DOT/FAA/TC-17/28

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Development of New Subgrade Failure Model for Flexible Pavements in FAARFIELD

May 2017

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-17/28		

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF NEW SUBGRADE FAILURE MODEL FOR FLEXIBLE PAVEMENTS IN FAARFIELD	May 2017
	6. Performing Organization Code
7. Author(s) Izydor Kawa	8. Performing Organization Report No.
9. Performing Organization Name and Address CSRA 1201 New Road, Suite 242 Linwood, NJ 08221	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Airport Engineering Division 800 Independence Ave., SW Washington, DC 20591	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code AAS-100

15. Supplementary Notes

The Federal Aviation Administration Aviation Research Division COR was Jeffrey Gagnon.

16. Abstract

In November 2016, the United States Federal Aviation Administration (FAA) released an updated version of its standard computer program for airport pavement thickness design and evaluation, FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD). The new version, FAARFIELD 1.41, contains a number of changes with respect to the modeling and design of flexible pavements. This report documents improvement to the method of assigning modulus values to aggregate base and subbase layer materials in FAARFIELD. It also documents the development of a new flexible failure model relating computed subgrade vertical strain to the number of coverages of the aircraft gear corresponding to expected structural failure of the flexible pavement. In this revised failure model, the logarithm of coverages to failure is defined mathematically as a Bleasdale function of vertical strain when failure coverages are equal to or greater than 1000. For coverages less than 1000, the failure model follows a linear tangent line to the Bleasdale curve. The parameters of the Bleasdale failure model were derived analytically by making use of the alpha factor curves for four- and six-wheel aircraft gears incorporated in the FAA's COMFAA computer program, and the resulting design model was compared to full-scale traffic tests from the FAA National Airport Pavement Test Facility (NAPTF). Data are presented to show that the new model is generally less conservative than the previous (FAARFIELD 1.3) model and provides a better fit to observed failure data, in particular at higher traffic coverage levels.

17. Key Words	18. Distribution Statement
FAARFIELD, Flexible pavement design, Layered elastic design, National Airport Pavement Test Facility	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	51	

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

2D	Four-wheel (dual-tandem) gear configuration
3D	Six-wheel (double dual-tandem) gear configuration
AC	Advisory Circular
ACN	Aircraft classification number
CBR	California Bearing Ratio
CC3	Construction Cycle 3
CC5	Construction Cycle 5
FAA	Federal Aviation Administration
FAARFIELD	FAA Rigid and Flexible Iterative Elastic Layered Design
HMA	Hot mix asphalt
LEAF	Layer Elastic Analysis–FAA (computer program)
LFC	Low-strength subgrade, Flexible surface, Conventional base (NAPTF traffic test item designator)
NAPTF	National Airport Pavement Test Facility
P/C	Pass-to-coverage ratio
WES	U.S. Army Engineer Waterways Experiment Station

EXECUTIVE SUMMARY

In September 2009, the Federal Aviation Administration (FAA) adopted FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) as its standard thickness design procedure for airport pavements. Version 1.41 of the FAARFIELD program was released in November 2016. FAARFIELD 1.41 includes an improved layered elastic analysis routine for flexible pavement design and a three-dimensional finite element structural analysis routine for rigid pavement design. This report describes a new subgrade failure model for flexible pavements implemented in version 1.41 of FAARFIELD.

This report consists of four sections. First, it describes the refinement of the FAARFIELD model that determines the elastic modulus of aggregate materials (FAA items aggregate subbase, P-154, and crushed aggregate base, P-209) at design time. The aggregate model was changed from previous FAARFIELD versions to alter the equivalent thickness relationship between P-209 and P-154 such that it is, on average, closer to a target value of 1.4 (that is, 1.4 units of the lower quality material replace a unit thickness of the higher quality material).

Second, the report describes the development of a new, smooth analytic function relating coverages to failure to vertical strain computed at the top of the subgrade layer. The new failure model was derived by backcalculation from four- and six-wheel alpha factor curves using the refined aggregate modulus model developed in the first section. The new failure model replaces the previous bilinear failure model in FAARFIELD 1.3 and had significant advantages over it as described in the report.

Third, the report compares pavement life predictions using the new model to the observed failures of full-scale flexible pavement test items that were part of construction cycles CC3 and CC5 at the FAA National Airport Pavement Test Facility.

Finally, the report compares flexible pavement designs using FAARFIELD with the new failure model to the equivalent designs performed using the California Bearing Ratio (CBR) design procedure as implemented in canceled Advisory Circular (AC) 150/5320-6D, and also using the COMFAA 3.0 computer program with revised (2007) alpha factor curves. For simplicity, multiple-gear aircraft, such as the Boeing B747 and Airbus A380, were not included in the CBR design comparisons. The results of this analysis show that, for the gear types considered, FAARFIELD 1.41 with the new flexible failure model yields designs closer to the COMFAA-based methodology than earlier FAARFIELD versions.

1. INTRODUCTION.

In September 2009, the Federal Aviation Administration (FAA) issued Advisory Circular (AC) 150/5320-6E, Airport Pavement Design and Evaluation [1], which adopted FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) as the approved design standard for airport pavement thickness. In November 2016, the FAA released a major update to the FAARFIELD program, designated FAARFIELD 1.41, as part of AC 150/5320-6F [2 and 3]. FAARFIELD 1.41 includes an improved layered elastic analysis routine for flexible pavement design.

Section 2 of this report documents the improvement to aggregate layer modulus assignment procedures in FAARFIELD 1.41. FAA standard aggregate materials (aggregate subbase, P-154, and crushed aggregate base, P-209) are characterized in FAARFIELD through an internally computed elastic modulus. The aggregate modulus model in FAARFIELD 1.3 (subroutine WESModulus) [4 and 5] was originally developed by the U.S. Army Engineer Waterways Experiment Station (WES) for the FAARFIELD predecessor program LEDNEW, a computer-based design procedure involving layered elastic computation of stresses and strains. This model has several known shortcomings, which are addressed and resolved in this report.

Section 3 describes the development of a new flexible failure model. The failure model was derived analytically by applying the FAARFIELD layered elastic structural model in combination with the thickness design function of the FAA computer program COMFAA 3.0. COMFAA is an FAA software program that computes flexible and rigid aircraft classification numbers (ACNs) and pavement thickness. The program incorporates empirical load repetition factors (alpha factors), to account for the different effects of two-, four-, and six-wheel gears in flexible design.

Section 4 documents the data analysis of full-scale flexible pavement tests conducted as part of National Airport Pavement Test Facility (NAPTF) construction cycles CC3 and CC5, and compares the full-scale test failure data to both the old and new FAARFIELD design models.

In section 5, the FAARFIELD designs are compared to equivalent design thicknesses based on COMFAA. Both the improved aggregate modulus model and the new flexible failure model were implemented in FAARFIELD 1.41.

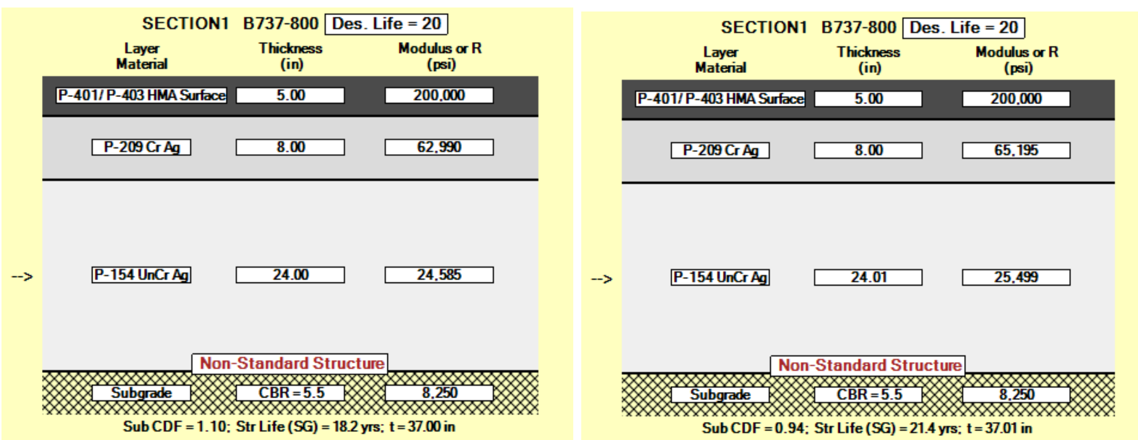
2. IMPROVEMENT OF AGGREGATE MODULUS MODEL.

As implemented in FAARFIELD, the numerical value of the modulus depends on two variables:

- the thickness of the layer under consideration; and
- the elastic modulus of the layer directly below the layer under consideration.

Furthermore, a thick aggregate layer is subdivided into sublayers to compute the elastic modulus. The modulus of each sublayer is computed using a recursive algorithm, and the average modulus for all sublayers is displayed on the FAARFIELD Structure screen as the layer modulus. The maximum thickness of a sublayer depends on the material. In FAARFIELD 1.3, the maximum sublayer thickness for P-154 is 8 inches; for P-209, it is 10 inches.

As stated above, the average modulus for an aggregate layer is calculated based on a discrete number of sublayers. If there are discontinuities in the layer thickness versus modulus curve at the points where the number of sublayers changes, then the design may fail to converge, as the iteration process alternates between *n* and *n*+1 sublayers. The following example in FAARFIELD 1.3 illustrates the potential for discontinuity in pavement life computation. Figure 1 shows two cases of pavement life calculation. In figure 1(a), the P-154 subgrade thickness is 24 inches and the corresponding structural life is 18.2 years; in figure 1(b) the P-154 thickness is 24.01 inches but the pavement life is 21.4 years. A thickness increase of only 0.01 inches produces an unreasonable 18% increase in the structure life. Table 1 shows the detailed input data for the Layered Elastic Analysis–FAA (LEAF) module used in FAARFIELD to calculate the primary responses in the pavement structure. The slight increase in thickness increased the number of discrete sublayers from 3 to 4. Figure 2 shows the corresponding discontinuity in the strain computation, which leads to the illogical result.



(a) P-154 Thickness = 24.00 Inches (b) P-154 Thickness = 24.01 Inches

Figure 1. Discrepancy in Life Calculation in FAARFIELD 1.3

Table 1. Layer Input Data for LEAF

<table>
<tr><th colspan="3">(a) P-154 Thickness = 24 Inches</th><th colspan="3">(b) P-154 Thickness = 24.01 Inches</th></tr>
<tr><th>Layer Type</th><th>Thickness (in.)</th><th>Modulus of Elasticity (psi)</th><th>Layer Type</th><th>Thickness (in.)</th><th>Modulus of Elasticity (psi)</th></tr>
<tr><td>P-401</td><td>5</td><td>200,000</td><td>P-401</td><td>5</td><td>200,000</td></tr>
<tr><td>P-209</td><td>8</td><td>62,990</td><td>P-209</td><td>8</td><td>65,195</td></tr>
<tr><td rowspan="3">P-154</td><td>8</td><td>32,337</td><td rowspan="4">P-154</td><td>6.0025</td><td>34,344</td></tr>
<tr><td>8</td><td>25,194</td><td>6.0025</td><td>29,640</td></tr>
<tr><td>8</td><td>16,225</td><td>6.0025</td><td>22,889</td></tr>
<tr><td>Subgrade</td><td>-</td><td>8,250</td><td>6.0025</td><td>15,123</td></tr>
<tr><td colspan="3"></td><td>Subgrade</td><td>-</td><td>8,250</td></tr>
</table>

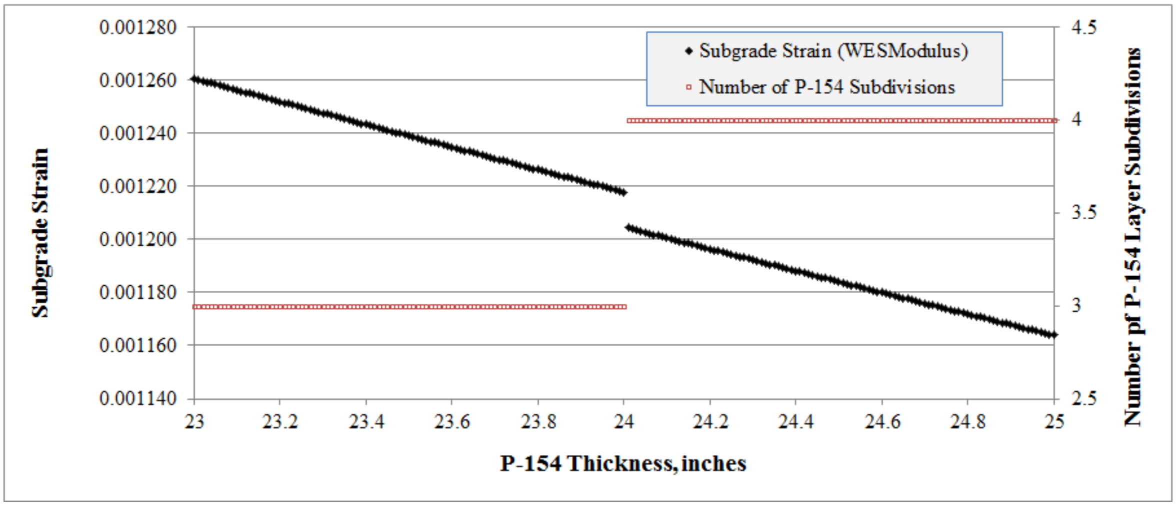


Figure 2. Relationship Between P-154 Thickness and Subgrade Strain for WESModulus Subroutine

To remedy this discontinuity, a new algorithm had to be developed, similar to WESModulus but with enforced continuity of the layer thickness versus modulus curve at the sublayer transition points. Another objective was to refine the parameters of the modulus model to realize, if possible, an equivalent thickness relationship between standard base (P-209) and subbase (P-154) layers that is, on average, closer to a value of 1.4 than is the case with the original WESModulus model. The value of 1.4 was selected because it is in the middle range of equivalency factors for the replacement of P-154 by the higher quality P-209 established in table 3-6 of canceled AC 150/5320-6D [6]. Thus, if the FAARFIELD modulus model can be calibrated such that 1.4 units of P-154 replaces a unit thickness of P-209 in layered elastic-based designs, this should result in an improved correspondence between FAARFIELD and the previous FAA design methodology. However, due to the inherent differences between the layered elastic and California Bearing Ratio (CBR) procedures, it is not possible to set the model parameters in such a way as to ensure that a ratio of 1.4 is achieved for all subgrade strengths. Rather, the goal was to assign the parameters to minimize the average deviation from 1.4 for a given set of design inputs.

2.1 MODIFICATIONS TO THE AGGREGATE SUBLAYERING MODEL.

Both the original (WES) procedure and the revised procedure involve sublayering. The WES procedure, which was also implemented in FAARFIELD 1.3, uses the following rules for uncrushed aggregate, FAA item P-154.

- Aggregate layers are divided into sublayers of equal thickness.
- The maximum sublayer thickness is 8 inches.

For an aggregate layer 18 inches thick, as shown in figure 3(a), the WES procedure results in three sublayers, each 6 inches thick. An increase in the total thickness results in a proportional increase in the thickness of all sublayers. Since the sublayer modulus is a function of its thickness, this results in all the sublayer moduli being recalculated at each thickness iteration.

By contrast, the new FAAModulus subroutine in FAARFIELD 1.41 implements the following rules.

- All sublayers below the top sublayer have a fixed thickness of 8 inches.
- Only the top sublayer thickness varies between 4 and 12 inches.

Following the new rules, an 18-inch P-154 layer would be subdivided into two sublayers, 8 inches and 10 inches, as shown in figure 3(b). Additional thickness increases up to 2 inches would be applied to the top layer, while the bottom layer would remain fixed at 8 inches. The progression of sublayering for additional thickness increases is illustrated in figure 4. By this method, the lower sublayers always remain fixed at 8 inches, and recalculation of the modulus is not required except at the upper layer. No sublayer is less than 4 inches for any given layer thickness. It is also noted that, at P-154 layer thicknesses that are multiples of 8 inches (16 inches, 24 inches, etc.), the new sublayering model coincides with the WES model.

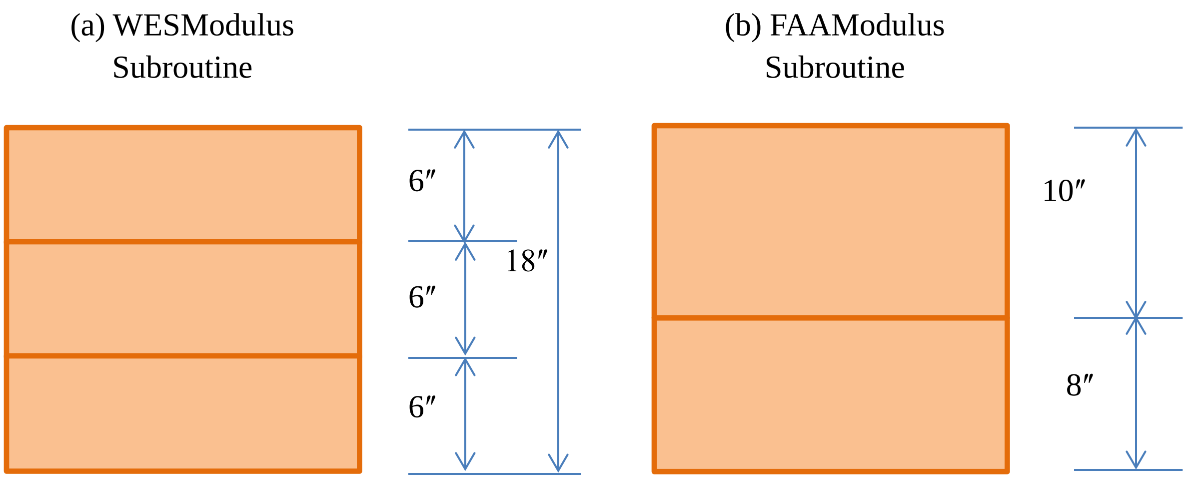


Figure 3. Layer Subdivisions in WES and FAA Subroutines

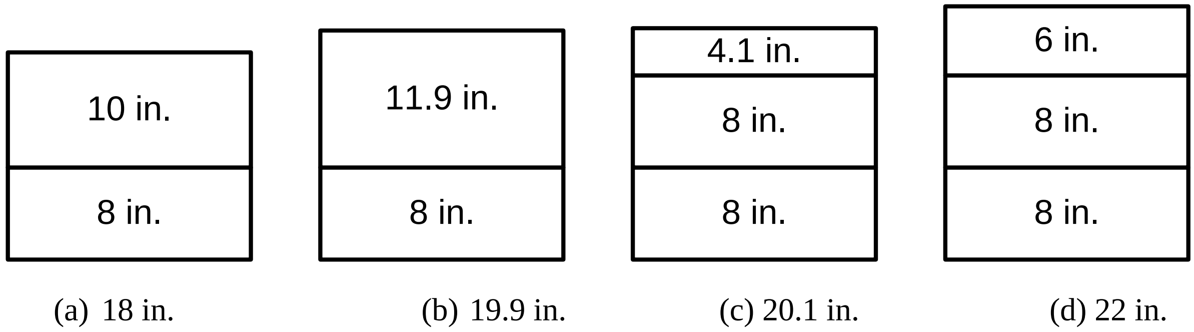


Figure 4. Progression of Sublayering for P-154 Layer Thickness Increases

With the new rules established for sublayering, as shown in figures 3 and 4, the moduli to the sublayers had to be assigned in such a way that continuity was preserved. This was done for each of the three cases as follows.

1. Case 1—P-154 thickness is an integral multiple of 8 inches. Assume that there are N sublayers, each of which is 8 inches thick. Respectively assign the sublayer moduli to sublayers n using the WES equation:

$$E_n = E_{n-1} \times \left[1 + \log_{10} t_n \times \left(c - d \times \log_{10} E_{n-1}\right)\right] \quad (1)$$

   where:

   E_n = the modulus of the current sublayer in psi
   E_{n-1} = the modulus of the sublayer immediately below (or the modulus of the subgrade in the case of the bottom sublayer
   t_n = the thickness of the current sublayer (= 8 inches)
   c and d = constants

   In the FAARFIELD 1.3 implementation, c and d have numerical values of 7.18 and 1.56, respectively.

2. Case 2—The P-154 thickness is up to 4 inches greater than an integral multiple of 8 inches. Again, assume there are N sublayers. Hold the thickness of the bottom n-1 sublayers at 8 inches, as shown in figure 4. Obtain t_n > 8 inches for the top sublayer only, and calculate E_n for the top sublayer using equation 1.

3. Case 3—The P-154 thickness is between 4 and 8 inches above an integral multiple of 8 inches. Again, assume there are N sublayers. The top sublayer (sublayer N) is between 4 and 8 inches, and all sublayers below it are 8 inches. In this case, the modulus of the sublayer immediately below the top sublayer (sublayer N-1) is computed using equation 1, but substituting t_n = 8 inches + (8 inches – t_N), where t_N is the thickness of the top layer. Then, the modulus of sublayer N is computed by linear interpolation between the modulus of sublayer N-1 and the modulus that would be computed for a top sublayer that is 8 inches thick. This method ensures that the modulus of all sublayers is a continuous function of layer thickness t.

Figure 5 shows that the FAAModulus subroutine eliminates the discontinuity in strain calculations. Figure 6 shows the average modulus of a sublayered P-154 aggregate layer as a function of layer thickness, for both the WESModulus and FAAModulus subroutines. For this comparison, the FAAModulus subroutine uses values of constants c and d identical to those in the WESModulus subroutine. From figure 6, it is apparent that the new model eliminates discontinuities while retaining the original modulus values at integral multiples of 8 inches.

In the case of crushed aggregate base material, item P-209, the same revised procedure for sublayering was adopted in FAARFIELD 1.41, except that the basic sublayer thickness remains 10 inches rather than 8 inches.

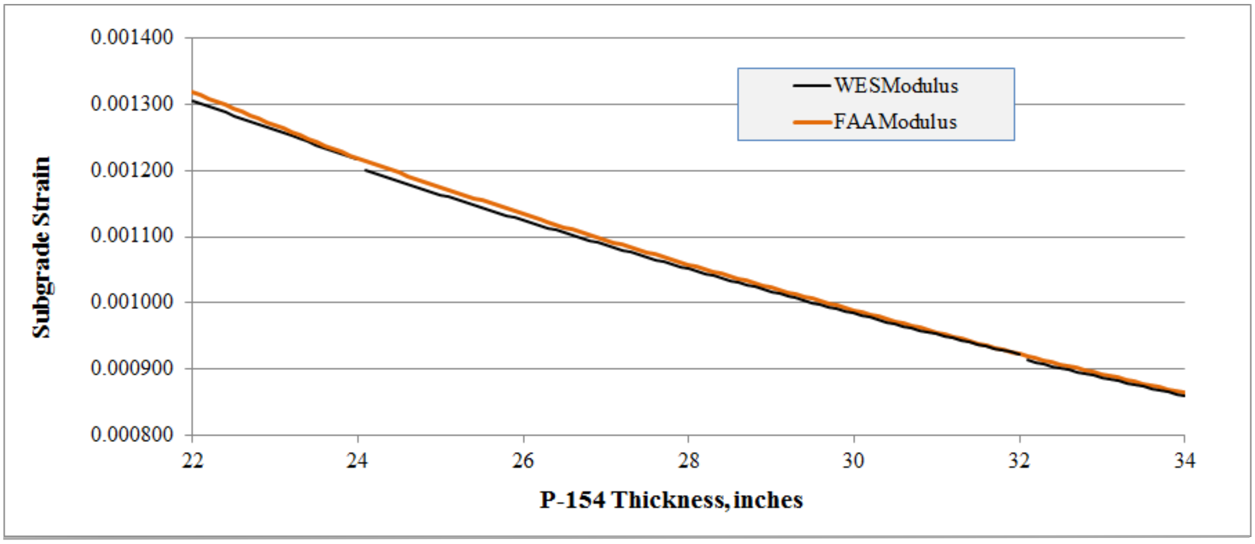


Figure 5. Subgrade Strain as a Function of P-154 Thickness for WESModulus and FAAModulus Subroutines

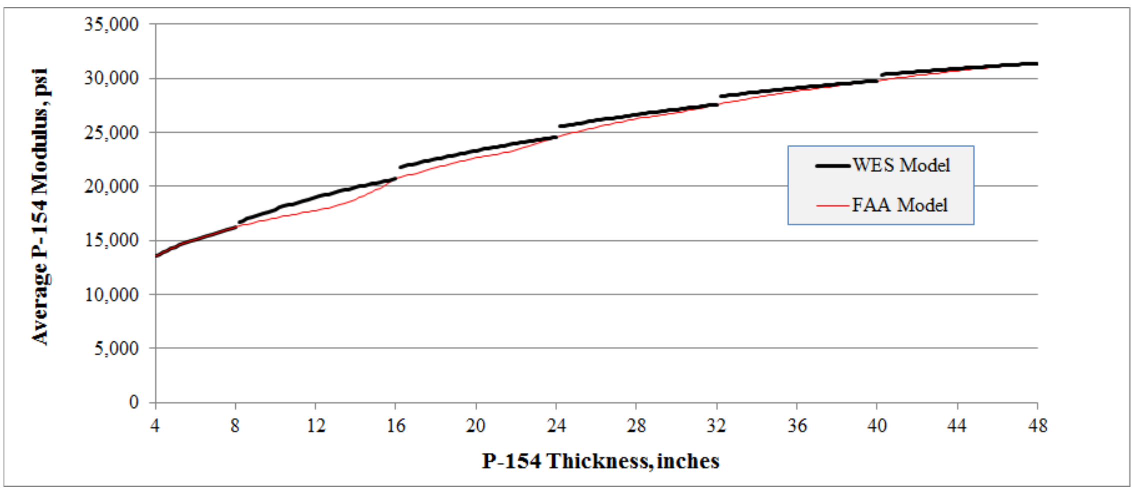
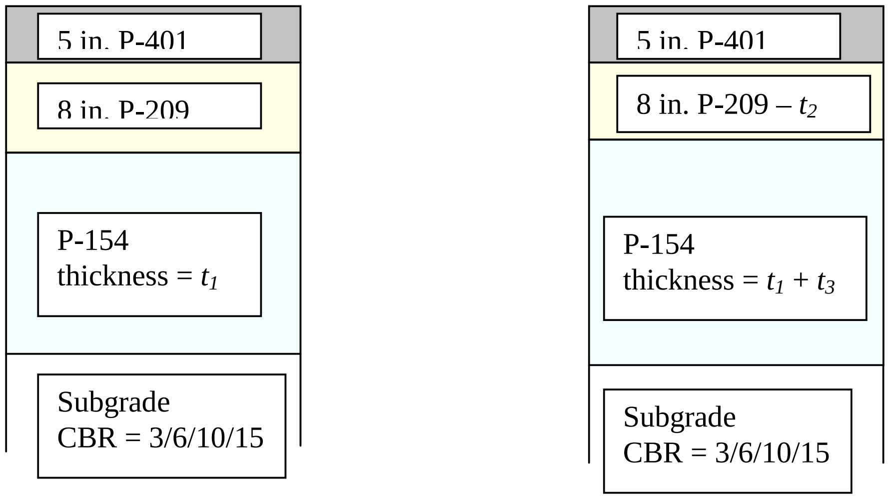


Figure 6. Average Modulus of P-154 Subbase Layer as a Function of Thickness (for CBR 3 Subgrade)

2.2 EFFECTIVE EQUIVALENCY FACTOR.

Table 3-6 of cancelled AC 150/5320-6D [6] defined ranges of recommended equivalency factors for converting a given thickness of a standard aggregate subbase (P-154) to an equivalent thickness of a higher quality material, for example P-209. In the case of P-209, the equivalency factor range is 1.2 to 1.8, with 1.4 being a commonly used value. Note that equivalency factors as used here should not be confused with the layer equivalency coefficients typically used in highway pavement design. The concept of equivalency factors is not used in FAARFIELD design, but for comparative purposes it is possible to determine an effective equivalency factor between P-209 and P-154 using a simple procedure. Consider two equivalent structures designed to carry equal traffic as shown in figure 7. Based on a comparison between figures 7(a) and (b), the effective equivalency factor for P-209 converted to P-154 is t_3/t_2.



(a) (b)

Figure 7. Equivalent Flexible Pavement Structures and Definition of Thicknesses for Effective Equivalency Factor Computation

In FAARFIELD, the effective equivalency factor is not fixed (as in the CBR method), but depends on the parameters of the equations that give the moduli of P-209 and P-154 in equation 1, as well as on the subgrade modulus, the subgrade failure model, and other problem variables.

Figure 8 shows an effective equivalency factor calculation using the WESModulus subroutine. Effective equivalency factors were computed in FAARFIELD 1.3 using the Boeing B737-800 as the loading aircraft gear. This graph shows that the effective equivalency factor can vary from 0.85 to 1.34. The WESModulus subroutine produces a discontinuous plot of effective equivalency factor versus subgrade modulus, with numerous breaks at the points where additional sublayers are generated. The FAAModulus subroutine eliminates this problem, as shown in figure 9 (lower curve). When run in conjunction with the existing *c* and *d* parameters, the FAAModulus curve is now a continuous (though not completely smooth) function of subgrade modulus. However, the average effective equivalency factor is still somewhat less than the target value.

To increase average effective equivalency factors, the P-154 modulus value was lowered by changing the value of parameter *c* in equation 1 from 7.18 to 6.88. However, this also decreased the value of the P-209 base layer modulus, since the P-209 modulus is dependent on the modulus of the layer below it. To maintain the P-209 modulus at a level similar to WESModulus, parameter *d* for P-209 was also reduced from 2.1 to 2.0. The upper curve in figure 9 shows the effective equivalency factors in FAARFIELD 1.3 computed with the FAAModulus subroutine, but with modified parameters *c* and *d* for P-154 and P-209. Figures 10 and 11 show computed P-154 and P-209 moduli, respectively.

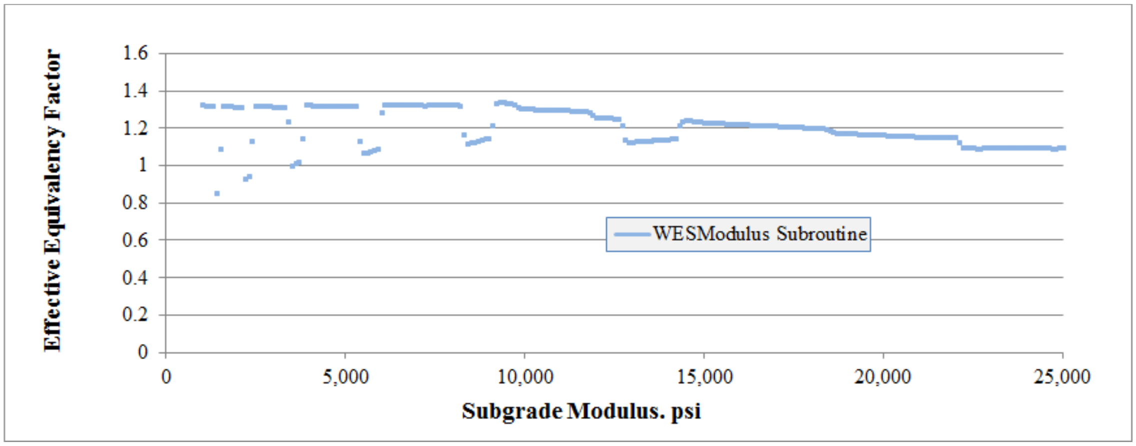


Figure 8. Effective Equivalency Factor Using FAARFIELD 1.3 With WESModulus Subroutine

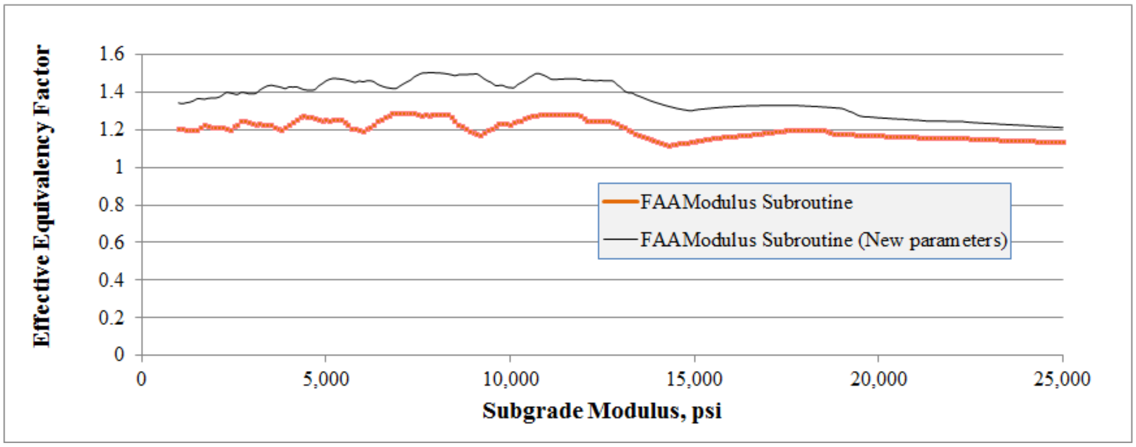


Figure 9. Effective Equivalency Factor Using FAARFIELD 1.3 With FAAModulus Subroutine

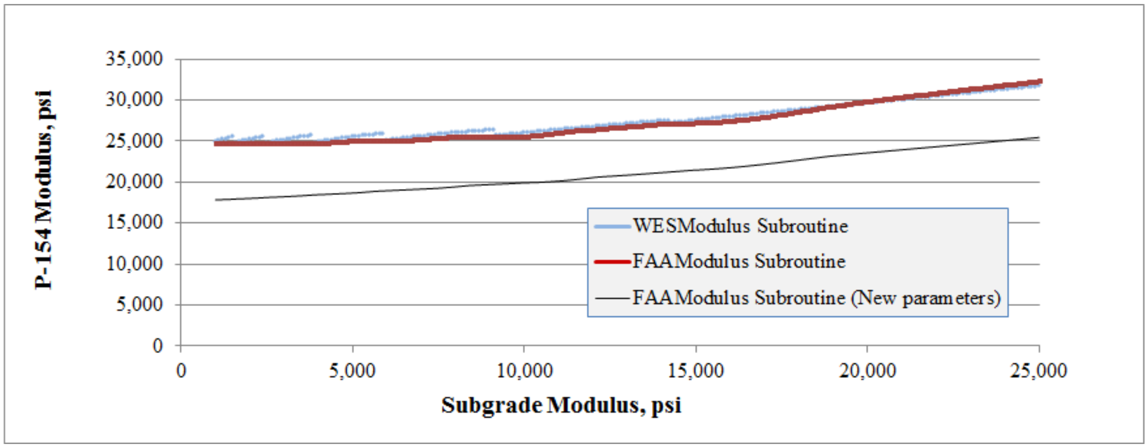


Figure 10. Computed P-154 Average Modulus as a Function of Subgrade Modulus

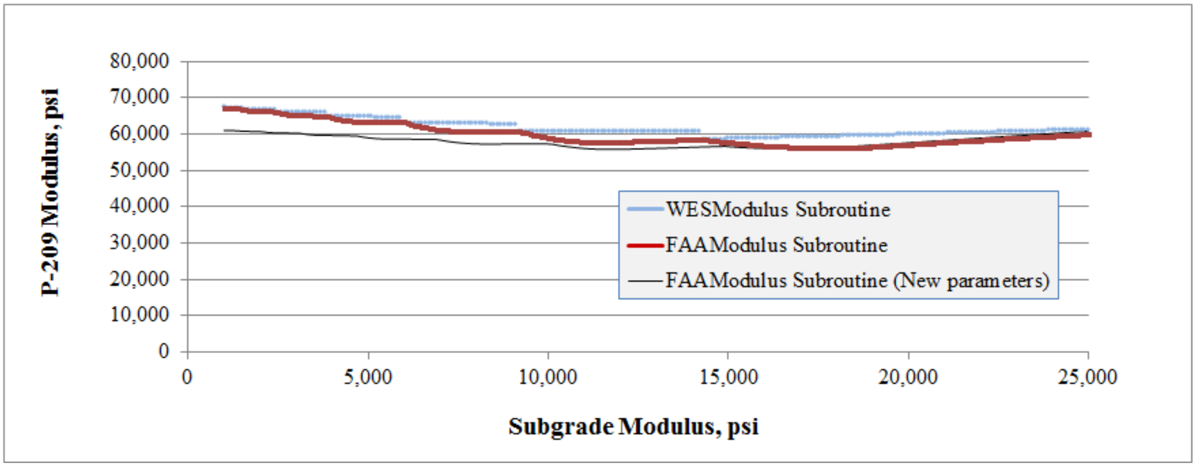


Figure 11. Computed P-209 Average Modulus as a Function of Subgrade Modulus

For example, consider a 20-year design for 1200 annual departures of the B737-800, based on the structure shown in figure 7(a). For four different values of subgrade CBR (3, 6, 10, and 15), FAARFIELD 1.41 gives the data in table 2.

Points to consider from table 2 include the following.

- The computed effective equivalency factors f_{eq} are in the range from 1.22 to 1.50 with average 1.37.
- The effective equivalency factor is relatively insensitive to t_2.
- The effective equivalency factor shows sensitivity to CBR within the range of values considered.

Table 2. Effective Equivalency Factors for FAAModulus Subroutine*

CBR ➔	3 (t_1 = 34.91 in.)		6 (t_1 = 20.95 in.)		10 (t_1 = 11.62 in.)		15 (t_1 = 6.06 in.)	
t_2, in.	t_3, in.	f_{eq}	t_3, in.	f_{eq}	t_3, in.	f_{eq}	t_3, in.	f_{eq}
0.5	0.71	1.42	0.75	1.50	0.66	1.31	0.61	1.22
1.0	1.40	1.40	1.50	1.50	1.31	1.31	1.23	1.23
1.5	2.12	1.41	2.24	1.50	1.96	1.30	1.86	1.24
2.0	2.83	1.42	2.98	1.49	2.64	1.32	2.49	1.24
2.5	3.53	1.41	3.72	1.49	3.33	1.33	3.12	1.25
3.0	4.23	1.41	4.46	1.49	4.02	1.34	3.76	1.25

*Traffic = 1,200 annual departures of B737-800, gross weight = 174,700 lb
Parametric values for the P-154 modulus model are c = 6.88 and d = 1.56.
Parametric values for the P-209 modulus model are c = 10.52 and d = 2.00.

3. DEVELOPMENT OF A NEW ANALYTIC FUNCTION.

This section describes the development of a new failure model relating allowable coverages of the loading gear to vertical strain at the top of the subgrade layer in a flexible pavement structure. The model takes the form of a smooth, continuous function. The model was derived by backcalculation from the COMFAA 3.0 program, and therefore reflects the characteristics of the four- and six-wheel alpha factor curves built into that program. Strains were determined from the FAARFIELD layered elastic structural model using the new P-154 and P-209 aggregate modulus models described in section 2 of this report.

3.1 STEPS IN DEVELOPING STRAIN VERSUS COVERAGES CURVES.

In developing curves of strain versus coverages, two types of typical structures were analyzed. Type I consists of a 3-inch P-401 surface hot mix asphalt (HMA), 6-inch P-209 base layer, and P-154 subbase layer. This type of structure was used for the Multiple-Wheel Heavy Gear Load (MWHGL) test series run by the U. S. Army Engineer WES [7]. Type II consists of a 5-inch P-401 surface HMA, 8-inch P-209 base layer, and P-154 subbase layer, and was used in full-scale tests at the NAPTF.

The following steps were executed to develop curves of strain versus coverages. The example provided is for 100 coverages. (This example is shown shaded and in bold text in table 3.)

Step 1: Run COMFAA. Load the external airplane file "*NAPTF 2D and 3D.ext*" (appendix A). In "Thickness" mode, find the required thickness for: Aircraft "NAPTF 2D," Flexible 20-year coverages = 100; CBR 4. Record the thickness value t = 32.56 inches in the "Total Thickness" column in table 3 (figure 12).

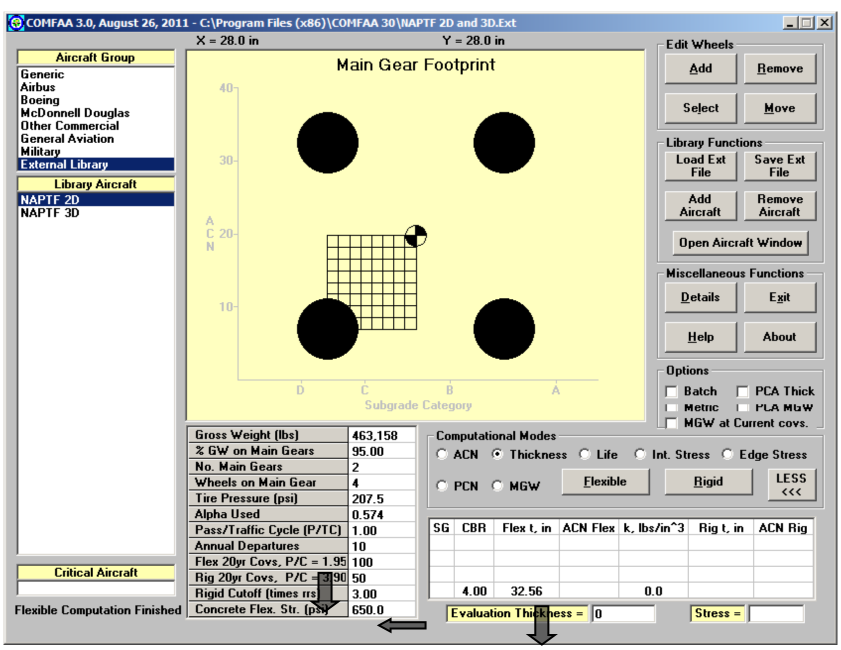


Figure 12. Computer Program COMFAA Main Window

Step 2: Obtain the pass-to-coverage ratio (P/C) from figure 12 ("Flex 20yr Covs. P/C = 1.95"). Record this value in the column "P/Cs" column in table 3.

Step 3: Obtain the P-154 thickness by deducting 3 inches of P-401 and 6 inches of P-209 from the total thickness *t* = 32.56 inches from Step 1. Record the result (23.56 inches) in the column "P-154 Thickness" column.

Step 4: Add airplanes "CC3 2D" (for four-wheel, dual-tandem gear configuration) and "CC3 3D" (for six-wheel, double dual-tandem gear configuration) to the internal library of FAARFIELD. The following snippets of Microsoft® Visual Basic® code were used to define the gear configurations and loads. (All dimensions are in inches.)

```
AC(IA).libACName = "CC3 2D" '55,000 lbs per wheel
AC(IA).libGL = 463158.0! : AC(IA).libMGpcnt = 0.475
AC(IA).libCP = 207.5!
AC(IA).libGear = "F"
AC(IA).libIGear = 3
AC(IA).libTT = 54.0! : AC(IA).libTS = 400.0!
AC(IA).libTG = 0.0! : AC(IA).libB = 57.0!

AC(IA).libACName = "CC3 3D" '47,500 lbs per wheel
AC(IA).libGL = 600000.0! : AC(IA).libMGpcnt = 0.475
AC(IA).libCP = 207.5!
AC(IA).libGear = "N"
AC(IA).libIGear = 3
AC(IA).libTT = 54.0! : AC(IA).libTS = 400.0!
AC(IA).libTG = 0.0! : AC(IA).libB = 57.0!
```

Step 5: In FAARFIELD, run the "Life" function for the Type I structure (3-inch P-401, 6-inch P-209, and 23.56-inch P-154) and an arbitrary number of departures of the 2D airplane defined in Step 4. (The departure level does not affect the strain or P/C values in the following steps.)

Step 6: In the FAARFIELD "Airplane" screen, scroll to the "P/C Ratio" column and read the value of P/C at the top of the subgrade level (0.616). Record it in the "P/Csg" column. Note that the value reported in this column will generally be different from the value of P/C given by FAARFIELD 1.41 or later. This is because the method of accounting for interaction between aircraft wheels in tandem was changed in version 1.41 [8]. The P/C values in this report were obtained using an earlier version (FAARFIELD 1.40). Therefore, they still reflect the earlier method and include a factor related to tandem wheel interaction.

Step 7: Obtain the maximum vertical strain value (0.002384) from the file "*LeafSG.out*." Record it in the "Subgrade Strain" column.

Step 8: Calculate FAARFIELD coverages from COMFAA coverages by multiplying by the ratio: (P/Cs)/(P/Csg). Record the value (100 × 1.95/0.616 = 317) in the "Coverage C_{FF}" column.

Step 9: Repeat Steps 1 through 8 for other coverage levels.

Step 10: Plot a graph of coverages to failure versus subgrade strain using the data in the "Coverage C_{FF}" and "Subgrade Strain" columns, as shown in figure 13.

Table 3. Example Calculation Data for Strain Versus Coverages Curves
(Data for Gear Load CC3 2D, Type I Structure With CBR 4 Subgrade)

	COMFAA			FAARFIELD		
Coverages	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs*	P/Csg**	C_{FF}***	Subgrade Strain[iv]
10	19.14	10.14	1.95	0.851	23	0.005062
20	23.33	14.33	1.95	0.759	51	0.003809
50	28.67	19.67	1.95	0.669	146	0.002844
100	**32.56**	**23.56**	**1.95**	**0.616**	**317**	**0.002384**
200	36.33	27.33	1.95	0.596	654	0.002096
500	41.21	32.21	1.95	0.606	1,609	0.001815
1,000	44.66	35.66	1.95	0.637	3,061	0.001661
2,000	47.80	38.80	1.95	0.67	5,821	0.001555
5,000	51.36	42.36	1.95	0.712	13,694	0.001454
10,000	53.69	44.69	1.95	0.743	26,245	0.001402
12,100	54.28	45.28	1.95	0.752	31,376	0.001390
20,000	55.75	46.75	1.95	0.774	50,388	0.001362
50,000	58.15	49.15	1.95	0.814	119,779	0.001317
100,000	59.74	50.74	1.95	0.843	231,317	0.001288
200,000	61.15	52.15	1.95	0.871	447,761	0.001262
500,000	62.78	53.78	1.95	0.906	1,076,159	0.001233
1,000,000	63.86	54.86	1.95	0.931	2,094,522	0.001214

*P/Cs = Pass-to-coverage in COMFAA program at the pavement surface level
**P/Csg = Pass-to-coverage computed by FAARFIELD at the top of the subgrade level
***C_{FF} = Calculated number of coverages to failure for FAARFIELD
[iv]Subgrade Strain = Maximum strain at the top of the subgrade calculated by FAARFIELD

3.2 DATA USED TO DEVELOP FAILURE MODEL.

Failure curves were calculated for the following eight cases:

Case 1: Gear Type 2D, Structure Type I, CBR 4 (used in the example in paragraph 3.1)
Case 2: Gear Type 2D, Structure Type I, CBR 5
Case 3: Gear Type 2D, Structure Type II, CBR 4
Case 4: Gear Type 2D, Structure Type II, CBR 5
Case 5: Gear Type 3D, Structure Type I, CBR 4
Case 6: Gear Type 3D, Structure Type I, CBR 5
Case 7: Gear Type 3D, Structure Type II, CBR 4
Case 8: Gear Type 3D, Structure Type II, CBR 5

Appendix B shows tablular results for the above cases that are similar to Case 1 in table 3. Figure 13 shows eight COMFAA-developed failure curves with their lower envelope. Additionally, figure 13 shows the FAARFIELD 1.3 model, which is a bilinear model. Equations 2 and 3 are the expression of the bilinear FAARFIELD 1.3 model in figure 13.

$$Coverages = \left(\frac{0.004}{\varepsilon}\right)^{8.1} \qquad (Coverages \leq 12{,}100) \qquad (2)$$

$$Coverages = \left(\frac{0.002428}{\varepsilon}\right)^{14.21} \qquad (Coverages > 12{,}100) \qquad (3)$$

where:

ε = maximum vertical strain at the top of the subgrade.

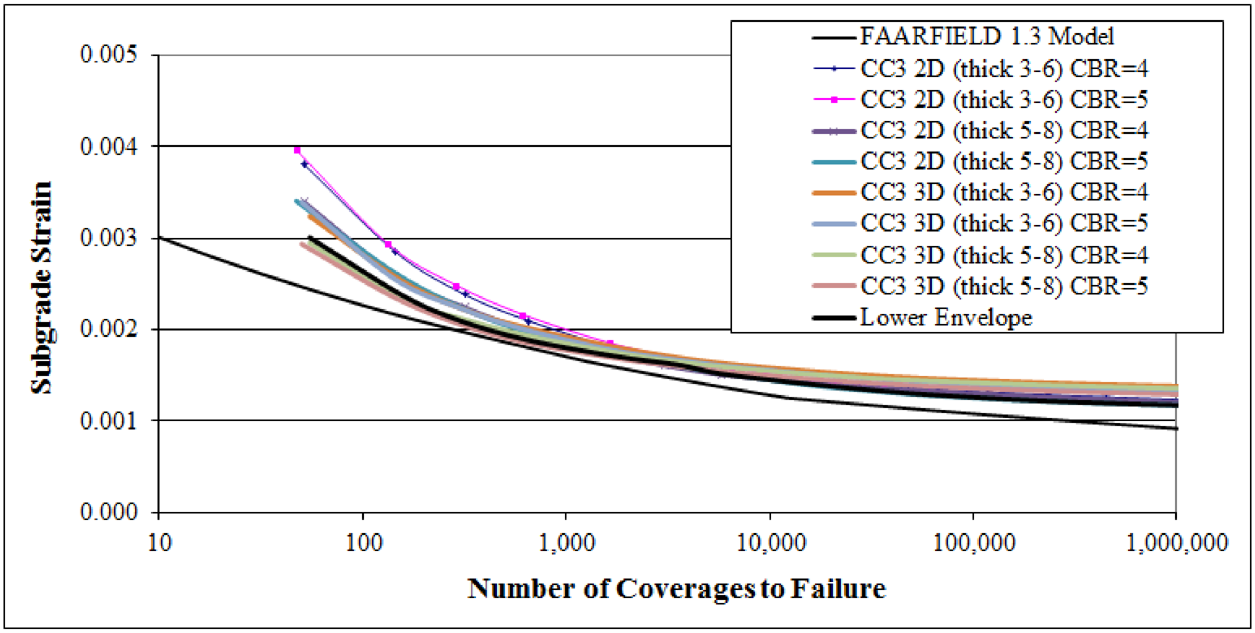


Figure 13. Lower Envelope for Developed Failure Curves

The next objective, discussed in section 3.3, was to obtain a simple analytical model that approximates the lower envelope in figure 13.

3.3 DERIVATION OF FATIGUE EQUATION.

Lower envelope data points, as shown in table 4, were determined by identifying points on the lower envelope line shown in figure 13.

A commercial analysis program, CurveExpert© Basic 1.4, was used to identify the best regression of the lower bound of vertical strain to the common logarithm (base10) of coverages. From generated possible models by CurveExpert, the Bleasdale model was selected as showing the best fit. Equations 4 and 5 show the format of the Bleasdale model:

$$Log_{10}(Coverages) = \left(\frac{1}{a + b * \varepsilon} \right)^{\frac{1}{c}} \quad (4)$$

$$Coverages = 10^{\left(\frac{1}{a + b * \varepsilon} \right)^{\frac{1}{c}}} \quad (5)$$

where coefficients:

a = -0.163768916705, *b* = 185.192806802, *c* = 1.65054449461 were identified by regression

and

ε = maximum vertical strain at the top of the subgrade.

Table 4. Data Used to Develop the Regression Equation

Subgrade Strain	Coverages	Log_{10}(Coverages)
0.002937	54.9	1.73959
0.002338	155.9	2.19285
0.002056	302.4	2.48055
0.001857	642.2	2.80767
0.001691	1,715.7	3.23444
0.001599	3,535.4	3.54843
0.001507	5,820.9	3.76499
0.001394	15,650.1	4.19452
0.001334	30,326.6	4.48182
0.001318	36,355.9	4.56058
0.001283	58,823.5	4.76955
0.001236	141,715.1	5.15142
0.001209	276,204.0	5.44123
0.001188	540,166.2	5.73253
0.001164	1,312,247.6	6.11802

Figure 14 shows the lower envelope data points along with the Bleasdale curve fitted to those points. Figure 15 shows the shape of the failure model based on the Bleasdale curve. For coverages equal or greater than 1000, the Bleasdale model (equation 1) is used directly. For coverages less than 1000, a straight line model was adopted, tangent to the Bleasdale curve and parallel to the FAARFIELD 1.3 failure model. As shown in figure 15, the point of tangency is at 1000 coverages. (At the point of tangency, the strain value is equal to 1. 765093×10^{-3}.)

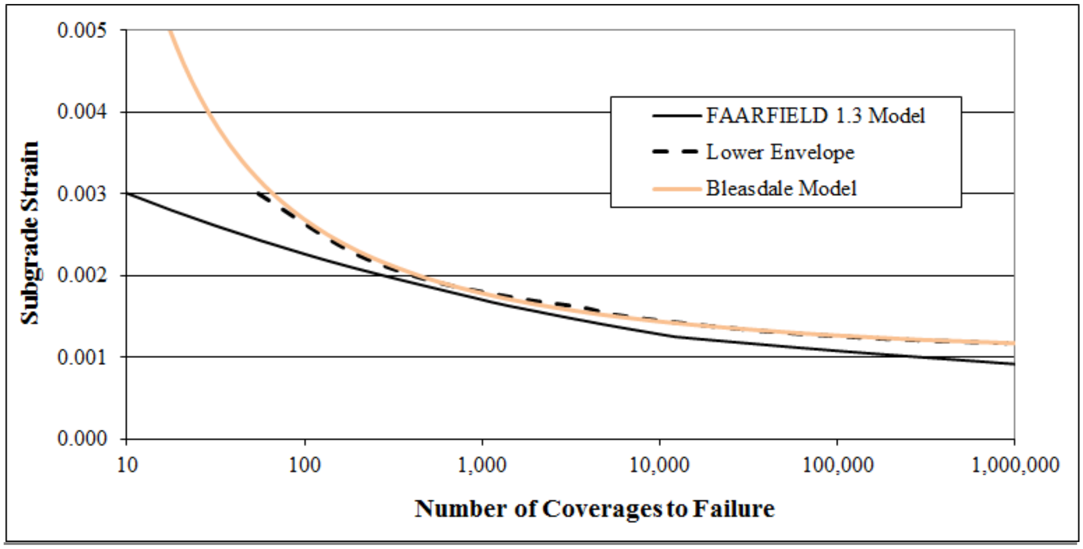


Figure 14. Failure Curves

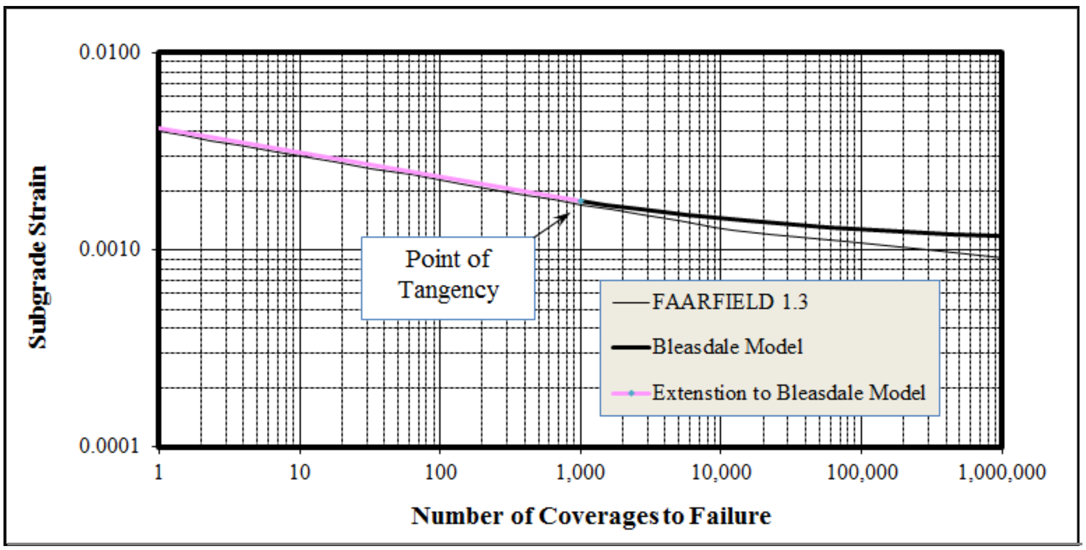


Figure 15. Fatigue Models in FAARFIELD

The equations of the straight line extension to the Bleasdale model for coverages less than 1000 can be written:

$$Coverages = \left(\frac{0.00414131}{\varepsilon} \right)^{8.1} \qquad (6)$$

where:

ε = maximum vertical strain at the top of the subgrade.

Note that equation 6 is linear in the log(Coverages) – log(ε) plane.

4. THE NAPTF DATA ANALYSIS.

Full-scale traffic test data collected at the NAPTF are organized by construction cycles. A construction cycle includes test pavement and instrumentation layout, traffic pre- and post-test plans, materials testing data, construction test data, traffic data and post-traffic testing (trenching activities and other tests), and pavement removal. Construction cycles CC3 and CC5 involved testing flexible pavement sections.

For the purposes of this analysis, failure of a flexible pavement test section refers to full structural failure. At the NAPTF, the technical failure criterion applied was the development of at least 1 inch of surface upheaval outside the limits of the trafficked area, indicating a general shear failure of the supporting layers. Test sections in CC3 and CC5 that did not meet this structural failure criterion were not considered to have failed, although they may have exhibited high surface rutting or other distresses.

4.1 METHODOLOGY OF DATA ANALYSIS.

The following steps [9] were used in the analysis of the NAPTF data.

Step 1: Assume that the mathematical form of the failure model is correct, but that it can be translated vertically along the strain axis to match the failure point of a particular full-scale test.

Step 2: Divide the traffic for the test section under consideration into analysis periods for which the asphalt temperature and the applied load were both approximately uniform.

Step 3: Calculate the P/C ratio for the loading gear traffic using the FAARFIELD program.

Step 4: Calculate the number of coverages by dividing the number of applied passes of the test vehicle by the P/C ratio computed in Step 3.

Step 5: Using FAARFIELD 1.41, calculate the maximum vertical strain at the top of the subgrade for each period.

Step 6: Using the FAARFIELD 1.41 failure model, compute the number of coverages to pavement failure for each load, corresponding to the maximum strains calculated in Step 5.

Step 7: Following equation 7, compute cumulative damage factor (CDF), which is the amount of the structural fatigue life of a pavement that has been used up (CDF = 1 corresponds to the failure condition):

$$CDF_T = \frac{C_1}{C_{1F}} + \frac{C_2}{C_{2F}} + ... + \frac{C_I}{C_{IF}} + ... + \frac{C_N}{C_{NF}} \qquad (7)$$

where:

C_i = The number of coverages applied during period *i*

C_{iF} = The number of coverages to failure computed for period *i*

$\frac{C_i}{C_{iF}}$ = The cumulative damage factor, CDF_i, for period *i*

CDF_T = The total CDF for the complete test to failure

Step 8: In terms of CDF, failure is defined as $CDF_T = 1.0$. The key to the analysis is that, in theory, the condition $CDF_T = 1.0$ should correspond to the observed physical failure of the test section. If the calculated CDF_T is higher than 1.0, then the failure model is shifted upward just enough to make CDF equal to 1.0. Likewise, if the calculated CDF_T is less than 1.0, then the failure model is shifted downward just enough to make CDF equal to 1.0.

4.2 CONSTRUCTION CYCLE CC3.

The CC3 traffic test was conducted at the NAPTF in 2002, and the test data are available on the NAPTF website [2]. The primary objectives for CC3 were

- to provide additional full-scale traffic testing data for incorporation in new thickness design procedures then under development by the FAA; and

- to provide additional full-scale pavement response and failure information in support of the reevaluation of alpha factors at 10,000 coverages for the calculation of ACNs of four- and six-wheel landing gear configurations.

In CC3, four new flexible pavement test sections conforming to the Type II structure (5 inches of P-401 asphalt surface, 8 inches of P-209 crushed stone base, and varying subbase thickness) were constructed on a CBR 3-4 subgrade, as shown on figure 16 [10 and 11]. Test sections were identified with the nomenclature LFC1 through LFC4, where LFC refers to a traffic test item with low-strength subgrade (L), flexible surface (F), and conventional aggregate base construction (C). Traffic tests were performed with 3D loading on the north side and 2D loading on the south track, as shown on figure 17. Figures 18 and 19 show the gear configurations used in FAARFIELD to calculate vertical strain at the top of the subgrade.

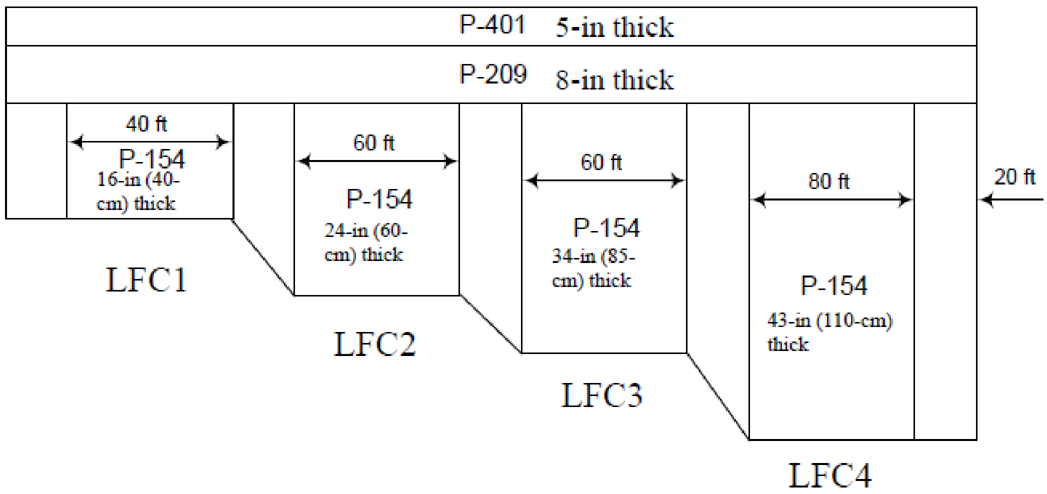


Figure 16. Cross-Sectional Layout of CC3 Test Sections

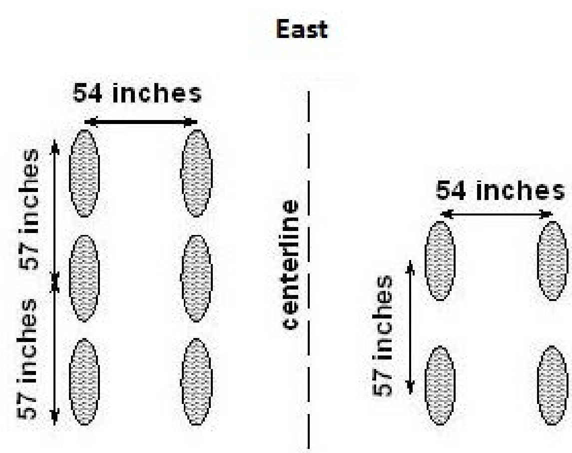


Figure 17. The CC3 Gear Configurations

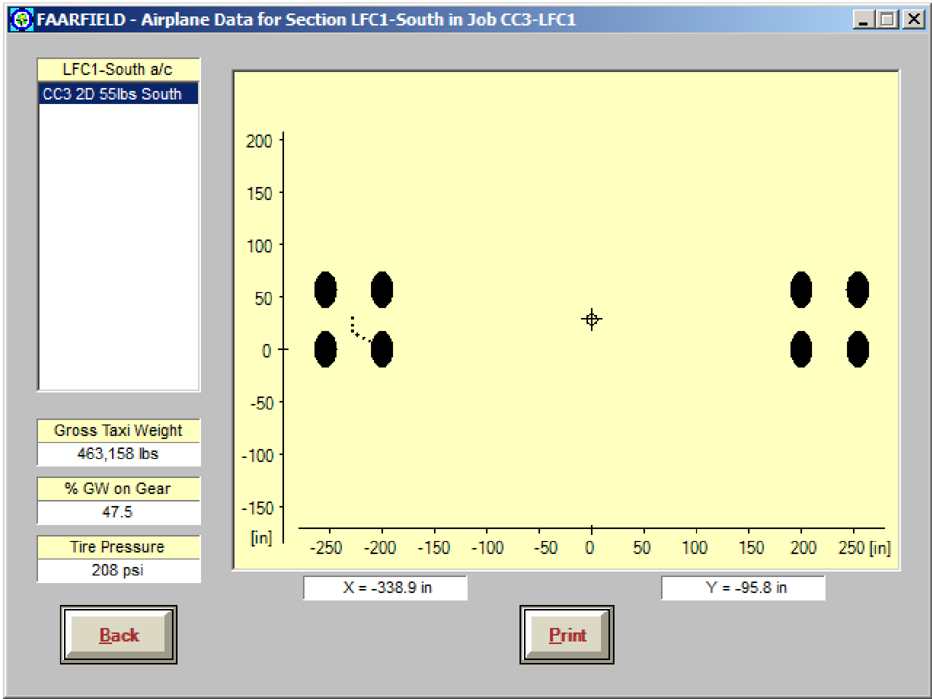


Figure 18. Screen Capture of 2D CC3 Gear Configuration in FAARFIELD

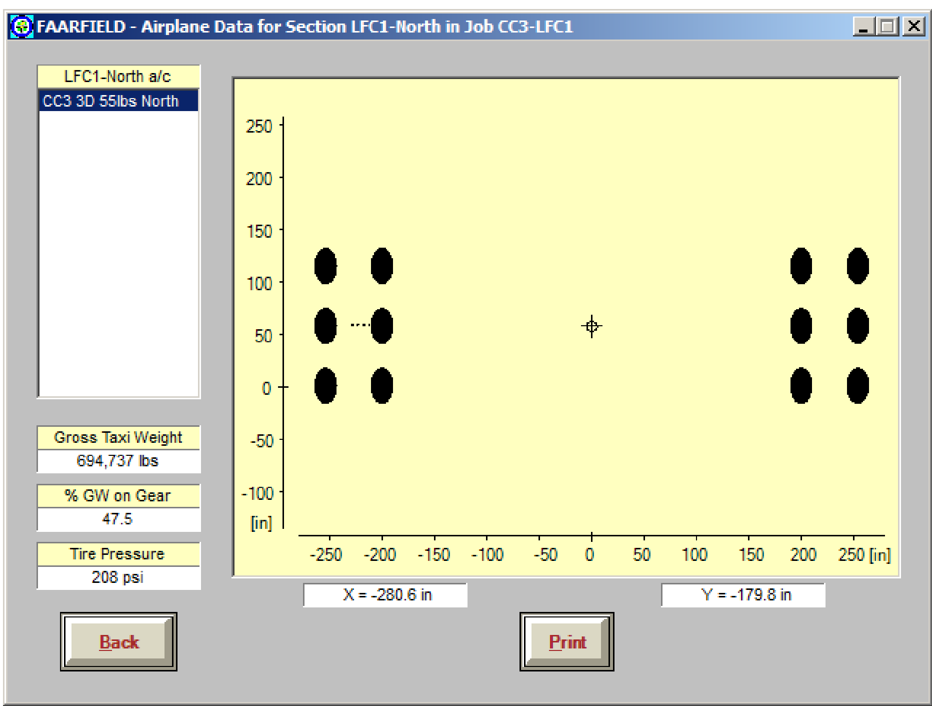


Figure 19. Screen Capture of 3D CC3 Gear Configuration in FAARFIELD

4.3 DATA ANALYSIS OF CC3 TEST SECTIONS.

CC3 was trafficked from September 3, 2002 to October 18, 2002. During this time, the HMA temperature varied, which needs to be accounted for when estimating HMA modulus. The total time during which the CC3 sections were trafficked was divided into periods of relatively constant temperatures. Based on temperature, the HMA modulus for each period was estimated. Table 5 presents a summary of HMA temperature, HMA modulus, and number of passes in each specific period. In table 5, the HMA modulus as a function of temperature was estimated using the formula [12]:

$$\log_{10}(E) = 1.53658 - 0.006447T - 0.00007404T^2 \quad (8)$$

where T is the HMA temperature in degrees Fahrenheit, and E is the HMA modulus in units of psi × 10^5.

Table 5. Summary of HMA Temperature, HMA Modulus, and Traffic for CC3

Test Item	North (3D)				South (2D)		
	HMA Temperature (°F)	HMA Modulus (psi)	Passes		HMA Temperature (°F)	HMA Modulus (psi)	Passes
LFC1	77	399,584	90		77	399,584	132
LFC2	77	399,584	1,584		77	399,584	2,970
LFC3	78	383,292	3,810		78	383,292	3,810
	80	352,269	2,658		80	352,269	2,658
	85	283,417	8,580		85	283,417	8,580
	88	247,738	4,952		88	247,738	5,082
	-	-	-		82	323,269	1,834
	-	-	-		75	433,769	18,036

All north and south sections for LFC1, LFC2, and LFC3 failed according to the test failure criteria discussed at the beginning of this section. Table 6 shows LFC1-North (3D) data analysis results using the FAARFIELD 1.40 model. The number of coverages to failure, C_F, is obtained from the subgrade vertical strain using equation 5 or 6. Since the computed CDF is greater than 1.0, the FAARFIELD model had to be shifted upward (as shown in figure 20), to force CDF to equal 1.0 (table 7). In table 7, the vertical subgrade strain is given for the reference HMA temperature of 77°F (giving an HMA modulus close to 400,000 psi, as shown in table 5) and for 90°F, the reference temperature corresponding to the standard FAARFIELD HMA modulus of 200,000 psi. The computed number of coverages corresponding to the latter strain is the final data point for CC3 LFC1-North (3D).

Table 6. Analysis Results for CC3 LFC1-North With FAARFIELD 1.41 Model

Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	77	90	0.44	204.55	0.002737	28.6	7.152

Table 7. Analysis Results for CC3 LFC1-North With Shifted FAARFIELD 1.41 Model

Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	77	90	0.44	204.55	0.002737	204.55	1.000
55,000	90	58.76	0.44	133.55	0.002885	133.55	1.000

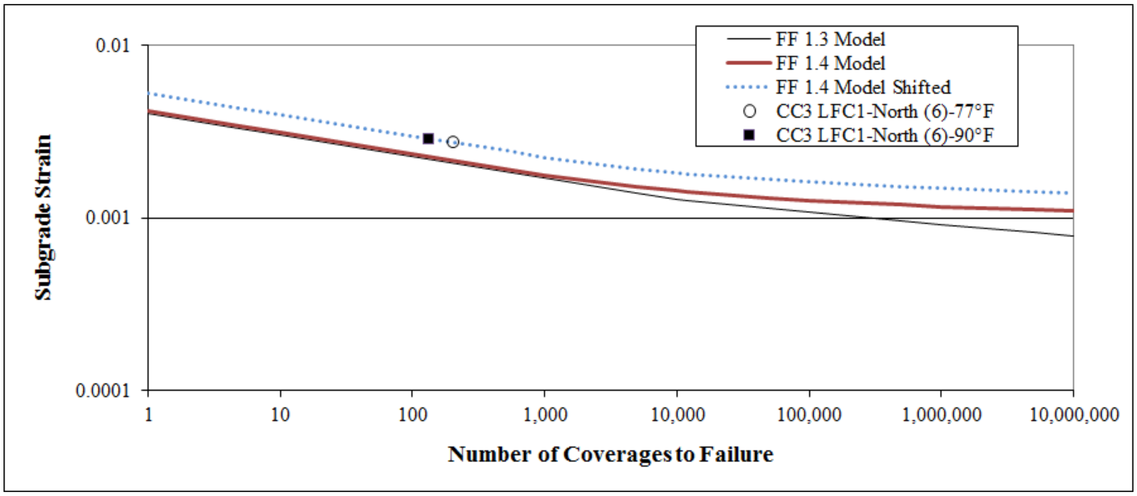


Figure 20. Subgrade Failure Models With CC3 LFC1-North (3D) Data Points

Tables 8 through 10 show the results of similar analyses for sections LFC1-South (2D), LFC2, and LFC3. Sections LFC1 and LFC2 were trafficked only at one wheel load level (55,000 lb). LFC3 was trafficked at multiple wheel load levels of 55,000 lb. and 65,000 lb. As with LFC1-North (3D), the final data points are computed for the reference HMA temperature 90°F.

Table 8. Analysis Results for CC3 LFC1-South (2D) With Shifted FAARFIELD 1.41 Model

Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	77	132	0.66	200.00	0.002239	200	1.000
55,000	90	76	0.66	115.10	0.002397	115	1.000

Table 9. Analysis Results for CC3 LFC2 With Shifted FAARFIELD 1.41 Model

CC3 LFC2-North (3D)							
Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	77	1,584	0.40	3,960	0.001948	3,960	1.000
55,000	90	1,063	0.40	2,658	0.002018	2,658	1.000
CC3 LFC2-South (2D)							
Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	77	2,970	0.59	5,034	0.001747	5,034	1.000
55,000	90	1,727	0.59	2,927	0.001830	2,927	1.000

Table 10. Analysis Results for CC3 LFC3 With Shifted FAARFIELD 1.41 Model

CC3 LFC3-North (3D)							
Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	78	3,810	0.48	7,938	0.001614	5.00E+06	0.002
65,000	80	2,658	0.52	5,112	0.001911	37,056	0.138
65,000	85	8,580	0.52	16,500	0.001927	31,501	0.524
65,000	88	4,952	0.52	9,523	0.001939	28,286	0.337
		20,000	-	39,072	-	∑ CDF = 1.000	
CC3 LFC3-North (3D)							
Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
65,000	90	12,493	0.52	23,822	0.001957	23,822	1.000
CC3 LFC3-South (2D)							
Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
55,000	78	3,810	0.66	5,773	0.001398	2.78E+06	0.002
65,000	80	2,658	0.70	3,797	0.001657	28,320	0.134
65,000	85	8,580	0.70	12,257	0.001674	23,610	0.519
65,000	88	5,082	0.70	7,260	0.001685	21,062	0.345
65,000	82	1,834	0.70	2,620	0.001650	30,355	0.086
65,000	75	18,036	0.70	25,766	0.001642	33,567	0.768
		40,000	-	29,087	-	∑ CDF = 1.000	
CC3 LFC3-South (2D)							
Wheel Load (lb)	Temperature (°F)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F	CDF
65,000	90	12,278	0.70	17,539	0.001703	17,539	1.000

4.4 CONSTRUCTION CYCLE CC5.

The CC5 traffic test was conducted at the NAPTF between 2008 and 2012, and the test data are available on the NAPTF website [2]. The primary objective of CC5 was to measure the performance of six- and ten-wheel gear configurations for comparison with predictions from the layered elastic-based model in FAARFIELD and the alpha factor-based model in the CBR method of design.

CC5 pavement sections were trafficked with loads of 50,000 lb, 58,000 lb, 65,000 lb, and 70,000 lb per wheel, sequentially. Loads were increased during testing because pavement distress was very slow to accumulate. Failure ultimately occurred under 70,000-lb wheel loads for two test sections, LFC1-NW (6) and LFC1-NE (10). The number in parentheses indicates the number of wheels in the loading gear.

Table 11 provides pavement sections constructed for both failed sections including CBR values obtained in post-traffic testing. Figure 21 shows gear configurations used to traffic section LFC1-NW (6) and LFC1-NE (10). Figures 22 and 23 show gear configurations used in FAARFIELD to calculate vertical strain at the top of the subgrade.

Table 11. Pavement Structure Data for LFC1-NW and LFC1-NE

Pavement Section	Layer Type	Layer Thickness (in.)
LFC1-NW (6)	P-401	5
	P-209	8
	P-154	34
	Subgrade (CBR=5.7)	-
LFC1-NE (10)	P-401	5
	P-209	8
	P-154	34
	Subgrade (CBR=5.2)	-

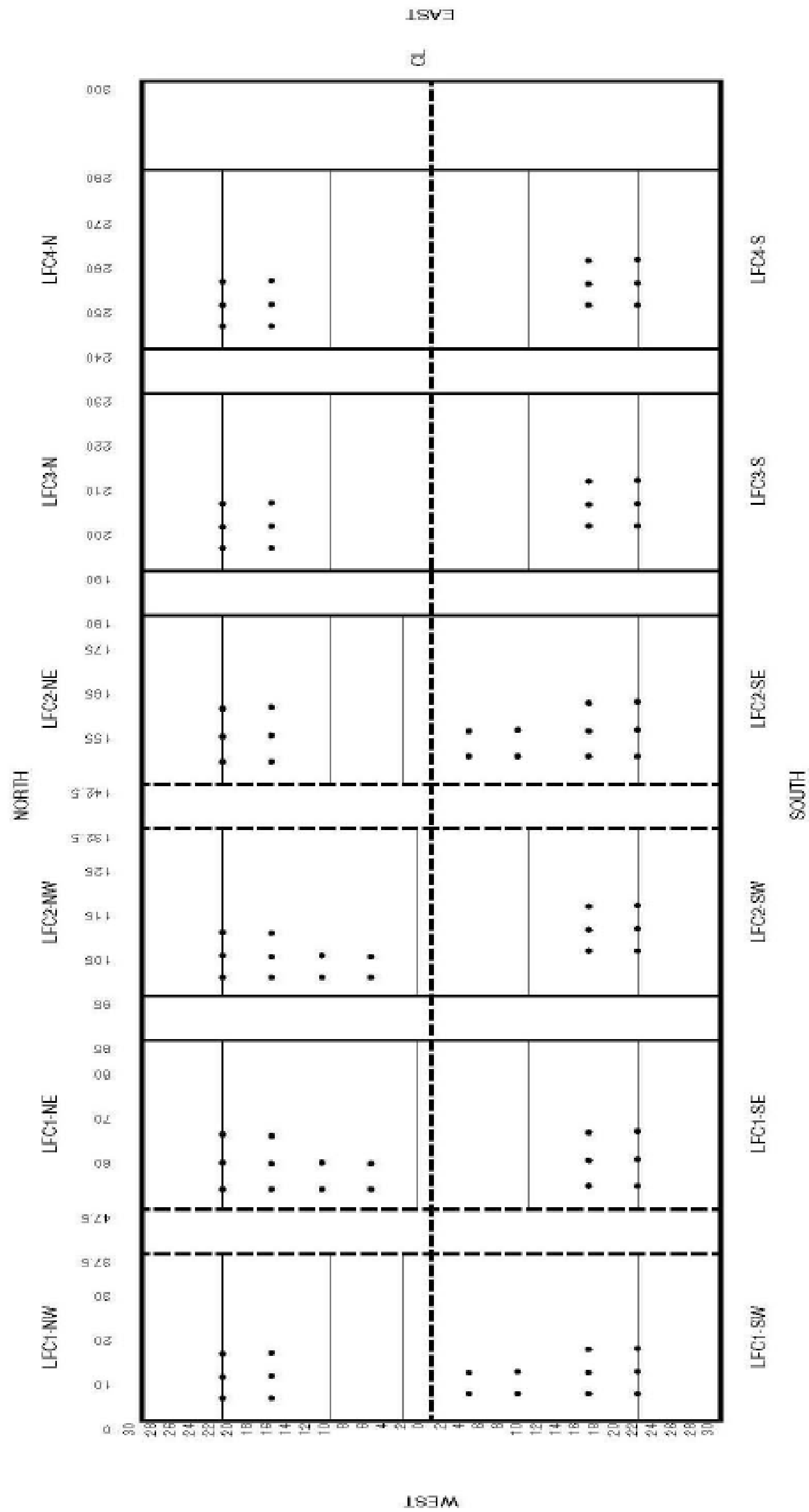


Figure 21. Wander Pattern—Test Items (CC-5)

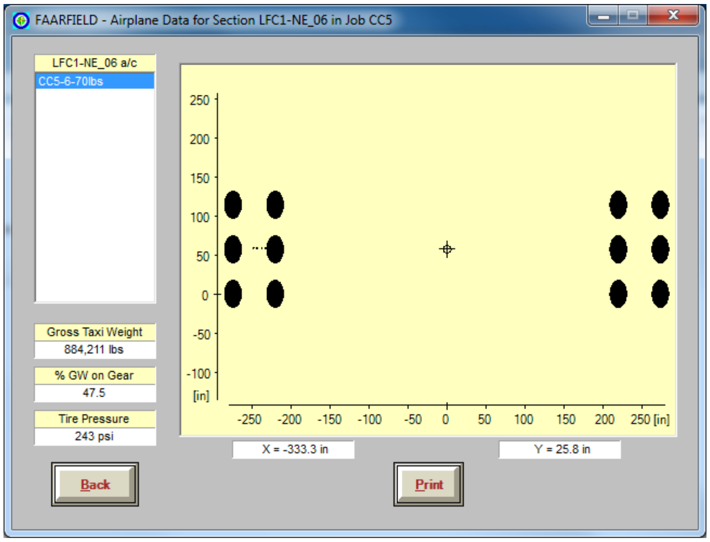


Figure 22. Gear Configuration Used in FAARFIELD for LFC1-NW (6)

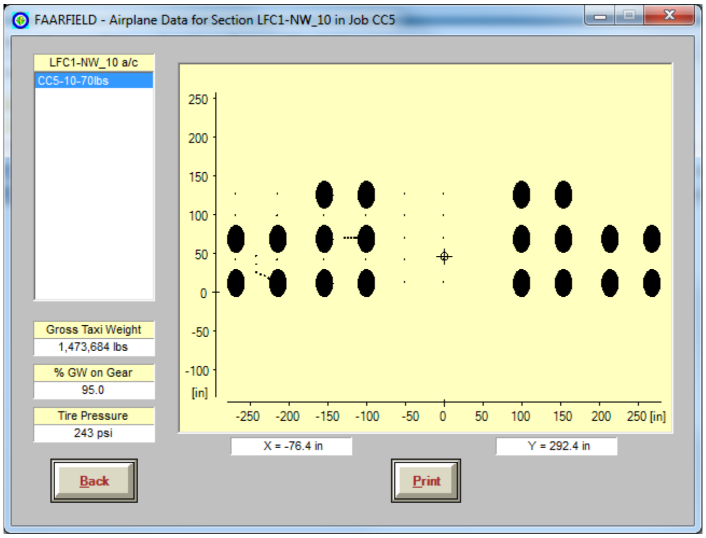


Figure 23. Gear Configuration Used in FAARFIELD for LFC1-NE (10)

4.5 DATA ANALYSIS OF CC5 TEST SECTIONS.

Table 12 shows analysis results for CC5 LFC1-NW (6) and CC5 LFC1-NE (10). The sections were trafficked with a combination of 50,000 lb, 58,000 lb, 65,000 lb, and 70,000 lb per wheel gear loads. Due to the mixed traffic loading, the separate contribution of each wheel load to the total CDF must be considered.

Table 12. Analysis Results for CC5 LFC1 (shifted FAARFIELD 1.41 model)

CC5 LFC1-NW (6)						
Wheel Load (lb)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F*	CDF
50,000	7,917	0.44	17,993	0.001215	4.00E+12	0.000
58,000	4,954	0.46	10,770	0.001407	2,946,629	0.004
65,000	5,621	0.48	11,710	0.001575	88,304	0.133
70,000	9,031	0.50	18,062	0.001695	20,912	0.864
						∑CDF=1.000
CC5 LFC1-NE (10)						
Wheel Load (lb)	Passes	P/C	Coverages	Subgrade Vertical Strain	C_F*	CDF
50,000	7,917	0.44	17,993	0.001431	5.20E+09	0.000
58,000	4,954	0.46	10,770	0.001657	650,272	0.017
65,000	5,621	0.48	11,710	0.001854	38,220	0.306
70,000	3,778	0.50	7,556	0.001995	11,160	0.677
						∑CDF=1.000

*C_F = Number of coverages to failure

4.6 SUMMARY OF RESULTS FOR CC3 AND CC5 TEST SECTIONS.

Figure 24 shows subgrade failure models plotted against the CC3 and CC5 data points. Both failure models are lower envelopes for the failure points (i.e., both failure models are conservative predictors of structural life). Figure 24 shows that, although both models predicted a longer life for the NAPTF test sections than was observed, the FAARFIELD 1.41 model was less conservative than FAARFIELD 1.3, especially at higher coverage levels.

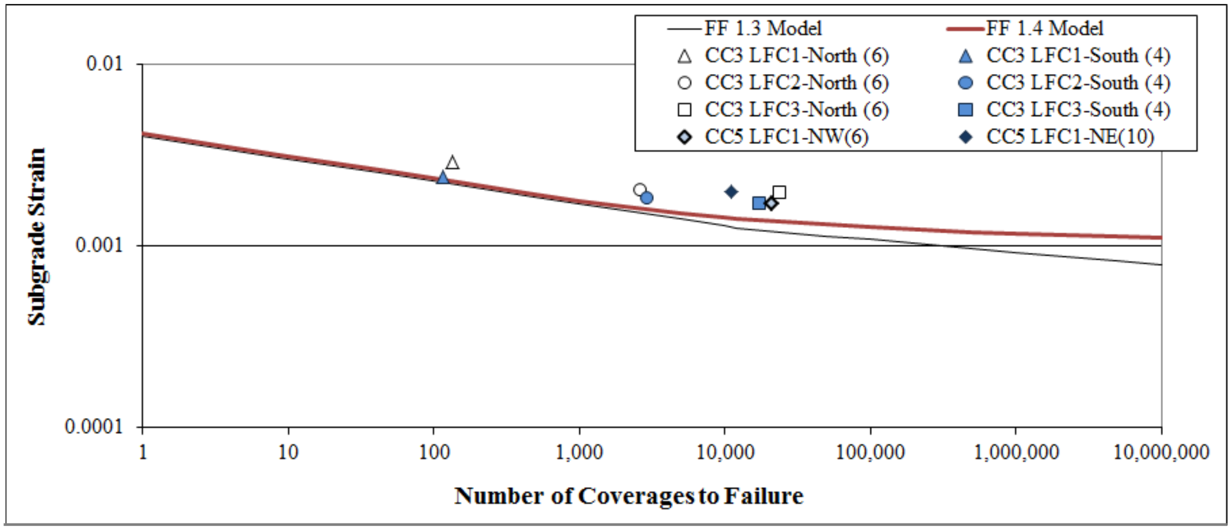


Figure 24. Subgrade Failure Models With CC3 and CC5 Data Points

5. COMPARISON OF PAVEMENT DESIGNS USING FAARFIELD AND COMFAA.

To compare, four gear types were selected: a 50,000-lb single-wheel load (SWL-50), Boeing B737-800, McDonnell Douglas DC10-10, and Boeing B777-200 Baseline. Calculations were made for four values of subgrade CBR: 3, 6, 10, and 15. Following Appendix B of AC 150/5335-5C [13], COMFAA uses a reference pavement structure of 3 inches of P-401 HMA surface, 6 inches of P-209 base, and a P-154 subbase when no aircraft in the traffic mix have four or more wheels on a main gear. When one or more aircraft in the traffic mix have four or more wheels on a main gear, the reference structure used is 5 inches P-401 and 8 inches P-209. Figure 25 shows an example of pavement structure selected for aircraft SWL-50 and B737-800 (no aircraft with four or more wheels), and figure 26 shows an example of pavement structure selected for the DC-10-10 and B777-200 Baseline.

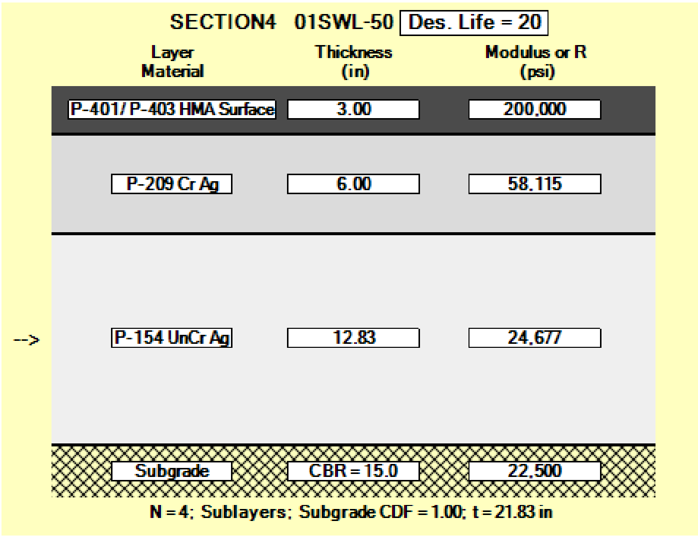


Figure 25. Example of Pavement Design for SWL-50 and B737-800 Aircraft

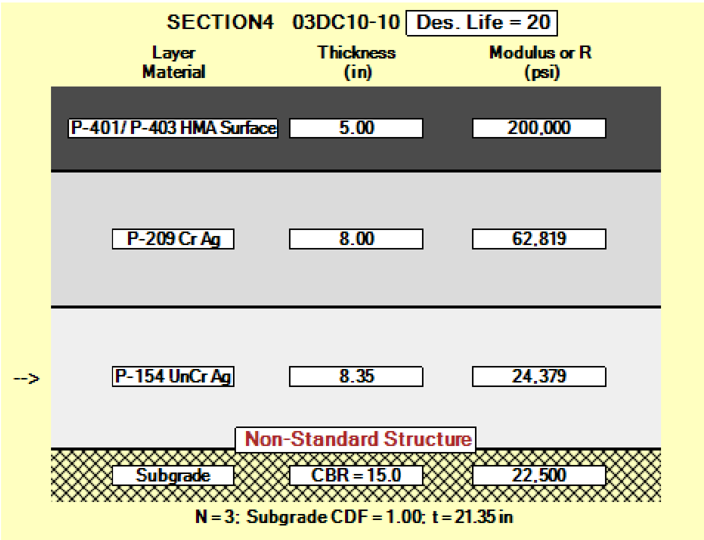


Figure 26. Example of Pavement Design for DC-10-10 and B777-200 Baseline Aircraft

Figures 27 through 38 show a comparison of total design thicknesses calculated with COMFAA, FAARFIELD 1.3, and FAARFIELD 1.4. The vertical axis is the difference, in inches between the FAARFIELD total thickness and the COMFAA required thickness. Note that, because standard reference structures were used, there was no need to apply layer equivalency factors to the COMFAA thickness. Overall, FAARFIELD 1.4 better matches the thickness design results from COMFAA than does FAARFIELD 1.3, by 1 inch on average. This shows that the new failure model described in section 2 of this report improved the correlation of FAARFIELD results with COMFAA results, in particular for higher traffic levels.

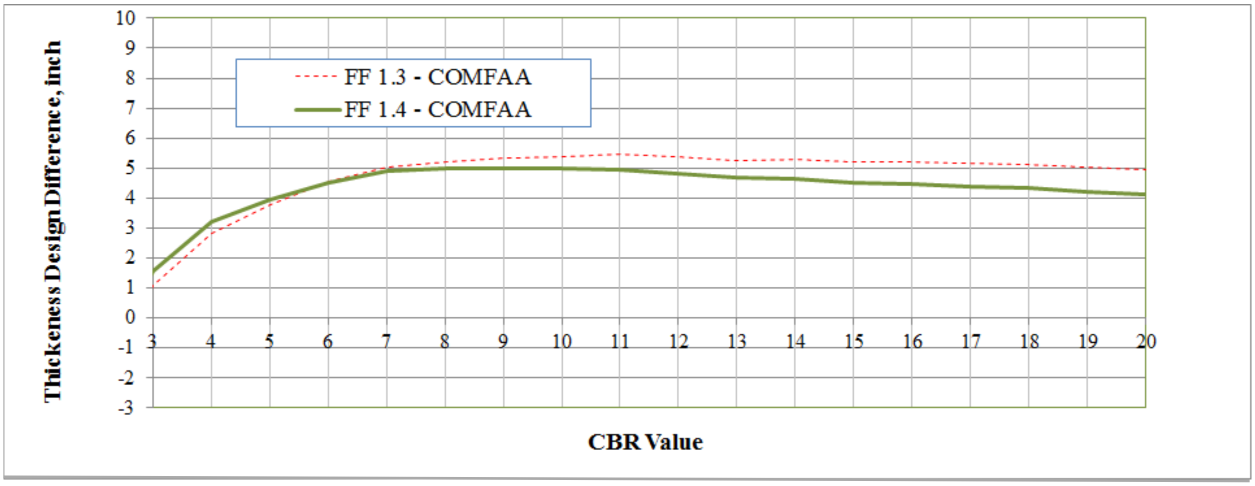


Figure 27. Difference in Thickness Designs for SWL-50 and 500 Annual Departures

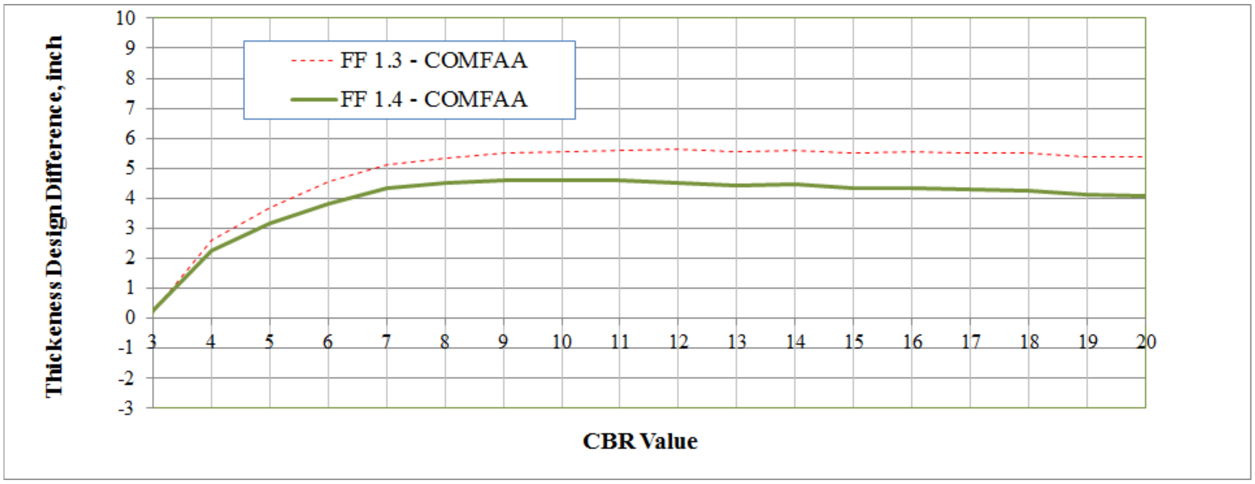


Figure 28. Difference in Thickness Designs for SWL-50 and 1000 Annual Departures

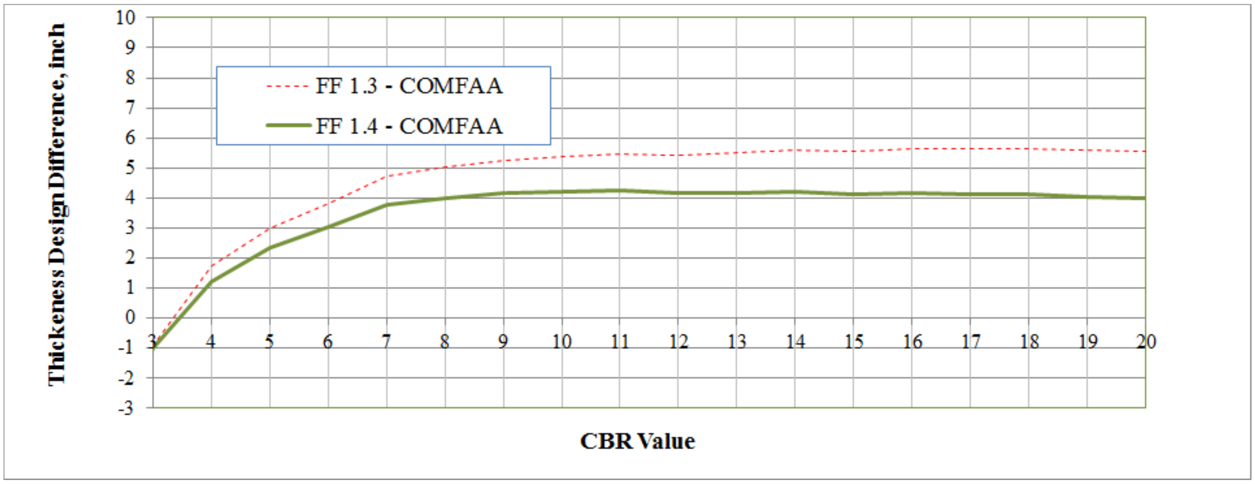


Figure 29. Difference in Thickness Designs for SWL-50 and 2000 Annual Departures

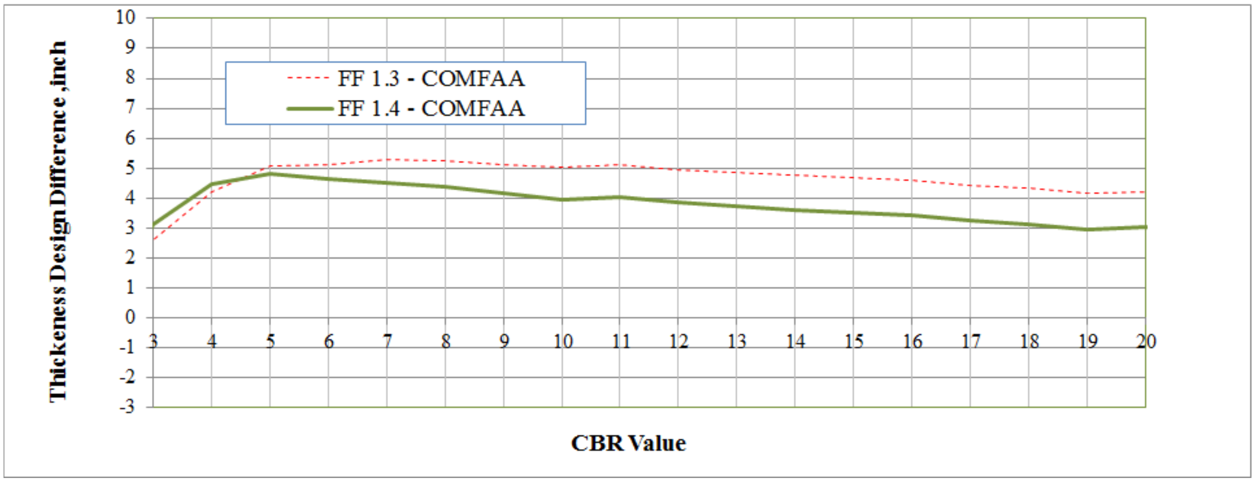


Figure 30. Difference in Thickness Designs for B737-800 and 500 Annual Departures

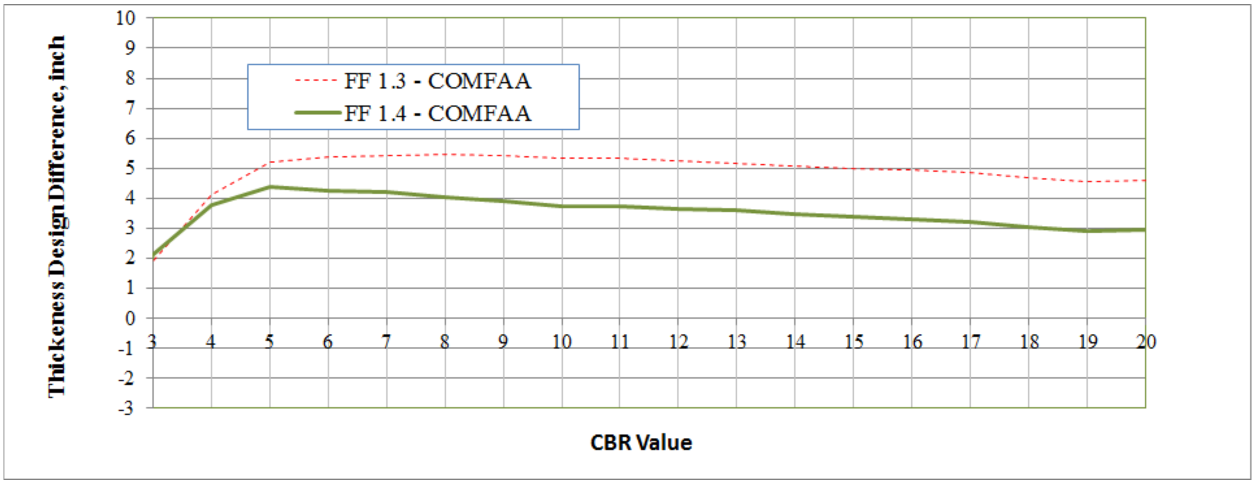


Figure 31. Difference in Thickness Designs for B737-800 and 1000 Annual Departures

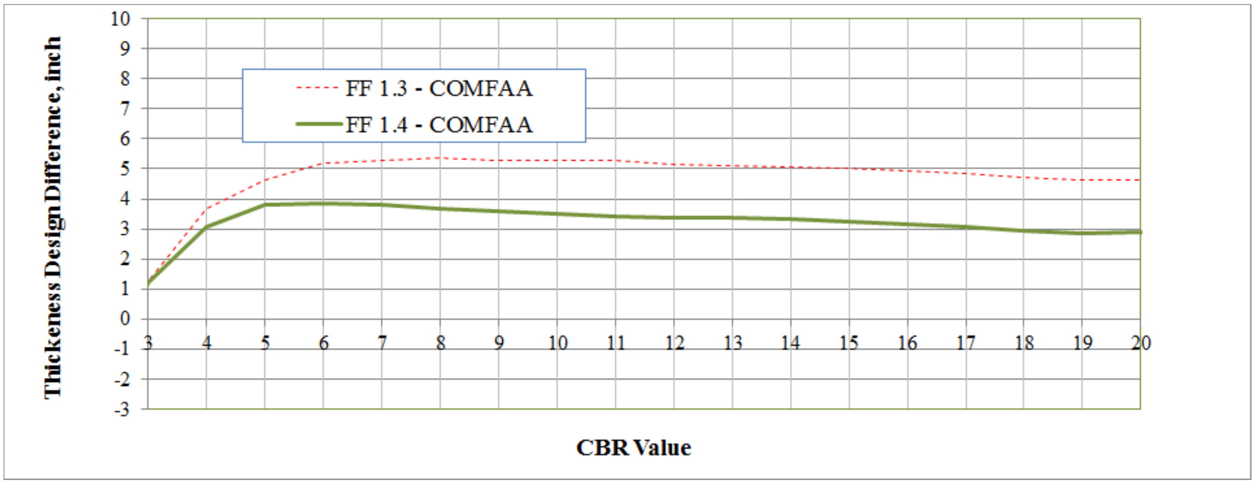


Figure 32. Difference in Thickness Designs for B737-800 and 2000 Annual Departures

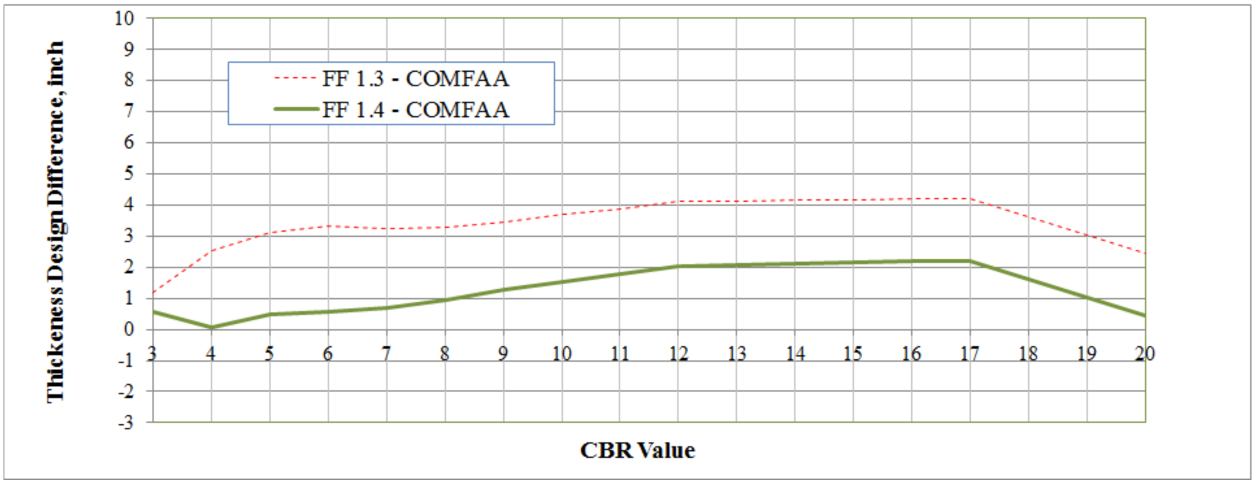


Figure 33. Difference in Thickness Designs for DC-10-10 and 500 Annual Departures

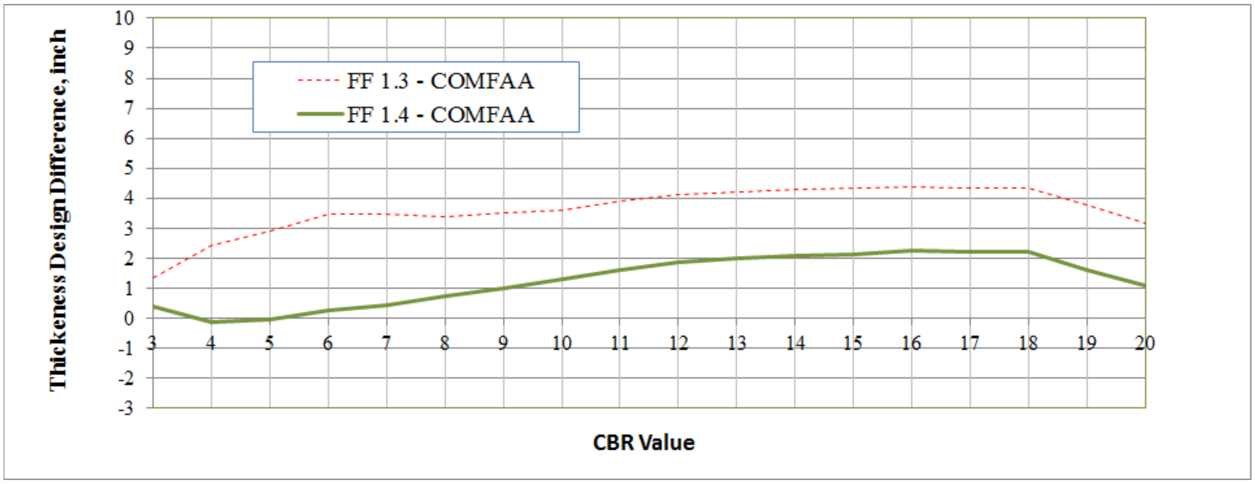


Figure 34. Difference in Thickness Designs for DC-10-10 and 1000 Annual Departures

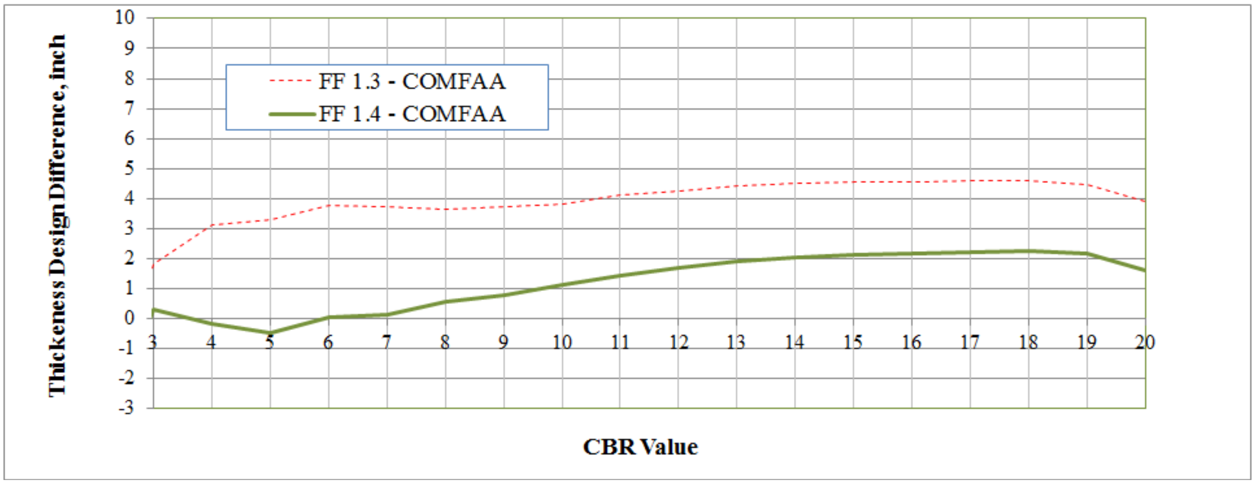


Figure 35. Difference in Thickness Designs for DC-10-10 and 2000 Annual Departures

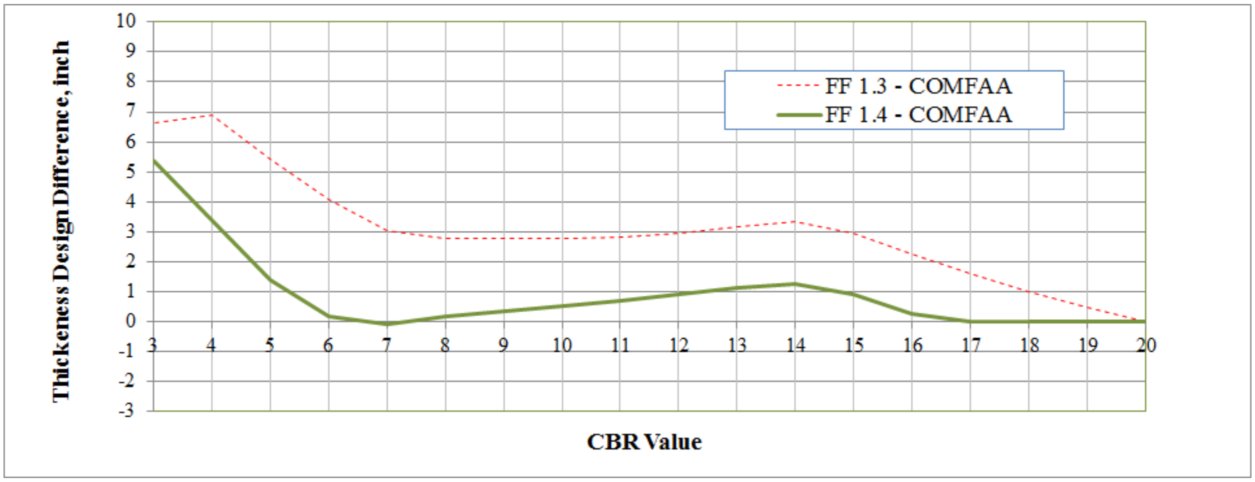


Figure 36. Difference in Thickness Designs for B777-200 Baseline and 500 Annual Departures

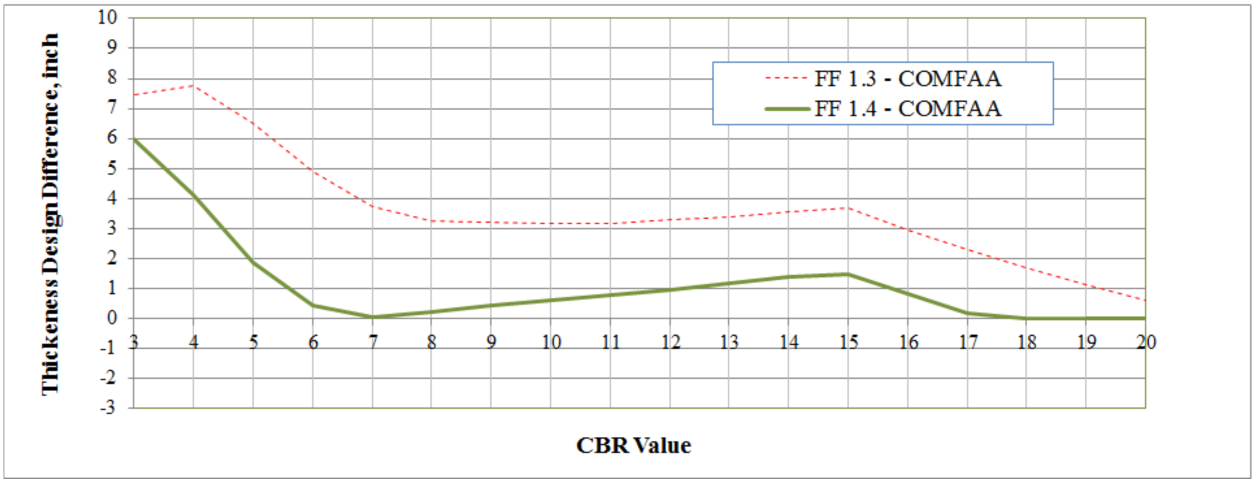


Figure 37. Difference in Thickness Designs for B777-200 Baseline and 1000 Annual Departures

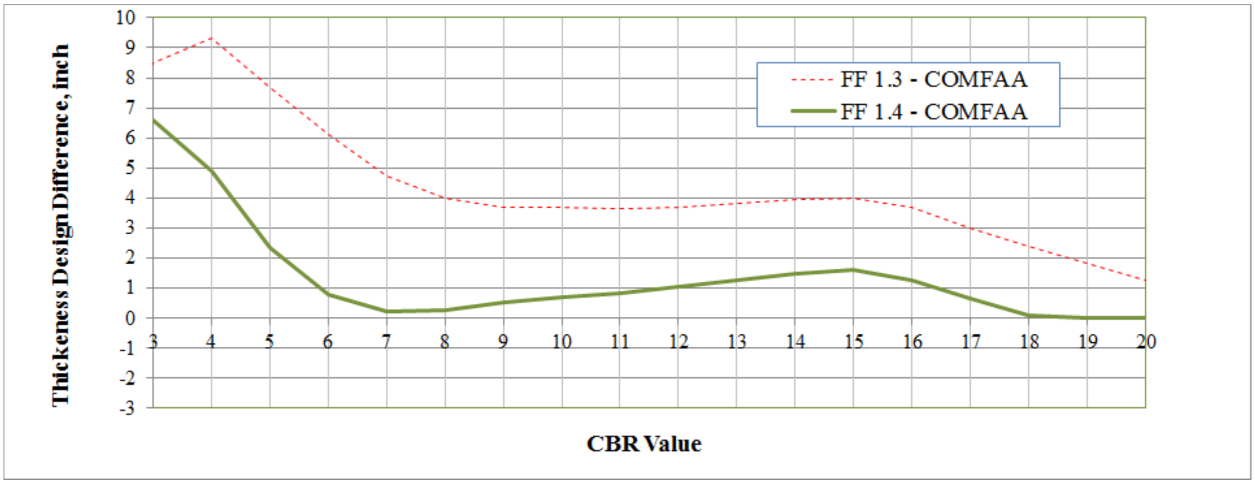


Figure 38. Difference in Thickness Designs for B777-200 Baseline and 2000 Annual Departures

6. CONCLUSIONS.

This report describes the development of a new subgrade failure model for flexible pavements in the Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) 1.4 pavement thickness design software. The model development included an extensive modification of the original U.S. Army Engineer Waterways Experiment Station (WES)-developed subroutine for aggregate layer modulus assignment. The new modulus assignment routine contains significant improvements. The sublayering procedure was rewritten to eliminate discontinuities in the thickness-versus-modulus curve, even at the boundaries between discrete numbers of sublayers. Also, the parameters were changed to produce effective equivalency factors for the conversion from P-209 and P-154, that are, on average, closer to the target value of 1.4.

The new failure model was derived by backcalculation from four- and six-wheel alpha factor curves used in the FAA COMFAA program, applying the new aggregate layer modulus model described in section 1. The resulting FAARFIELD failure model was then compared to full-scale test results from National Airport Pavement Testing Facility (NAPTF) construction cycles CC3 and CC5 full-scale traffic tests.

Two conclusions can be stated about the new failure model:

- The new failure model implemented in FAARFIELD 1.4 is generally less conservative than the previous (FAARFIELD 1.3) model when compared to results obtained from full-scale test pavements in CC3 and CC5 at the NAPTF. Both models are a lower envelope to the observed failure points. However, the FAARFIELD 1.4 model is a better fit to observed data at high coverage levels, where the previous model was excessively conservative.

- There are still significant design thickness differences between COMFAA and FAARFIELD 1.4. Because of the fundamentally different design methods in these two programs, the differences can be reduced, but not totally eliminated. However, because of the method by which the failure curve was derived from alpha factor data, the new failure model in FAARFIELD 1.4 now produces flexible design thicknesses that differ less from COMFAA results than FAARFIELD 1.3.

7. REFERENCES.

1. Federal Aviation Administration, "Airport Pavement Design and Evaluation," Advisory Circular (AC) 150/5320-6E, September 30, 2009 (cancelled and replaced with AC 150/5320-6F on November 10, 2016).

2. FAA Airport Technology Research & Development Branch Home Page, available at http://www.airporttech.tc.faa.gov/ (date last visited 04/06/17).

3. FAA, "Airport Pavement Design and Evaluation," AC 150/5320-6F, November 10, 2016.

4. Joint Departments of the Army and Air Force, "Pavement Design for Roads, Streets, and Open Storage Areas, Elastic Layered Method," Army TM 5-822-13, Air Force AFJMAN 32-1018, Washington, DC, October 24, 1994.

5. Unified Facilities Criteria (UFC), "Airfield Pavement Evaluation," UFC 3-260-03, April 15, 2001.

6. FAA, "Airport Pavement Design and Evaluation," AC 150/5320-6D, July 7, 1995 (cancelled and replaced with AC 150/5320-6E on September 30, 2009).

7. Ahlvin, R.G., Ulery H. H., Hutchinson, R. L., and Rice, J.L., "Multiple-Wheel Heavy Gear Load Pavement Tests, Volume I, Basic Report," Technical Report S-71-17 (AFWL-TR-70-113, Vol I), November 1971.

8. Tuleubekov, K., "Replacement of FAARFIELD Tandem Factors With Cumulative Damage Factor Methodology," FAA Final Report DOT/FAA/TC-16/46, October 2016.

9. Hayhoe, G.F. and Kawa, I., "Methodology for Temperature and Load Compensation in Full-Scale Traffic Tests on Flexible Airport Pavements," *Ninth International Conference on the Bearing Capacity of Roads, Railways and Airfields (BCRRA),* Trondheim, Norway, June 24-27, 2013.

10. Hayhoe, G.F., "Traffic Testing Results From the FAA's National Airport Testing Facility," *2nd International Conference on Accelerated Pavement Testing*, University of Minnesota, Minneapolis, Minnesota, September 26-29, 2004.

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12. Witczak, M.W. and Uzan, J., "The Universal Airport Pavement Design System, Report II: Asphalt Mixture Material Characterization," University of Maryland, May 1989.

13. FAA, "Standardized Method of Reporting Airport Pavement Strength—PCN," AC 150/5335-5C, August 14, 2014.

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APPENDIX A—COMFAA AIRCRAFT EXTERNAL LIBRARY LISTING

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COMFAAFormat2
This line, and all lines up to, but not including, the Start Data marker
are for information and are not required. All other lines must be provided
in the given format, including the first line above this message and the
line with "Start Data" on it, or the file will not be read correctly.
The routine which reads the file has very little error checking.

Y coordinate is longitudinal and X is transverse.

The fields below are required for each aircraft.
All fields must contain valid data except where noted.

Aircraft Name
Gross Weight of Aircraft, lbs
Number of main gears
Percent of Gross Weight on all of the main gears
Number of tires on the evaluation gear (shown in the display), NTires
  TX TY (for NTires), two numbers in inches
Tire pressure, psi (used in ACN calculations)
Tire contact area, in^2 (used in thickness calculations)
For the X direction: (grid origin) (maximum grid dimension) (number of grid
points), three numbers in inches
For the Y direction: (grid origin) (maximum grid dimension) (number of grid
points), three numbers in inches
Data from the last two lines is only used when (number of grid points) is
greater than zero.
When this is true, the field values define the grid. Otherwise, a default
grid is computed.
The grid is used for flexible pavements only.
Coverages.


Start Data
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           4
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      27.000     -57.000
     -27.000       0.000
      27.000       0.000
     207.547
     265.000
     -57.000     -28.500           0
     -27.000       0.000           0
   10000.000
NAPTF 3D
      600000
           2
      95.000     100.000
           6
     -27.000     -57.000
```

27.000	-57.000	
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27.000	0.000	
27.000	57.000	
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2145.985		

APPENDIX B—BACKCALCULATION RESULTS

Tables B-1 through B-8 present the tabular results for the data used to develop failure curves for four-wheel (2D) and six-wheel (3D) gear configurations at various California Bearing Ratios (CBRs). COMFAA refers to COMFAA 3.0 and FAARFIELD to FAARFIELD 1.41.

In this appendix, P/Cs represents the pass-to-coverage ratio at the top of the pavement surface in COMFAA, P/Csg represents the pass-to-coverage ratio at the subgrade level in FAARFIELD 1.40, and C_{FF} represents the number of coverages to failure for FAARFIELD, obtained by multiplying the coverages in the first column by the ratio of P/Cs to P/Csg.

Table B-1. Results for 2D Gear Load, Structure Type I, CBR 4

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	2D C_{FF}	Subgrade Strain
10	19.14	10.14	1.95		0.851	23	0.005062
20	23.33	14.33	1.95		0.759	51	0.003809
50	28.67	19.67	1.95		0.669	146	0.002844
100	32.56	23.56	1.95		0.616	317	0.002384
200	36.33	27.33	1.95		0.596	654	0.002096
500	41.21	32.21	1.95		0.606	1,609	0.001815
1,000	44.66	35.66	1.95		0.637	3,061	0.001661
2,000	47.80	38.80	1.95		0.670	5,821	0.001555
5,000	51.36	42.36	1.95		0.712	13,694	0.001454
10,000	53.69	44.69	1.95		0.743	26,245	0.001402
12,100	54.28	45.28	1.95		0.752	31,376	0.001390
20,000	55.75	46.75	1.95		0.774	50,388	0.001362
50,000	58.15	49.15	1.95		0.814	119,779	0.001317
100,000	59.74	50.74	1.95		0.843	231,317	0.001288
200,000	61.15	52.15	1.95		0.871	447,761	0.001262
500,000	62.78	53.78	1.95		0.906	1,076,159	0.001233
1,000,000	63.86	54.86	1.95		0.931	2,094,522	0.001214

Table B-2. Results for 2D Gear Load, Structure Type I, CBR 5

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	2D C_{FF}	Subgrade Strain
10	16.70	7.70	1.95		0.916	21	0.005077
20	20.18	11.18	1.95		0.826	47	0.003964
50	24.66	15.66	1.95		0.734	133	0.002937
100	27.84	18.84	1.95		0.681	286	0.002487
200	30.84	21.84	1.95		0.638	611	0.002165
500	34.60	25.60	1.95		0.599	1,628	0.001856
1,000	37.30	28.30	1.95		0.594	3,283	0.001706
2,000	39.91	30.91	1.95		0.596	6,544	0.001581
5,000	43.13	34.13	1.95		0.623	15,650	0.001450
10,000	45.26	36.26	1.95		0.643	30,327	0.001376
12,100	45.84	36.84	1.95		0.649	36,356	0.001360
20,000	47.21	38.21	1.95		0.663	58,824	0.001324
50,000	49.42	40.42	1.95		0.688	141,715	0.001268
100,000	50.87	41.87	1.95		0.706	276,204	0.001235
200,000	52.16	43.16	1.95		0.722	540,166	0.001210
500,000	53.66	44.66	1.95		0.743	1,312,248	0.001183
1,000,000	54.67	45.67	1.95		0.758	2,572,559	0.001168

Table B-3. Results for 2D Gear Load, Structure Type II, CBR 4

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	2D C_{FF}	Subgrade Strain
10	19.14	6.14	1.95		0.851	23	0.004292
20	23.33	10.33	1.95		0.759	51	0.003394
50	28.67	15.67	1.95		0.669	146	0.002586
100	32.56	19.56	1.95		0.616	317	0.002241
200	36.33	23.33	1.95		0.596	654	0.001986
500	41.21	28.21	1.95		0.606	1,609	0.001735
1,000	44.66	31.66	1.95		0.637	3,061	0.001608
2,000	47.80	34.80	1.95		0.670	5,821	0.001510
5,000	51.36	38.36	1.95		0.712	13,694	0.001425
10,000	53.69	40.69	1.95		0.743	26,245	0.001377
12,100	54.28	41.28	1.95		0.752	31,376	0.001365
20,000	55.75	42.75	1.95		0.774	50,388	0.001337
50,000	58.15	45.15	1.95		0.814	119,779	0.001291
100,000	59.74	46.74	1.95		0.843	231,317	0.001261
200,000	61.15	48.15	1.95		0.871	447,761	0.001235
500,000	62.78	49.78	1.95		0.906	1,076,159	0.001205
1,000,000	63.86	50.86	1.95		0.931	2,094,522	0.001186

Table B-4. Results for 2D Gear Load, Structure Type II, CBR 5

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	2D C_{FF}	Subgrade Strain
10	16.70	3.70	1.95				
20	20.18	7.18	1.95		0.826	47	0.003408
50	24.66	11.66	1.95		0.734	133	0.002670
100	27.84	14.84	1.95		0.681	286	0.002266
200	30.84	17.84	1.95		0.638	611	0.001990
500	34.60	21.60	1.95		0.599	1,628	0.001756
1,000	37.30	24.30	1.95		0.594	3,283	0.001616
2,000	39.91	26.91	1.95		0.596	6,544	0.001507
5,000	43.13	30.13	1.95		0.623	15,650	0.001394
10,000	45.26	32.26	1.95		0.643	30,327	0.001334
12,100	45.84	32.84	1.95		0.649	36,356	0.001318
20,000	47.21	34.21	1.95		0.663	58,824	0.001283
50,000	49.42	36.42	1.95		0.688	141,715	0.001236
100,000	50.87	37.87	1.95		0.706	276,204	0.001209
200,000	52.16	39.16	1.95		0.722	540,166	0.001188
500,000	53.66	40.66	1.95		0.743	1,312,248	0.001164
1,000,000	54.67	41.67	1.95		0.758	2,572,559	0.001149

Table B-5. Results for 3D Gear Load, Structure Type I, CBR 4

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs*		P/Csg**	3D C_{FF}***	Subgrade Strain
10	19.76	10.76	1.40		0.574	24	0.004288
20	24.07	15.07	1.40		0.510	55	0.003240
50	29.35	20.35	1.40		0.449	156	0.002533
100	33.06	24.06	1.40		0.415	337	0.002195
200	36.43	27.43	1.40		0.396	707	0.001997
500	40.42	31.42	1.40		0.400	1,750	0.001811
1,000	43.13	34.13	1.40		0.420	3,333	0.001704
2,000	45.50	36.50	1.40		0.440	6,364	0.001625
5,000	48.14	39.14	1.40		0.466	15,021	0.001551
10,000	49.87	40.87	1.40		0.485	28,866	0.001506
12,100	50.29	41.29	1.40		0.490	34,571	0.001495
20,000	51.33	42.33	1.40		0.502	55,777	0.001471
50,000	52.95	43.95	1.40		0.523	133,843	0.001436
100,000	53.98	44.98	1.40		0.538	260,223	0.001414
200,000	54.88	45.88	1.40		0.551	508,167	0.001397
500,000	55.88	46.88	1.40		0.567	1,234,568	0.001378
1,000,000	56.52	47.52	1.40		0.578	2,422,145	0.001366

Table B-6. Results for 3D Gear Load, Structure Type I, CBR 5

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	3D C_{FF}	Subgrade Strain
10	17.08	8.08	1.40		0.623	22	0.004347
20	20.64	11.64	1.40		0.559	50	0.003393
50	25.00	16.00	1.40		0.498	141	0.002565
100	27.99	18.99	1.40		0.463	302	0.002233
200	30.75	21.75	1.40		0.436	642	0.001995
500	33.96	24.96	1.40		0.408	1,716	0.001775
1,000	36.11	27.11	1.40		0.396	3,535	0.001670
2,000	38.06	29.06	1.40		0.397	7,053	0.001589
5,000	40.30	31.30	1.40		0.399	17,544	0.001506
10,000	41.78	32.78	1.40		0.409	34,230	0.001457
12,100	42.14	33.14	1.40		0.412	41,117	0.001446
20,000	43.05	34.05	1.40		0.419	66,826	0.001418
50,000	44.50	35.50	1.40		0.431	162,413	0.001377
100,000	45.43	36.43	1.40		0.439	318,907	0.001352
200,000	46.23	37.23	1.40		0.447	626,398	0.001332
500,000	47.12	38.12	1.40		0.455	1,538,462	0.001313
1,000,000	47.69	38.69	1.40		0.461	3,036,876	0.001301

Table B-7. Results for 3D Gear Load, Structure Type II, CBR 4

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	3D C_{FF}	Subgrade Strain
10	19.76	6.76	1.40		0.574	24	0.003666
20	24.07	11.07	1.40		0.510	55	0.002948
50	29.35	16.35	1.40		0.449	156	0.002338
100	33.06	20.06	1.40		0.415	337	0.002094
200	36.43	23.43	1.40		0.396	707	0.001915
500	40.42	27.42	1.40		0.400	1,750	0.001749
1,000	43.13	30.13	1.40		0.420	3,333	0.001656
2,000	45.50	32.50	1.40		0.440	6,364	0.001586
5,000	48.14	35.14	1.40		0.466	15,021	0.001516
10,000	49.87	36.87	1.40		0.485	28,866	0.001476
12,100	50.29	37.29	1.40		0.490	34,571	0.001466
20,000	51.33	38.33	1.40		0.502	55,777	0.001443
50,000	52.95	39.95	1.40		0.523	133,843	0.001410
100,000	53.98	40.98	1.40		0.538	260,223	0.001390
200,000	54.88	41.88	1.40		0.551	508,167	0.001372
500,000	55.88	42.88	1.40		0.567	1,234,568	0.001353
1,000,000	56.52	43.52	1.40		0.578	2,422,145	0.001341

Table B-8. Results for 3D Gear Load, Structure Type II, CBR 5

COMFAA					FAARFIELD		
Coverage	Total Thickness (in.)	P-154 Thickness (in.)	P/Cs		P/Csg	3D C_{FF}	Subgrade Strain
10	17.08	4.08	1.40		0.623	22	0.003680
20	20.64	7.64	1.40		0.559	50	0.002937
50	25.00	12.00	1.40		0.498	141	0.002361
100	27.99	14.99	1.40		0.463	302	0.002056
200	30.75	17.75	1.40		0.436	642	0.001857
500	33.96	20.96	1.40		0.408	1,716	0.001691
1,000	36.11	23.11	1.40		0.396	3,535	0.001599
2,000	38.06	25.06	1.40		0.397	7,053	0.001527
5,000	40.30	27.30	1.40		0.399	17,544	0.001454
10,000	41.78	28.78	1.40		0.409	34,230	0.001411
12,100	42.14	29.14	1.40		0.412	41,117	0.001401
20,000	43.05	30.05	1.40		0.419	66,826	0.001375
50,000	44.50	31.50	1.40		0.431	162,413	0.001341
100,000	45.43	32.43	1.40		0.439	318,907	0.001320
200,000	46.23	33.23	1.40		0.447	626,398	0.001302
500,000	47.12	34.12	1.40		0.455	1,538,462	0.001284
1,000,000	47.69	34.69	1.40		0.461	3,036,876	0.001272