire Forces

LEGEND

- - TFP
----- PHASE 4
APPENDIX B

COMPARISON OF TIRE FORCE PREDICTIONS FROM TFP WITH EXPERIMENTAL DATA
TFP vs. Experimental Data

Straight Track, 60 mph, Site 4
Drive Axle Tire Forces

LEGEND

- EXP
- TFP
TFP vs. Experimental Data
Tractor-Semiutrailer, 10 mph, Site 6
Leading Drive Axle on Tractor Tire Forces

LEGEND

\[ \text{exp} \]

\[ \text{TFP} \]

TFP vs. Experimental Data
Tractor-Semiutrailer, 10 mph, Site 6
Leading Axle on Semiutrailer Tire Forces

LEGEND

\[ \text{exp} \]

\[ \text{TFP} \]
TFP vs. Experimental Data
Straight Truck, 10 mph, Site 6
Drive Axle Tire Forces

TFP vs. Experimental Data
Straight Truck, 40 mph, Site 6
Drive Axle Tire Forces
APPENDIX C

EVALUATION OF THE SIOMETER AS A DEVICE FOR MEASUREMENT OF PAVEMENT PROFILES
INTRODUCTION

Pavement roughness is the principal determinant of riding quality as perceived by the road user. In order to provide roads that offer a smooth and comfortable ride, a transportation agency requires measurement techniques for quantifying pavement surface roughness. This appendix presents the findings from an evaluation made of a profile measuring device known as the Siometer. This device, developed by Dr. Roger Walker of the University of Texas at Arlington, is used by the Texas State Department of Highways and Public Transportation (SDHPT) for evaluating the riding quality of pavement sections in the state.

In this study, pavement surface profiles measured with the Siometer were compared with those determined from the Surface Dynamics Profilometer (SDP). Over the years, the Profilometer has gained wide acceptance as a device for evaluating pavement profiles. It is classified as a Class 2 instrument by the World Bank (C1) for the measurement of the International Roughness Index.

The Surface Dynamics Profilometer was designed by General Motors and built by K. J. Law Engineers in 1967. Originally, it had, as primary sensors, two accelerometers and two linear potentiometers connected to road-following wheels. The accelerometers determine the amount and direction of vertical acceleration undergone by the vehicle while the potentiometers and wheels measure the distance from the vehicle body to the road surface. A profile measurement is calculated by summing the double integral of the accelerometer signal and the displacement signal from the potentiometer (C2). In the latest version of this device, the
potentiometers and road following wheels have been replaced by non-
contact sensors.

The SDP is capable of measuring profiles of considerable accuracy
and consistency at normal highway speeds without the need for
calibration. It has been used as a reference device for measurement of
Present Serviceability Index (PSI) within the Texas SDHPT. The principal
statistic currently used by the Department in computing PSI from profile
data is the root-mean-square vertical acceleration (C3).

Although the Profilometer provides a fairly rapid and accurate
method of determining pavement profiles from which various roughness
statistics can be computed, it requires a high initial capital outlay and
is relatively expensive to operate. Consequently, many state
transportation agencies generally use response-type road roughness
measuring devices, such as the Mays meter, for collecting roughness data
on a network-wide basis. However, such devices require periodic
calibration which often entails significant effort. What is clearly
needed is a device that can be used to collect fairly accurate and
consistent profile data at normal highway speeds, that is relatively
inexpensive to own and operate, and does not require difficult
calibration procedures. A device that has the potential of offering all
of these advantages is the Siometer. The applicability of this device
for measuring pavement profiles is evaluated herein.

THE SIOMETER

The development of the Siometer was initiated by Walker during the
early 1970's. A unique feature of this device is the statistical
modeling procedure for characterizing the vehicle on which it is
installed. Through this procedure, the influence of the vehicle on the
measurement process is identified and removed (C4, C5). The statistical
model is parameterized with the Siometer's on-board microcomputer using
vertical accelerations of the vehicle measured at fixed distances as the
vehicle is driven down the road. Vertical accelerations are obtained
from an accelerometer that is housed in a small case and installed in the
trunk of the vehicle. Once the parameters of the vehicle are determined,
the Siometer is said to be "calibrated" and ready for profile
measurements. The vehicle is then driven over the roadway sections for
which profiles are to be determined and the resulting accelerations are
measured. The differences between the actual measurements and those
predicted from the statistical model are used to estimate the road
profile by integrating the acceleration differences with the time between
successive samples.

The primary application of the Siometer within the Texas SDHPT is
for evaluation of riding quality. Thus, the device became known as the
Siometer since its primary output is the Serviceability Index (SI) for a
particular pavement section even though the SI is calculated using
statistics derived from the predicted road profile. The device is
portable and can be easily transferred from one vehicle to another.
Furthermore, since it implements a self-calibration procedure, the
device, in theory, can be installed in any vehicle since the vehicle's
influence is modeled in the process.

The current version of the Siometer used by the Texas SDHPT is the
R680 system manufactured by Micro-sher Incorporated. The R680 system
consists of three components, namely: 1) a sensor unit; 2) a main control module; and 3) a lap-top computer for storing the results. The system computes and displays serviceability index and predicts the pavement profile. The sensor unit and the main control module cost $20,000 at the time of this report. The lap-top computer can be purchased separately by the user from any other vendor.

The sensor unit includes the accelerometer and a distance measuring signal. The accelerometer is housed in a small case which is weighed down with a sandbag and mounted vertically inside the trunk of the vehicle, where it measures the vertical acceleration. The signal from the accelerometer is transmitted to the main control module where it is digitized in accordance with the distance signal and processed.

The main control module contains two Motorola 68000 microprocessors working in parallel. One performs input/output operations and the other performs numerical computations.

The data storage component is a portable lap-top computer. A communications program provides the interface between the control module and the lap-top computer. This program and the personal computer provide the means of obtaining continuous SI and/or profile measurements. The entire Siometer system is portable and can be easily installed in most standard vehicles.

An enhanced version has also been developed that implements the South Dakota method of measuring longitudinal profiles. The South Dakota profiler, currently considered by many to be a Class 2 instrument, is becoming a popular device for measuring pavement profiles. This device measures pavement profile elevations by the use of an accelerometer and
acoustic sensors, which perform the same function as the laser probes in the Profilometer. The South Dakota profiler differs from the Profilometer in this respect and also in the procedure used for integrating the accelerometer signal. The current version of the device measures longitudinal profile elevations at the inner wheelpath and also provides estimates of pavement rutting using data from the acoustic sensors. At present, the roll of the vehicle is not considered in the determination of pavement rutting although numerous tests indicate reasonable agreement between rut depth data obtained manually, and rut depth estimates from the profiler. Because the Siometer can easily implement the South Dakota profiler concept by the simple installation of acoustic sensors in the test vehicle, it has recently been upgraded for this purpose and is undergoing evaluation by the Texas SDHPT. In addition, the possibility of using additional accelerometers in conjunction with up to 5 acoustic sensors, to identify the influence of vehicle roll, is being considered. This will require modifications to the Siometer hardware but consideration of vehicle roll will provide the Texas SDHPT with the capability of measuring transverse pavement profiles in addition to longitudinal profiles.

EVALUATION OF PAVEMENT PROFILES MEASURED FROM THE SIOMETER

In order to evaluate the applicability of the Siometer for profile measurements, the Surface Dynamics Profilometer (SDP) was used as a reference. In this evaluation, nine bituminous test sections were selected on which profile measurements using the Profilometer and the Siometer were made. Three of the tests sections were smooth, three were
rough, and the other three were intermediate. All sections were 0.2 miles in length. The serviceability indices calculated from the SDP profiles on the nine selected sections are shown in Table 1. All sections, with the exception of TC7 in Tarrant County, are located within the general vicinity of Austin, Texas.

The pavement profiles of the nine sections were measured using the Profilometer and Siometer of the Texas SDHPT. The Department's Profilometer is similar in design to that originally built by K. J. Law except that the potentiometer/road-following wheel combination has been replaced with two non-contact Selcom laser probes. This has reduced maintenance problems associated with the mechanical road-following wheels and has allowed profile measurements to be conducted at faster highway speeds. In addition, data acquisition and processing capability was upgraded to take advantage of improvements in hardware technology and thus allow data reduction to be conducted in the field. Consequently, roughness statistics and profile data can now be obtained as soon as a run is completed on a particular highway segment.

For each test section selected, two profile measurements were obtained from each device. Profile elevations were taken at 0.50 ft. intervals along each 0.2 mile section. Since the Siometer is portable, the device was installed inside the Profilometer van. This allowed profile measurements to be made simultaneously on both devices for any given run, thus eliminating errors associated with run-to-run variations, such as differences in wheelpaths tracked between runs, differences in vehicle track widths, and differences in starting times between profile measurements. All measurements were taken at 20 miles/hour in an attempt
to traverse the same wheelpaths each time a run was made on a particular section. On two of the rough sections (Sections 1 and 4), yellow dots painted at regular intervals on the wheelpaths were used to guide the direction of travel between runs.

In order to establish a bench mark for evaluating Siometer profiles, a comparison of the profiles from repeat runs of the Profilometer was initially made. Figure C1 compares measured left wheelpath profile elevations from repeat runs of the Profilometer on Section 1. The correlation coefficient 'r' between the measured profile elevations was determined to be 0.985 as shown in Figure C1, with a standard error of the estimate of approximately 91 mils. Similarly, standard errors of estimate and correlation coefficients between measured profile elevations from repeat runs of the Profilometer on the other test sections were calculated. The results are summarized in Table C2.

The correlation coefficients and standard errors of estimate shown in Table C2 were compared with the corresponding statistics calculated using Siometer and SDP profile elevations measured during a given run (Table C3). In general, the correlation coefficients between SDP and Siometer profiles taken during the same run are comparable with the correlation coefficients between corresponding SDP replicate runs. In addition, for 6 of the 9 test sections (i.e., Sections 1, 7, 12, 40, 42, and TC7), the standard errors of estimate calculated using SDP and Siometer profiles are somewhat better than those calculated using SDP replicate profiles. Figures C2, C3, and C4 illustrate the generally favorable agreement obtained between SDP and Siometer profiles for data measured from the left wheelpaths of Sections 1, 7, and 40 respectively.
An overall measure of the agreement between Siometer and SDP profile elevations was obtained by calculating the overall correlation coefficient between measured profile elevations from the two devices. Figure C5 shows a comparison of all measured profile elevations from the Siometer with the corresponding profile elevations from the Profilometer. The overall correlation coefficient between measured profiles taken during the same run from the two devices was determined to be 0.971 as indicated in Figure C5. This is slightly greater than the overall correlation coefficient of 0.960 between profile elevations from repeat runs of the Profilometer. In addition, the overall standard error of the estimate between corresponding profile elevations from the Siometer and the Profilometer was calculated to be approximately 90 mils. The same statistic calculated using corresponding profile elevations from repeat Profilometer runs was determined to be approximately 107 mils.

The slightly lower correlation coefficient between profile elevations from repeat Profilometer runs and the higher standard error of the estimate obtained are largely attributed to variations in wheelpaths tracked between runs of the instrument. It is also likely that differences in starting times between repeat runs would have contributed to the slightly higher variation between corresponding profile elevations from the Profilometer. However, to compensate for the effect of this factor, the Profilometer profiles from repeat runs were initially lined-up prior to the calculation of the statistics presented. This was done through cross-correlation analysis wherein profiles from repeat Profilometer runs were shifted relative to each other until a maximum cross-correlation was obtained.
The close agreement between SDP and Siometer profiles taken under identical operating conditions lends credibility to the Siometer's approach for estimating pavement profiles. The essential element of this technique is the self-calibration scheme for parameterizing the statistical model of the vehicle on which the device is installed. The calibrated statistical model provides a way of separating the vehicle contribution, to the measured vertical accelerations, from the input attributable to the road profile. In essence, the road profile is estimated from integration of the differences between measured accelerations and those predicted from the statistical model. For this study, the right and left sides of the Profilometer van were modeled differently so that the statistical models for the right and left wheelpaths were different.

In estimating pavement profiles with the Siometer, measured accelerations from the accelerometers mounted inside the Profilometer van were used in the computations. Thus, the operating conditions under which the SDP and Siometer profiles were taken were as close to being completely identical as can be arranged. In this way, the comparisons between the SDP and Siometer profiles clearly demonstrate the degree of capability of the Siometer's method of measuring pavement profiles. Judging from the results obtained, the Siometer's approach, based on measured vertical accelerations coupled with a statistical model of the vehicle, leads to profiles which are comparable to those obtained from the Profilometer, which is based on measured vertical accelerations and the use of non-contact probes (lasers) for determining the distance between the vehicle and the ground at any given time.
EVALUATION OF PROFILE POWER SPECTRA

The comparison of measured profiles between the SDP and Siometer forms a basis for evaluating the applicability of the Siometer as a device for measuring pavement profiles. However, the evaluation should not stop here since differences in the frequency content of two pavement profiles may exist that are not readily apparent from a visual examination of the measured profiles. One can picture pavement profiles as consisting of the sum of a variety of waveforms of different frequencies and amplitudes. Waveforms of low frequencies or long wavelengths may be identifiable from a visual examination of a particular pavement profile. However, the high frequency components will in all likelihood be masked because of the scales involved. Consequently, in order to obtain complete information on the frequency content of a particular pavement profile, its power spectrum must be evaluated through spectral analysis. A power spectrum is a graph of the frequency (as the abscissa) versus the power, which is the square of the amplitude of each frequency. In this way, the dominant frequencies or wavelengths within the profile can be identified. In addition, by comparing the characteristics of two profiles in the frequency domain, the similarity in the waveform composition of the two profiles can be evaluated.

With the above in mind, a spectral analysis was conducted to determine the frequency or power spectra of the measured SDP and Siometer profile elevations. Figures C6 and C7 illustrate the power spectra determined for the left wheelpath profiles of Sections 1 and 7 respectively. The higher the power at a given frequency, the more
dominant are the waveforms of that particular frequency within a given pavement profile.

The results shown in Figures C6 and C7 are typical of those that were obtained for all of the other profiles and illustrate the reasonable agreement between the power spectral densities of corresponding SDP and Siometer profile elevations. In these figures, the power spectral density (PSD) is expressed in db units, defined herein as \(10 \times \log_{10}(\text{amplitude squared per cycle per foot})\). In order to evaluate the agreement between SDP and Siometer power spectral densities, the overall correlation coefficient between the PSD’s was determined. Figure C8 compares the PSD’s of Siometer profile elevations with the corresponding PSD’s of SDP profile elevations. Power spectral densities determined from SDP and Siometer profiles taken during the same run were compared.

The overall correlation coefficient between SDP and Siometer power spectral densities was determined to be 0.990. This value compares favorably with the overall correlation coefficient of 0.993 between the PSD’s of profile elevations from repeat Profilometer runs.

In addition, a root-mean-square statistic that provides an overall measure of the match between the amplitudes of SDP and Siometer power spectra was calculated from the following expression:

\[
RMSD = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - Y_i')^2}{n}}
\]

(C1)

where,

\(RMSD\) = root-mean-square deviation, mils

\(Y_i\) = SDP amplitude, mils
Y'i = Siometer amplitude, mils

n = number of observations

Using the above expression, the RMSD associated with the Siometer power spectra was determined to be 2.46 mils with 2340 observations. A similar statistic calculated from the power spectra between repeat SDP runs was found to equal 3.87 mils with 1170 observations. On the average therefore, the amplitudes of the waveforms associated with Siometer profile elevations deviated from the amplitudes of the corresponding SDP waveforms by approximately 2.5 mils. Similarly, the amplitudes of the waveforms from repeat runs of the Profilometer differed, on the average, by about 4 mils. The higher RMSD obtained between amplitudes of power spectra from repeat Profilometer runs is again indicative of the effects of variations in wheelpaths tracked between runs of the instrument. Judging from the statistics presented, it is evident that the Siometer power spectra compares favorably with the corresponding SDP power spectra.

However, while this may be true, the statistics presented only provide an overall measure of the agreement between SDP and Siometer profiles. It is also important to evaluate the agreement between profiles frequency-by-frequency. Consequently, the correlation coefficients and RMSD's were also compared frequency-by-frequency.

Figure C9 shows the correlation coefficients across the frequency domain, between PSD's from repeat Profilometer runs, and between PSD's from corresponding Siometer and Profilometer runs. Figure C10 shows the RMSD's. It is generally observed that the Siometer power spectra compares favorable with the SDP power spectra. However, at a frequency
of 0.125 cycles/foot (about 3.7 hertz at 20 miles/hour), the agreement is not as good compared with the other frequencies. At 0.125 cycles/foot, the correlation coefficient between Siometer and profilometer PSD's drops to about 0.65 as observed from Figure C9. This result suggests that a fundamental response frequency of the vehicle has not been removed and that a need exists for fine-tuning the procedure to parameterize the statistical model of the vehicle so that better agreement between the power spectra of Siometer and Profilometer profile elevations may be achieved within the entire frequency range.

EVALUATION OF LOAD PROFILES PREDICTED FROM SIOMETER ROAD PROFILES

Pavement surface roughness affects the vehicle dynamic loadings that are imparted to the pavement. Consequently, it is also appropriate to compare the load profiles associated with SDP and Siometer pavement profiles. After all, the dynamic loadings produced will affect pavement service life, and it is of value to know how the predicted dynamic load profiles differ from each other. This would provide another basis for judging the acceptability of the Siometer as a device for profile measurements.

A vehicle simulation program developed at Texas A&M University was used to predict the dynamic loadings produced by a given vehicle running over the measured SDP and Siometer profiles. The vehicle modeled was a tractor-semitrailer (3-S2) combination with a 12,000-pound steering axle load and a 34,000-pound tandem axle load on each of the drive and trailer axles. The measured profiles for Sections 1 and 7 were used in the
analysis. Two different vehicle speeds, 45 and 27 miles/hour were used in the simulation.

Figure C11 compares axle loads predicted using profiles from repeat SDP runs on Sections 1 and 7. In the simulation, dynamic axle loads were evaluated at 0.50 ft. intervals along a given section, for all five axles of the tractor-semitrailer combination. The overall correlation coefficient between axle loads associated with profiles from repeat SDP measurements was found to be 0.990.

Similarly, dynamic axle loads predicted using Siometer profiles were compared with those predicted using corresponding SDP profiles. Figure C12 compares the axle loads evaluated using profiles from the two devices. In this instance, the overall correlation coefficient between dynamic axle loads was found to be 0.952. This compares favorably with the overall correlation coefficient of 0.990 between axle loads associated with profiles from repeat SDP measurements. In addition, the root-mean-square of the deviations between dynamic axle loads predicted from SDP and Siometer profile elevations was determined to be 986 lbs. with 82,160 observations. This statistic was determined using Equation (Cl) with $Y_i$ being the dynamic axle load predicted using SDP profile elevations and $Y'_i$ the dynamic axle load associated with Siometer profiles. A similar statistic calculated between dynamic axle loads predicted using replicate SDP profiles was found to equal 446 lbs. with 41080 observations. On the average therefore, the dynamic axle loads associated with Siometer profiles differed from the corresponding axle loads associated with SDP profiles by 986 lbs. This is 8.2 percent of the nominal static axle load of 12,000 lbs. on the steering axle of the
vehicle used in the simulation, and approximately 5.8 percent of the nominal static axle load of 17,000 lbs. on each axle of the drive and trailer tandems. The results therefore indicate reasonable agreement between SDP-based and Siometer-based dynamic axle loads.

The power spectra of the predicted dynamic loads were also evaluated to check the degree of similarity in the frequency content of the SDP and Siometer load profiles. Figures C13 and C14 illustrate the load power spectral densities associated with the two devices for profile measurements made on Section 1. The load power spectral densities were determined using the predicted dynamic axle loads for the lead axles of the drive and trailer tandems, at a simulation speed of 45 miles/hour. As seen from the figures, there is good agreement between the load PSD's associated with SDP and Siometer profiles.

In order to evaluate the agreement between SDP and Siometer load power spectral densities, the overall correlation coefficient between PSD's was determined. Figure C15 compares the load power spectral densities associated with SDP and Siometer profiles. An overall correlation coefficient of 0.982 was determined, as indicated in the figure. This compares favorably with the overall correlation coefficient of 0.997 between power spectral densities associated with repeat SDP profile measurements.

In addition, the root-mean-square of the deviations between the amplitudes of SDP and Siometer load spectra was determined to be 29.58 lbs. with 2600 observations. A similar statistic between the amplitudes of load spectra associated with repeat SDP profile measurements was found to equal 12.68 lbs. with 1300 observations. Consequently, the amplitudes
of the waveforms associated with the Siometer and Profilometer load power
spectra differ on the average by about 30 lbs. Similarly, the amplitudes
of the waveforms associated with load power spectra from replicate SDP
profiles differ on the average by about 13 lbs. These figures suggest
that the Siometer-based load power spectra matches fairly with the
corresponding SDP-based load spectra.

The similarity in the load spectra associated with SDP and Siometer
profile measurements was also evaluated frequency-by-frequency. Figure
C16 compares the correlation coefficients between replicate load PSD’s
associated with repeat Profilometer runs, with the correlation
coefficients between load PSD’s associated with Siometer and Profilometer
roughness measurements. The trends observed are similar to those in
Figure C9 which shows the correlation coefficients, across the frequency
domain, between power spectral densities of SDP and Siometer profile
elevations. It is observed that the correlation coefficients across the
frequency domain between SDP and Siometer load power spectral densities
are generally acceptable. However, at a frequency of 0.125 cycles/foot,
the correlation coefficient drops slightly below 0.50. This drop
coincides with the decrease, at this same frequency, in the correlation
coefficient between PSD’s of SDP and Siometer profile elevations (see
Figure C9). This result again points to a need for refining the vehicle
modeling procedure on which the Siometer is based.

CONCLUSIONS

From the results of the evaluation conducted, the following findings
are noted:
1. From an examination of the pavement profiles obtained from the same run, there is close agreement between SDP and Siometer profiles. This finding suggests that for practical purposes, the Siometer can show just as well as the Profilometer can, where the "rough spots" are on a particular stretch of highway.

2. From a comparison of predicted load profiles, Siometer profiles can reasonably be used in conjunction with a vehicle simulation program, for identifying which portions of a given highway segment are likely to be subjected to severe dynamic loadings.

3. From the spectral analysis of SDP and Siometer profile elevations, it was generally observed that the Siometer power spectra compare favorably with the SDP power spectra. However, at a frequency of 0.125 cycles/foot, the correlation coefficient between power spectral densities of SDP and Siometer profile elevations drops to approximately 0.65, indicating a need for fine-tuning the vehicle modeling procedure on which the Siometer is based.

4. From the spectral analysis of dynamic axle loads associated with SDP and Siometer profiles, reasonable agreement between computed load PSD's was observed. The results also suggest that improving the correlation between power spectral densities of SDP and Siometer profile elevations at 0.125 cycles/foot will lead to better agreement between SDP and Siometer load PSD's within the entire frequency spectrum.

Overall, the results obtained are promising and has shown the potential of the Siometer as an economical, practical, and useful device for collecting profile data on a network-wide scale. Future measurements
using the Siometer and the Profilometer are planned to get more data to further verify the acceptability of the Siometer as a device for profile measurements. Plans include measurements on Portland cement pavement sections and re-evaluation of the parameterization procedure for modeling the vehicle in the measurement process.

REFERENCES


Table CI. Test sections where profile measurements were collected.

<table>
<thead>
<tr>
<th>Section</th>
<th>Location</th>
<th>Present Serviceability Index (PSI)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Decker Lake Road West, approximately 0.2 miles west of FM 973</td>
<td>1.87</td>
</tr>
<tr>
<td>4</td>
<td>Decker Lake Road East, approximately 0.3 miles west of FM 973</td>
<td>1.30</td>
</tr>
<tr>
<td>7</td>
<td>U.S. 183 South, 1.5 miles north of Burleson Road</td>
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</tr>
<tr>
<td>12</td>
<td>U.S. 183 North, 1.1 miles north of Burleson Road at one-way sign at cross-over north of creek</td>
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<td>21</td>
<td>Pearce Lane West, approximately 0.9 miles east of FM 973</td>
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</tr>
<tr>
<td>31</td>
<td>FM 685 North, approximately 0.2 miles north of Phillips 66 gas station</td>
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</tr>
<tr>
<td>40</td>
<td>FM 973 South, 0.56 miles south of Schmidt Lane</td>
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</tr>
<tr>
<td>42</td>
<td>FM 3177 South, at Texas Heritage Center sign</td>
<td>4.01</td>
</tr>
<tr>
<td>TC7</td>
<td>U.S. 183 frontage road, west bound, near intersection with U.S. 157, in Tarrant county, north of Arlington</td>
<td>3.36</td>
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</table>

* average PSI from 2 SDP runs on section
Table C2. Correlation coefficients and standard errors of estimate between repeat Profilometer measurements.

<table>
<thead>
<tr>
<th>Section</th>
<th>Wheelpath</th>
<th>Correlation Coefficient</th>
<th>Standard Error of Estimate (mils)</th>
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<td>left</td>
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<td>70</td>
</tr>
<tr>
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<td>0.936</td>
<td>70</td>
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<td>21</td>
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<td>168</td>
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Table C3. Correlation coefficients and standard errors of estimate between Profilometer and Siometer measurements taken during the same run.

<table>
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<th>Section</th>
<th>Run Number</th>
<th>Wheelpath</th>
<th>Correlation Coefficient</th>
<th>Standard Error of Estimate (mils)</th>
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Table C3. Correlation coefficients and standard errors of estimate between Profilometer and Siometer measurements taken during the same run. (continued)

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<th>Section</th>
<th>Run Number</th>
<th>Wheelpath</th>
<th>Correlation Coefficient</th>
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<td>0.937</td>
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<td></td>
<td>0.990</td>
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<tr>
<td>40</td>
<td>1 right</td>
<td></td>
<td>0.987</td>
<td>94</td>
</tr>
<tr>
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Figure C1. Comparison of left wheelpath profile elevations from repeat runs of the Profilometer on Section 1.

N = 2198 OBS
r = 0.985
Figure C2. Comparison of profile elevations measured with the SDP and the Siometer for the left wheelpath of Section 1 (run 1).
Figure C3. Comparison of profile elevations measured with the SDP and the Siometer for the left wheelpath of Section 7 (run 1).
Figure C4. Comparison of profile elevations measured with the SDP and the Siometer for the left wheelpath of Section 40 (run 1).
Figure C5. Comparison of Siometer profile elevations with SDP profile elevations.
Figure C6. Power spectra of pavement profiles measured with the SDP and the Siometer for the left wheelpath of Section 1 (run 1).
Figure C7. Power spectra of pavement profiles measured with the SDP and the Siometer for the left wheelpath of Section 7 (run 1).
Figure C8. Comparison of power spectral densities of Siometer profile elevations with the power spectral densities of SDP profile elevations.
Figure C9. Correlation coefficients between roughness power spectral densities across frequency domain.
Figure C10. Root-mean-square deviations between amplitudes of profile spectra across frequency domain.
Figure C11. Comparison of dynamic axle loads predicted using replicate SDP profile measurements.

N = 41,080 OBS
r = 0.990
Figure CI2. Comparison of dynamic axle loads predicted using Siometer profiles with dynamic axle loads predicted using SDP profiles.

N = 82,160 OBS
r = 0.952
Figure C13. Power spectra of dynamic axle loads associated with profiles measured with the SDP and the Siometer on Section 1 (run 1), for the leading axle of the tractor drive tandem assembly.
Figure C14. Power spectra of dynamic axle loads associated with profiles measured with the SDP and the Siometer on Section 1 (run 1), for the leading axle of the trailer tandem assembly.
Figure C15. Comparison of load power spectral densities associated with Siometer and SDP profiles.

N = 2600 OBS
r = 0.982
Figure C16. Correlation coefficients between load power spectral densities across frequency domain.