Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-03/9-1502-01-2		
4. Title and Subtitle VESYS5 RUTTING MODEL CALIBRATIONS WITH LOCAL ACCELERATED PAVEMENT TEST DATA AND ASSOCIATED IMPLEMENTATION		5. Report Date September 2002 6. Performing Organization Code
7. Author(s) Fujie Zhou and Tom Scullion		8. Performing Organization Report No. Report 9-1502-01-2
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project No. 9-1502
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Research: September 2000-August 2002 14. Sponsoring Agency Code

15. Supplementary Notes
Research performed in cooperation with Texas Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration
Research Project Title: Model Calibrations with Local ATP Data & Implementation for Focus on Solution to NAFTA Problems

16. Abstract

The Texas Department of Transportation (TxDOT) in cooperation with the Federal Highway Administration (FHWA) has established a Pooled Fund Study. The objective of this study is to integrate the accelerated pavement test technologies of Texas and other participating states with modeling capabilities developed by the FHWA in their Truck Pavement Interaction (TPI) program. This study will focus on the calibration and implementation of the latest version of the TPI software: VESYS5 to address truck size and weight policy issues related to the economic impact of heavy loads along the NAFTA corridor.

This report summarizes the research accomplishments of the Texas Transportation Institute (TTI). First, a comprehensive framework of calibrating performance model using APT data is developed. Then, as the full case study, TxMLS data on US281 are used to calibrate the VESYS5 model. The reasonable rutting parameters (GNU and ALPHA) of asphalt mixtures are backcalculated and used to calibrate the laboratory-determined rutting parameters which are measured based on the test protocol developed at TTI. In addition, the effectiveness of VESYS test methodology is validated by US281-SPS1 and LA-ALF field data. The information of truck size and weight in the U. S., Mexico, and Canada is compiled based on the comprehensive literature review. Then this information is used as the input of the calibrated VESYS5 model to demonstrate the influence of different types of trucks in the U. S., Mexico, and Canada on pavement rutting damage.

17. Key Words	18. Distribution Statement
Accelerated Pavement Test, VESYS, Rutting, Overload, Repeated Load Test	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	88	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

VESYS5 RUTTING MODEL CALIBRATIONS WITH LOCAL ACCELERATED PAVEMENT TEST DATA AND ASSOCIATED IMPLEMENTATION

by

Fujie Zhou
Research Associate
Texas Transportation Institute

and

Tom Scullion
Research Engineer
Texas Transportation Institute

Report 9-1502-01-2
Project Number 9-1502
Research Project Title: Model Calibrations with Local ATP Data & Implementation for Focus on Solution to NAFTA Problems

Sponsored by the
Texas Department of Transportation
In cooperation with the U. S. Department of Transportation
Federal Highway Administration

September 2002

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation. The engineer in charge was Tom Scullion, P.E., # 62683.

ACKNOWLEDGMENTS

This work was been completed as part of a pooled fund study entitled "Model Calibrations with Local ATP Data & Implementation for Focused Solutions to NAFTA Problems." The states of Texas, Louisiana, and New York provide funds for this study. Dr. Bill Kenis of the FHWA provided a copy of the VESYS5 program for use in this study. The DOT contacts are Dr. Dar-Hao Chen (Texas), Dr. Julian Bendana (New York), and Mr. Marsood Rasoulian (Louisiana). Their guidance throughout this study is acknowledged and greatly appreciated.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

CHAPTER 1
INTRODUCTION

BACKGROUND

The implementation of the North American Free Trade Agreement (NAFTA) between Canada, Mexico, and the United States has re-focused the attention of the Departments of Transportation (DOTs) on the need to understand the impact of heavier axle loads and new axle configurations on their highway networks. Highways designed to carry vehicle loads of 80,000 lb could be trafficked with gross loads of over 120,000 lb. New tire and axle configurations are also major concerns. Specified haulage vehicles in Mexico are equipped with "super-single" tires, and in Canada tridem-axles and triple trailers are used on many long haul routes. The use of these heavy loads and different vehicle configurations will undoubtably provide profits for the haulers but they will also have a major impact on the performance of the highway network. DOTs urgently need defensible systems to predict the additional damage and the economic impacts.

This pooled fund study is aimed at providing these tools. The work-horse of this effort will be VESYS5 pavement damage prediction model, which will be calibrated with local materials and performance data (*1*). This latest VESYS version (VESYS5) includes the capability to include both tandem and tridem-axles and prediction of the rutting within each pavement layer. This prediction is based upon the computed strains in each layer together with the layer material properties of GNU and ALPHA. Both of these parameters can be obtained from the laboratory or backcalculated from APT data. The GNU parameter is the permanent deformation parameter representing the proportionality between permanent and elastic strains, and ALPHA is the parameter which indicates the rate of increase in permanent deformation against number of load applications.

To address the issue of defensibility of damage prediction it is proposed to use in this project the controlled pavement performance data generated in accelerated pavement testing programs which are active in many DOTs around the U. S. For example, the Texas Mobile Load Simulator Program (TxMLS) is monitoring the increase in layer deformation under load using sophisticated pavement instrumentation. These data will be used extensively in this project to calibrate the VESYS model prior to making predictions with either overloads or new axle configurations.

REPORT ORGANIZATION

This report is organized into five chapters. Chapter 1 focuses on the background information relative to the project. Chapter 2 provides the compiled truck information which is going to be used to analyze the effect of overload on the pavement distresses. In Chapter 3 the VESYS5 rutting model is calibrated using TxMLS results on US281 based on the expanded internal calibration method. The shift factors for rutting input parameters (α and μ) are established. Furthermore, the rutting caused by overload is simply discussed. Chapter 4 describes and validates the laboratory test method to determine the input of material properties for VESYS5. A case study is presented in Chapter 5 to simulate the influence of different trucks on the pavement performance. Finally, Chapter 6 presents a summary of findings and accomplishments in this research.

CHAPTER 2

INVESTIGATION OF TYPE OF TRUCK AND AXLE CONFIGURATIONS TO BE USED UNDER NAFTA

A literature review was conducted to document the types of truck and axle configurations to be used under NAFTA. In addition to the trucks in U. S., both Mexican and Canadian trucks were also documented. All of the information about trucks is summarized and presented in Appendix A. The main information is described as follows.

Table 1 presents the information about truck size and weight regulations in Texas, Mexico, and Canada. Figure 1 illustrates the typical trucks in Texas, Mexico, and Canada. Table 2 shows the detailed comparison of typical truck axle weight and gross vehicle weight. More than 80 percent of trucks on main U. S. highways are 5-axle tractor-semitrailers. Thus, this kind of truck will be used to analyze the effect of trucks in Texas, Canada, and Mexico on the pavement performance in this report.

Table 1. General Comparison of Truck Size and Weight Regulations in Texas, Mexico, and Canada.

Item	Texas (ft and lb)	Mexico (ft and lb)	Canada (MoU) (ft and lb)
Dimensions			
Height	14.0	13.9	13.6
Tractor WB (min. to max.)	NR	NR	9.8 to 20.3
Semitrailer length	59.0	NR	53.0
Tractor-Semi length	NR	68.2	75.0
Kingpin to Rear axle for Semi-trailers (min. to max.)	NR	NR	20.5 to 41.0[a]
Weight			
Steering axle	20,000	14,300	12,128
Single axle	20,000	22,045	20,066
Tandem axle	34,000	42,998	37,485
Tridem axle	BFB	49,604	46,305
GVW for 3-S2	80,000[b]	97,020	87,098
Tire pressure (psi)	NR	Manufacturer rating	NR
Tire load/unit width	650 lb/in	NR	559 lb/in
Tire load/tire	NR	NR	6,614 lb
Other considerations			
Spread Tandem Axle	BFB	NR	Ontario&Quebec[c]
Lift axles	NR	NR	Ontario&Quebec[c]
Super single tires	Yes (limited to 650 lb/in)	No, limited by max wt/tire	No, limited by max wt/tire
Allowance for powered axles	No	Yes	No
Allowance for suspension type	No	Yes	Yes, varies
Spring bans/winter premiums	No	No	Yes, varies

NR=Not regulated
BFB=Governed by Bridge Formula B.
[a] Measured from kingpin to center of rear axle group.
[b] With weight tolerance permit, off the IH system, can increase to 84,000 lb.
[c] Other provinces do not allow.

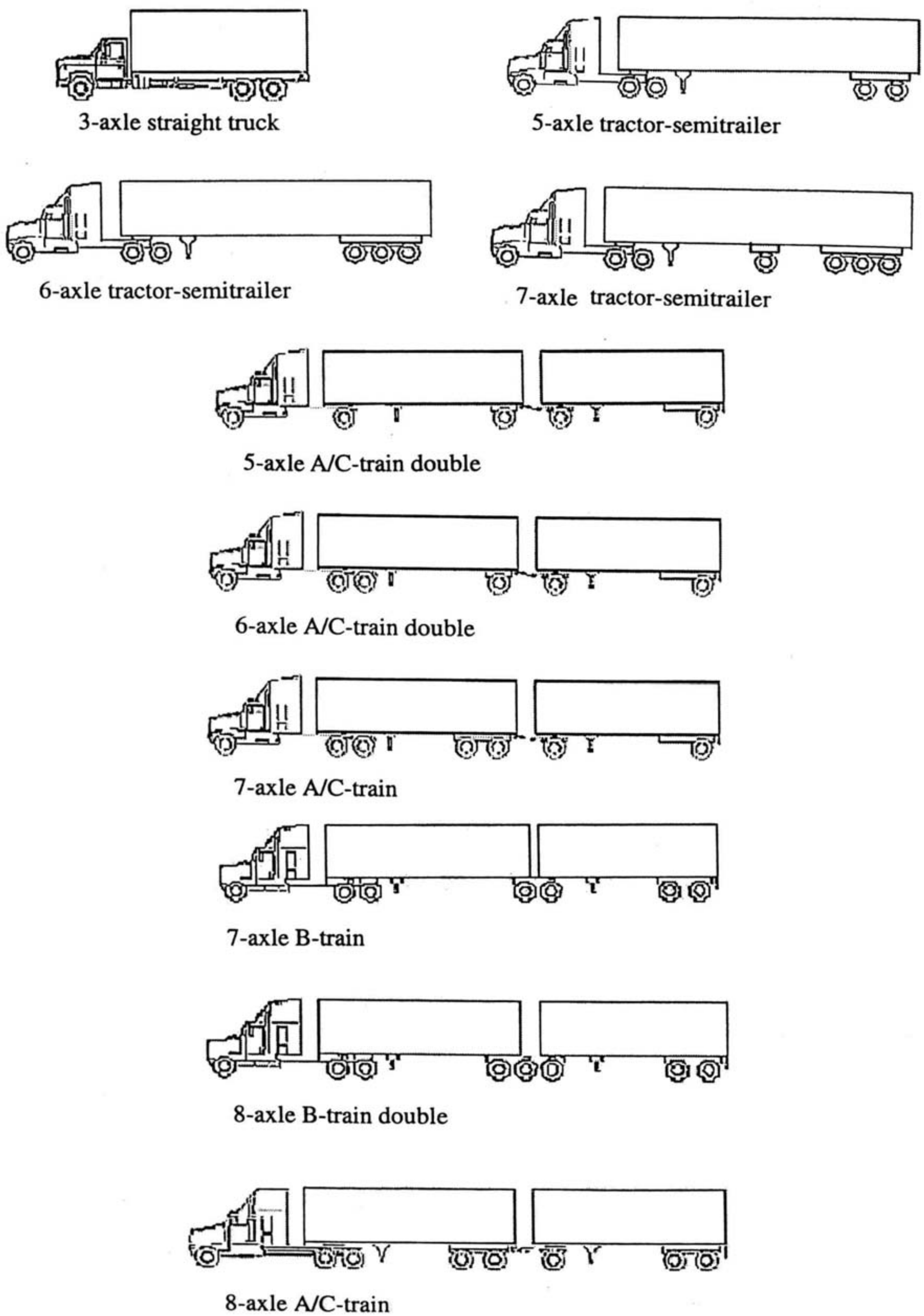


Figure 1. Typical Vehicle Configuration.

Table 2. Basic Maximum Weight Limits in Texas, Mexico, and Canada.

Item	Texas	Mexico	Canada	
			MoU	Ontario/Qu.
Tire loads				
lb/in	650	NR	560	560
lb/tire	NR	NR	6614	6614
Tire pressure (psi)	NR	Manufacturer rating	NR	NR
Axle loads (lb.)				
Steering axle (tractor)	20,000	14,300	12,128	12,128
Steering (straight truck)	NR	NR	15,984	15,984
Single (dual tires)	20,000	22,045	20,066	22,045
Tandem (48 in spacing)	34,000	42,988	37,479	37,479
Tandem (72 in spacing)	34,000	42,988	37,479	42,108
Tridem (96 in spacing)	42,000	49,604	46,297	46,958
Tridem (120 in spacing)	43,500	49,604	50,706	50,706
Tridem (144 in spacing)	45,000	49,604	52,911	53,793
Tri-axle (13.1 in spacing)	NR	NR	NP	61,509
Tri-axle (15.7 in spacing)	NR	NR	NP	64,155
Quad (100 in +60 in+60in)	NR	NR	NP	70,548
Quad (100 in+72 in+72 in)	NR	NR	NP	74,957
GVWs (lb)				
3-axle straight truck	NR	57,268	49,604	59,304
5-axle tractor-semitrailer	NR	96,916	87,083	97,003
6-axle tractor-semitrailer	NR	160,828	102,515	119,050
7-axle tractor-semitrailer	NR	NR	NP	124,561
5-axle A-train double	NR	104,625	92,374	100,310
6-axle A-train double	NR	123,348	109,790	120,152
7-axle A-train double	NR	133,260	117,047	136,025
7-axle B-train double	NR	NR	124,561	136,025
8-axle B-train double	NR	132,158	137,789	139,994
7-axle C-train double	NR	NR	120,372	136,025
8-axle C-train double	NR	138,766	128,970	139,970
9-axle train double	NR	146,475	No	No

NR=Not Regulated; NP= Not Permitted.

CHAPTER 3

PREDICTION OF PAVEMENT DAMAGE USING THE VESYS CALIBRATED WITH THE US281 APT DATA FROM TEXAS

VESYS5 LAYER RUTTING MODEL

VESYS5 includes two different flexible pavement rutting models: system rutting and layer-rutting model. The layer rutting model predicts both surface rutting and the permanent deformation in each layer. And, based on the layer rutting and the multi-depth deflectometer (MDD) result in accelerated pavement test (APT), the unique backcalculated GNU, ALPHA values are determined. Therefore, only the layer rutting model was used to predict the rutting depth.

The layer rutting model estimates the permanent deformation in each finite layer as the product of the elastic compression in that layer and the layer material permanent deformation law associated with that layer. For infinite layer, the permanent deformation in the subgrade is defined differently because of the consideration of the effect of multiaxle load.

The total elastic strain within a pavement layer is, of course, simply the total compression within the layer, which in layer theory is given by the difference in deflections of the top and bottom of the layer. For any pavement layer this difference can be written as:

$$R_D(N) = \left(W^+ - W^-\right) * \frac{\mu}{1-\alpha} N^{(1-\alpha)} \qquad (1)$$

For the semi-infinite subgrade layer, Equation 1 reduces to:

$$R_{sub}(N) = W_{sub}^+ * \frac{e_t}{e_s} \frac{\mu}{1-\alpha} N^{(1-\alpha)} \qquad (2)$$

In which,

R_D = the permanent deformation (rutting) level after N load repetitions;

W^+, W^- = the elastic deflection amplitudes of the top and bottom surfaces of the layer, respectively;

μ, α = the laboratory permanent deformation parameters for the each layer material;

W_{sub}^+ = the deflection at top of subgrade due to single axle load;

e_t = the strain at top of subgrade due to the axle group; and

e_s = the strain at top of subgrade due to single axle.

Comment: *In above Equations 1 and 2, W (or ε) is linear to the load level, and if α and μ values are stress-independent, the rutting depth predicted by VESYS5 will be linear to the load level, which is different from the observed rutting depth in the field.*

SENSITIVITY ANALYSIS OF VESYS RUTTING MODEL

A standard pavement structure (Figure 2), associated with normal material properties and standard traffic volume, was used to check the VESYS5 program. And the input parameters: ESAL, thickness of AC and base, and GNU, ALPHA values for different layers were changed to run the sensitivity analysis. Only one parameter was changed in the sensitivity analysis, others kept standard value. Table 3 presents the GNU, ALPHA values of different layers for the sensitivity analysis.

As shown in Figure 3, it was found that all of the results were reasonable, and the rutting parameters: α, μ have the biggest effect on rutting. But the increase of rutting is proportional to the load level. For other pavement structures, similar results were found. Those results are consistent with the comments on the VESYS 5 rutting model. Therefore, *it is very important, for overload and associated rutting, to develop both temperature- and stress-dependent permanent deformation parameters, α, μ.*

AC 4 in. E=500 ksi μ=0.5, α=0.73

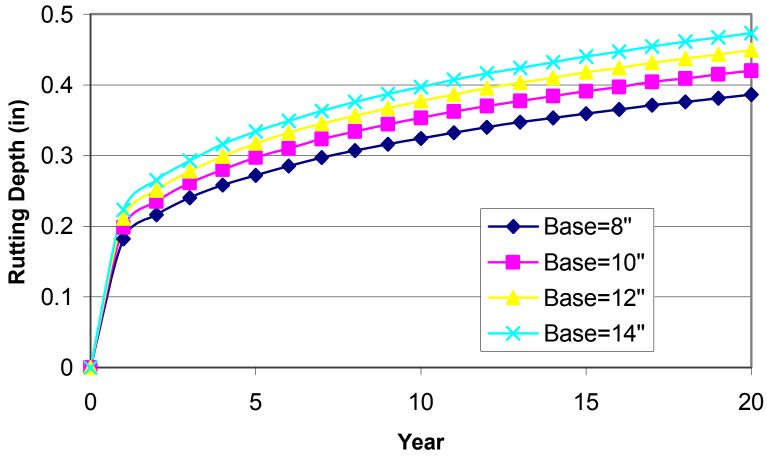
BASE 10 in. E= 45 ksi μ=0.4, α=0.75

Subgrade E=15 ksi μ=0.025,α=0.75

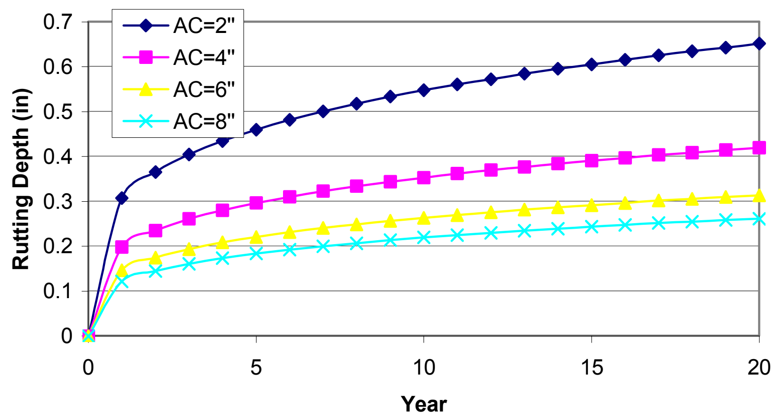
Figure 2. Standard Pavement Structure (3 million 18 kips ESAL in 20 years design period).

Table 3. Sensitive Analysis Parameters: α and μ.

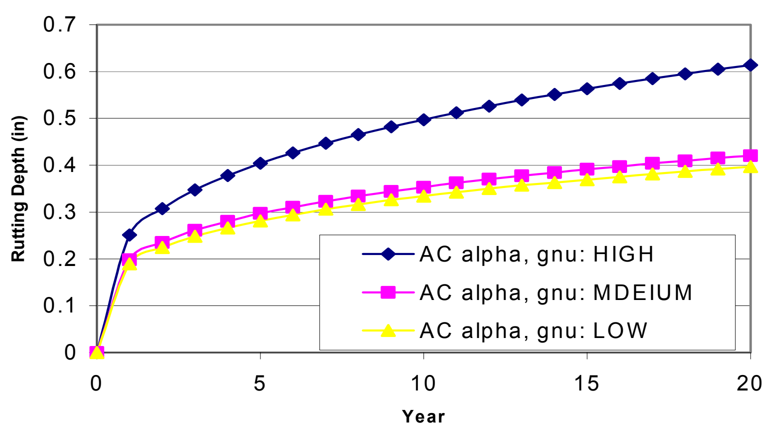
Material	AC		Base		Subgrade	
	α	μ	α	μ	α	μ
High	0.65	0.60	0.70	0.50	0.70	0.04
Medium	0.73	0.50	0.75	0.40	0.75	0.025
Low	0.80	0.40	0.80	0.30	0.80	0.01



(a) Effect of base thickness on rutting

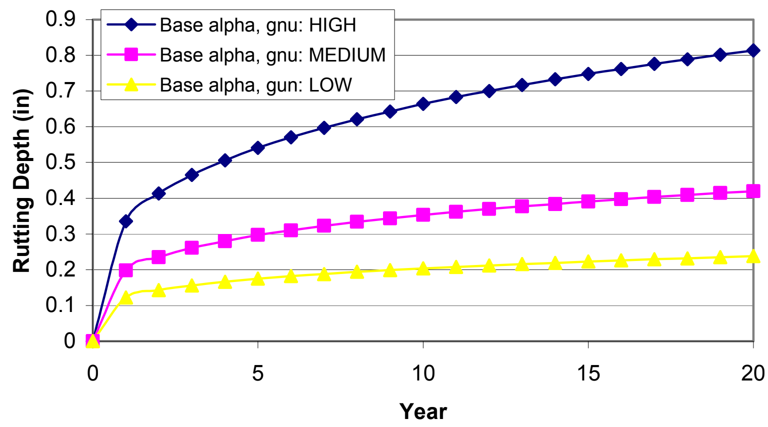


(b) Effect of thickness of AC on rutting

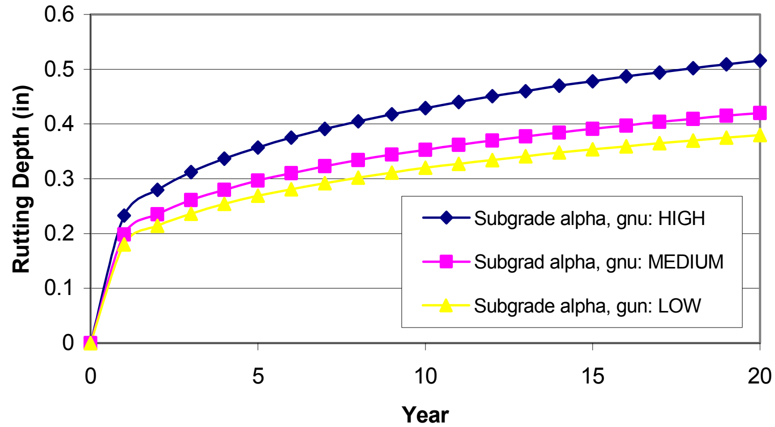


(c) Effect of α, μ value of AC on rutting

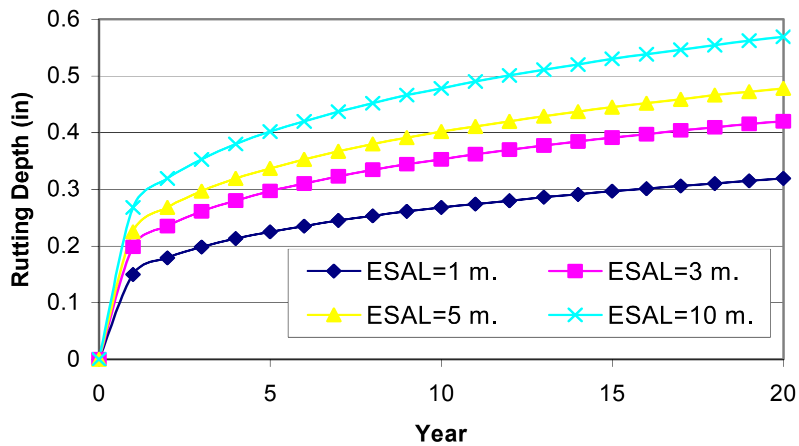
Figure 3. Sensitive Analysis of VESYS5 Layer Rutting Model.



(d) Effect of α, μ value of base on rutting

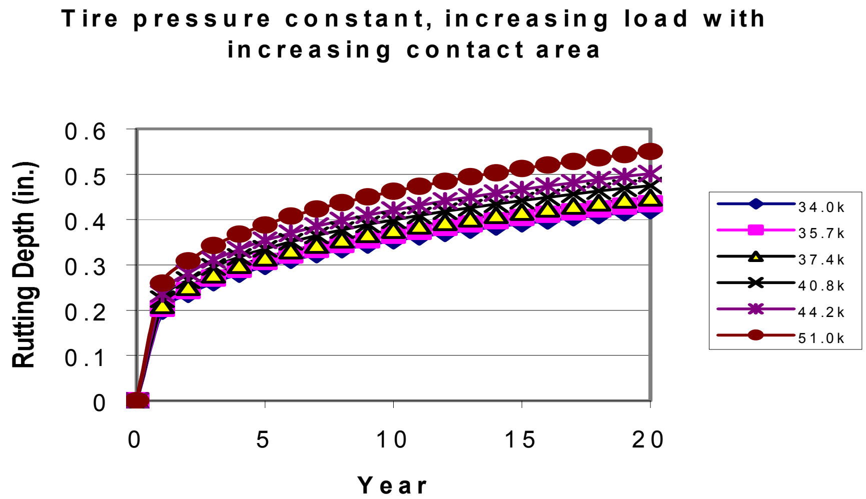


(e) Effect of α, μ value of subgrade on rutting

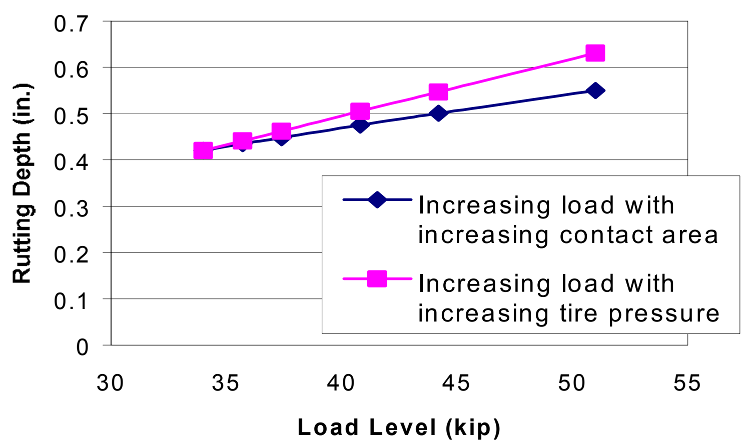


(f) Effect of EASL on rutting

Figure 3. Sensitive Analysis of VESYS5 Layer Rutting Model (Continued).



(g) Effect of overload by increasing contact area on rutting



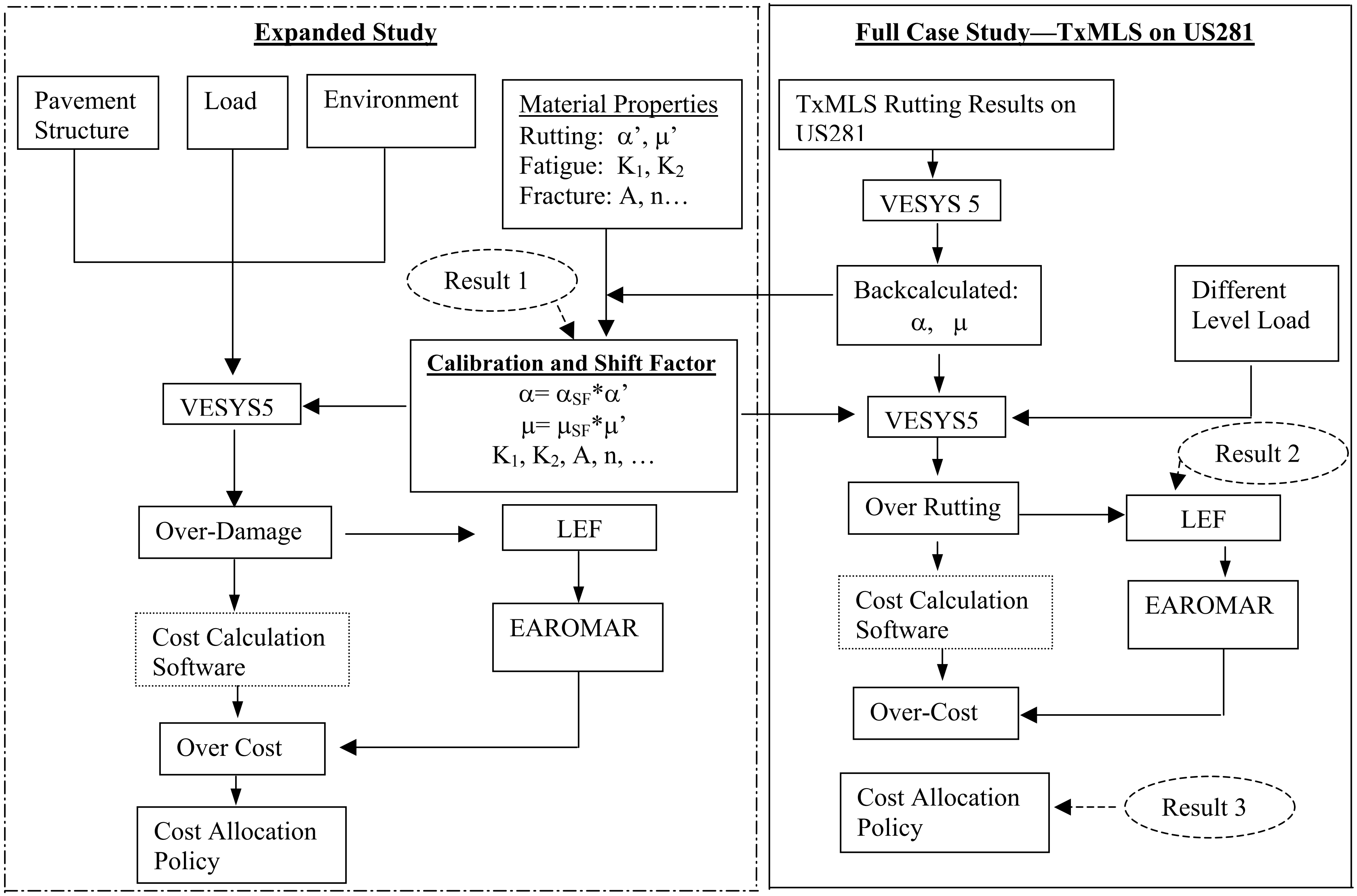
(h) Comparison of the effects of increasing tire pressure and contact area on rutting

Figure 3. Sensitive Analysis of VESYS5 Layer Rutting Model (Continued).

FRAMEWORK OF VESYS5 MODEL CALIBRATION AND APPLICATION

The key of the research project is the calibration of VESYS5 model by the APT data and field performance data. After that, the relationship among overload, over-damage, and over-cost can be developed using the calibrated model, which is the goal of the project. The framework of the research work is described as follows:

Framework of VESYS5 Model Calibration and Application



CALIBRATION OF VESYS5 LAYER-RUTTING MODEL USING TXMLS DATA ON US281N

This case study is used to demonstrate the workability of the framework recommended above.

Background of TxMLS on US281 (2)

TxMLS was conducted to evaluate two rehabilitation processes during 1995-1996. Figure 4 shows the general profiles of the pavement structures at the test site prior to the last rehabilitation and thereafter. The first asphalt layer in the test section was constructed in 1957. There were four major rehabilitations that were completed in 1971, 1976, 1986, and 1995, respectively. The last major rehabilitation was completed using two processes. In 1995, the Rehab A process was used on southbound lane with 50 mm of recycled ACP, while the Rehab B process was used in 1996 on the northbound lane. It consisted of an overlay of nominally 25 mm on top of in situ treated material. Prior to that, the major rehabilitation in 1986 consisted of nominally 50 mm of lightweight aggregate asphalt concrete (LWACP) that was thickened up to 100 mm where it was considered necessary.

The pavement test pads were both 3 m wide by 12 m long. The mean of the maximum falling weight deflectometer (FWD) tests for pad US281S, prior to testing and normalized to 40 kN, was 0.25 mm, with a 24 percent coefficient of variation. This variation was probably due to two visible cracks in the test pad. The deflections are 60 percent higher at the two ends of the test pad, 0 m and 10.5 m lines. The cracks are believed to be due to thermal effects. A diagnostic investigation through coring after trafficking showed that the cracks extended throughout the ACP layer.

Test pad US281N had characteristics similar to those of test pad US281S, except for the difference in the rehab process. In this case, the rehab was done using the Rehab B process. It had an overlay of nominally 25 mm of conventional ACP on top of the in situ treated upper layer of LWACP. The average maximum FWD values were slightly higher than those of the US281S pad (0.33 mm vs. 0.25 mm). Figure 1 also shows the two rehabilitation profiles with typical void characteristics.

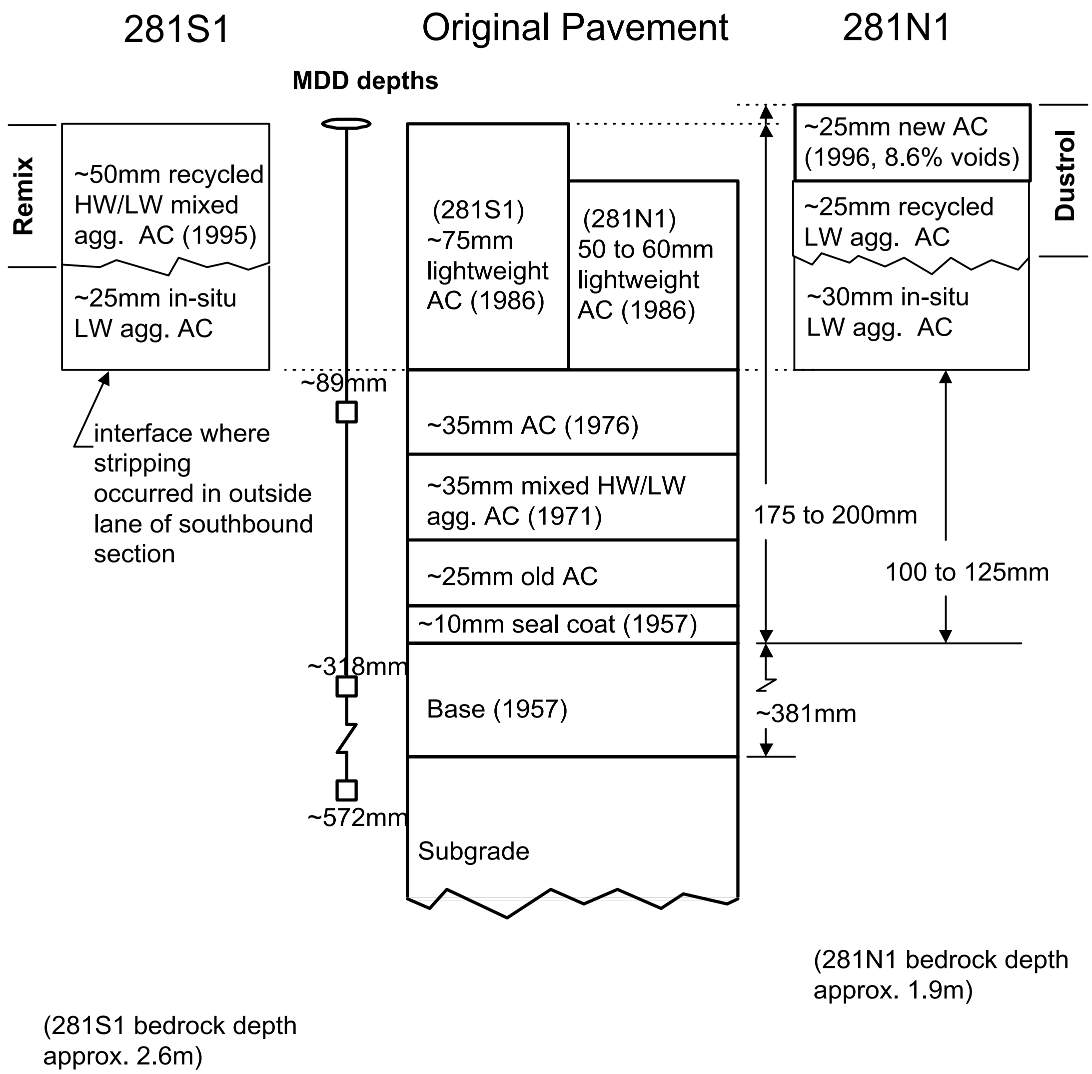


Figure 4. Pavement Sections for Pads 281S1 and 281N1 (2).

TxMLS Test Results on US281N and Material Properties

The basic information about TxMLS on US281N shown in Table 4 is cited from Chen and Hugo (*2*).

Table 4. TxMLS Test Results on US281N and Material Properties.

TxMLS load repetition	10000	20000	40000	75000	150000	225000	300000
Rutting depth (mm)	1.987	2.450	2.904	4.247	7.051	8.702	9.536
Temperature, °F	89	84	84	92	95	91	89
AC modulus (psi)	210808	242836		194387	179712	200000	210808
Base modulus (psi)	38000						
Subgrade modulus (psi)	8000						

Backcalculation of α, μ Using VESYS5 Layer-Rutting Model on US281N

Table 5 presents the backcalculated μ, α results. The comparisons of the measured with the predicted surface total rutting and layer rutting are listed in Figures 5 and 6, respectively.

Table 5. Backcalculated μ, α Value.

Temperature (°F)		89	84	92	95	91	89
Asphalt concrete	α	0.610	0.638	0.598	0.568	0.598	0.610
	μ	0.260	0.263	0.250	0.245	0.259	0.260
Base	α	0.78					
	μ	0.10					
Subgrade	α	0.75					
	μ	0.01					

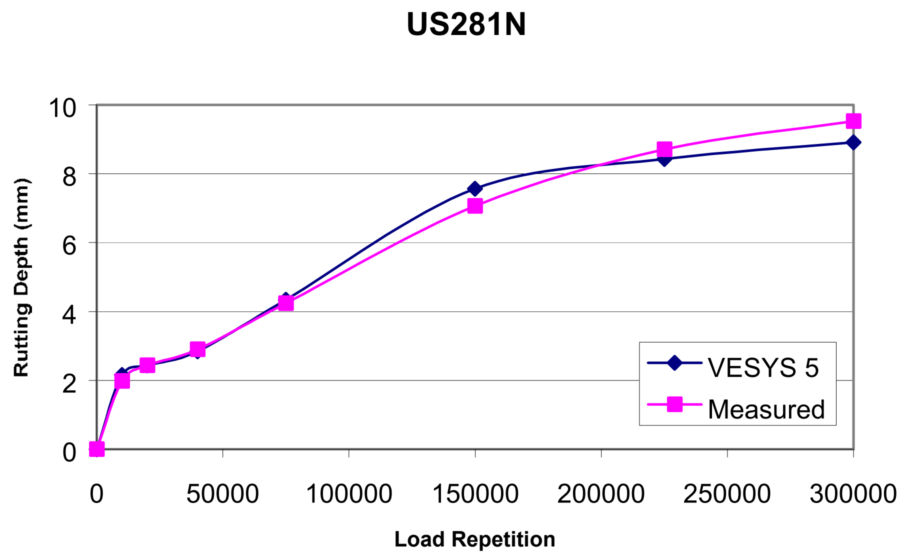


Figure 5. Comparison of the Predicted with the Measured Total Rutting.

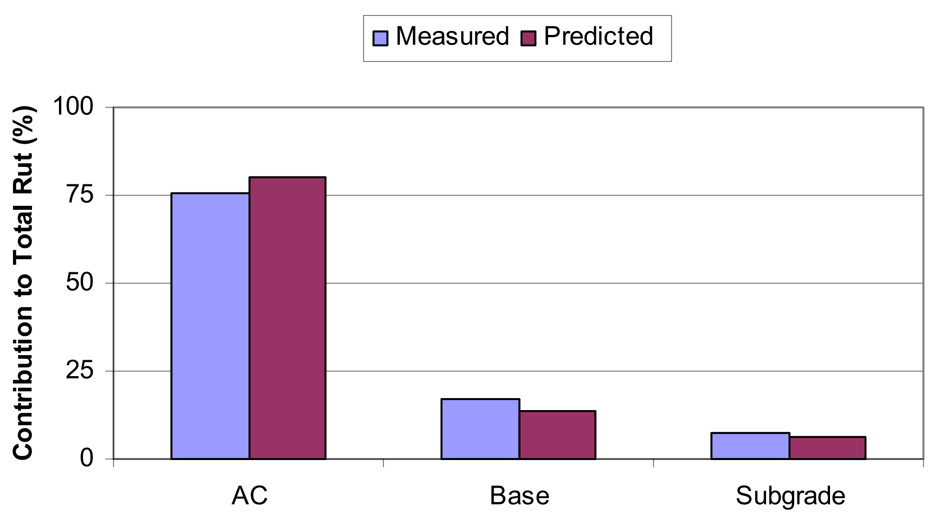


Figure 6. Comparison of the Predicted with the Measured Layer Rutting.

In summary, predicted rutting from the VESYS5 rutting model matches the TxMLS results very well, including both surface total rutting and layer rutting. Therefore, the VESYS5 model has potentiality to be used to develop the relationship between overload and over-damage.

The Shift Factor for α, μ on US281N

The Shift Factors for α, μ, α_{SF}, μ_{SF}, are introduced to bridge the gap between α, μ value predicted from regression equation and real α, μ value that is backcalculated from VESYS5 program. α_{SF}, μ_{SF} is defined as follows:

$$\alpha_{SF} = \frac{\alpha_{VESYS5}}{\alpha_{predicted}} \quad (3)$$

$$\mu_{SF} = \frac{\mu_{VESYS5}}{\mu_{predicted}} \quad (4)$$

where, α_{SF} = Shift Factor for $\alpha_{predicted}$;

$\alpha_{Predicted}$ = α predicted from the following regression Equation 5;

α_{VESYS5} = α backcalculated from VESYS5 program;

μ_{SF} = Shift Factor for $\mu_{Predicted}$;

$\mu_{Predicted}$ = μ predicted from the following regression Equation 6; and

μ_{VESYS5} = μ backcalculated from VESYS5 program;

$$\alpha = 1.748418 - 0.446558\log T - 2.65284\frac{\log\sigma_D}{34.03532 - 0.253679T} \qquad R^2{=}0.75 \quad (5)$$

$$\mu = 1.663759 - 0.438729\log T - 1.25191\frac{\log\sigma_D}{1.918523 + 0.066875T} \qquad R^2{=}0.36 \quad (6)$$

where, T = Temperature, °F; and

σ_D = Deviator stress (equal to σ_1-σ_3,), psi.

It should be noted that the two Equations (5 and 6) above are regressed based on the repeated load test results in Leahy's PhD dissertation (*4*).

Based on the definition and results backcalculated from US281N, the following shift factors shown in Table 6 and Figure 7 are developed.

Table 6. Shift Factor for α, μ on US281N.

Temp. (°F)	α_{VESYS5}	μ_{VESYS5}	σ_1	σ_3	σ_D	$\alpha_{Predicted}$	$\mu_{Predicted}$	α_{SF}	μ_{SF}
89	0.610	0.260	75.304	6.410	68.894	0.4422	0.5092	1.3794	0.5106
84	0.638	0.263	76.162	6.559	69.603	0.5050	0.5134	1.2633	0.5123
92	0.598	0.250	74.405	6.336	68.069	0.4169	0.5179	1.4344	0.4827
95	0.568	0.245	73.808	6.272	67.536	0.3768	0.5192	1.5076	0.4719
91	0.598	0.259	74.624	6.361	68.263	0.4292	0.5174	1.3931	0.5006

Note: σ_1, σ_3, and σ_D are computed outside edge of tire at the depth of 2 inches.

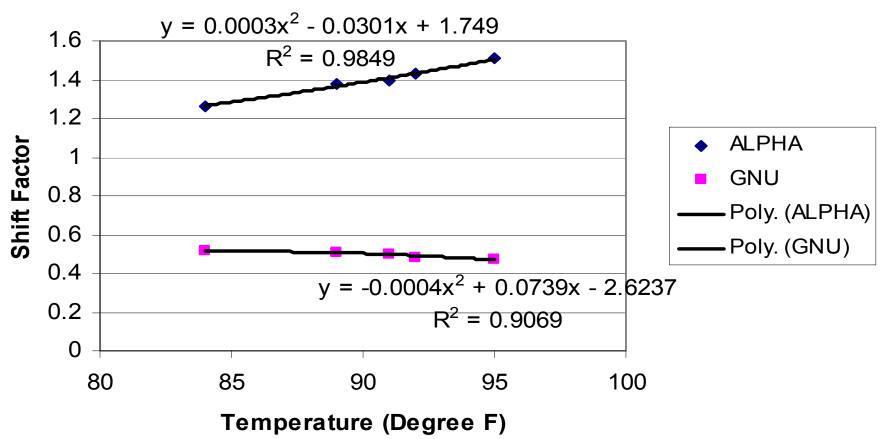
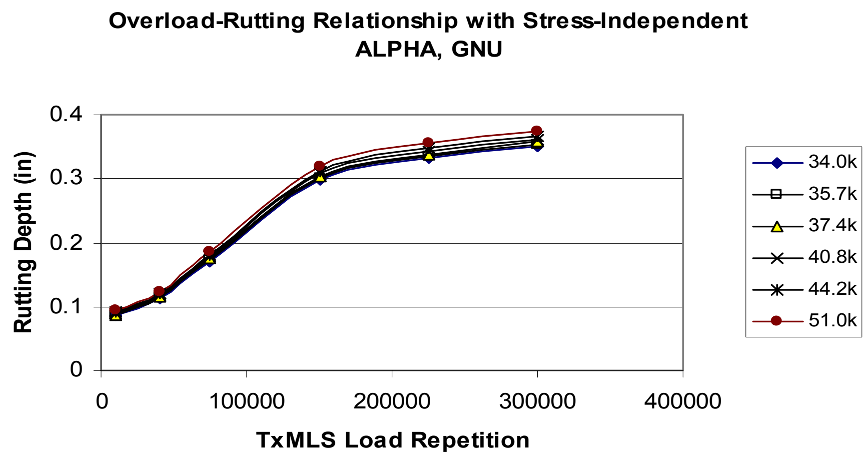


Figure 7. Relationship between Shift Factors of α and μ and Temperatures on US281N.

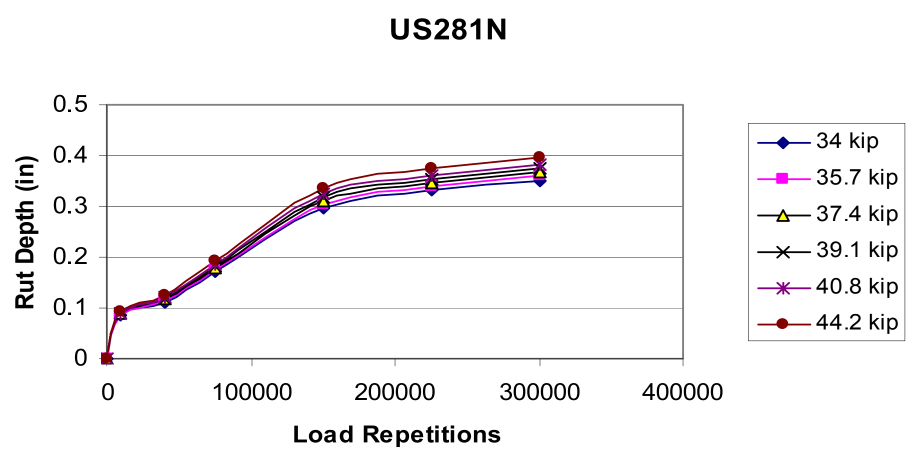
Discussion: Relationship between Overload and Over-Damage

In fact, the backcalculated α and μ values can be directly used to estimate the effect of overload on the pavement rutting, if α and μ are stress independent. Here, both the stress dependent and independent α and μ parameters are discussed.

Figure 8 presents the predicted rutting depths and associated comparison. It can be seen that the rutting depth is underestimated when using the stress-independent permanent deformation parameters α and μ. And it increases linearly with the increase of load level no matter whether load repetition is less or more or the temperature and load level are higher or lower. However, these problems are overcome if the stress-dependent permanent deformation parameters α, μ are used. So *the stress-dependent permanent deformation parameters α, μ are strongly recommended.*



(a). Rutting and Load Repetitions Relationship with Stress-Independent α, μ.



(b). Rutting and Load Repetition Relationships with Stress-Dependent α, μ.

Figure 8. Rutting and Load Repetition Relationship with Different α, μ.

CALIBRATION OF VESYS5 LAYER-RUTTING MODEL USING TXMLS DATA ON US281S

Similar to US281N, the calibration process on US281S is explained as follows.

Tables 7 and 8 show the surface rutting, layer rutting, seasonal traffic, and temperature. Table 9 presents the modulus data. The backcalculated α and μ values and the comparison of surface and layer rutting are shown in Tables 10, 11, and 12. Figure 9 illustrates the comparison between the measured and predicted surface rutting from the VESYS5 layer rutting model. Based on the definition and results backcalculated from US281S, the following Shift Factors were developed and are shown in Table 13 and Figure 10. In addition, Figure 11 shows briefly the influence of overload on rutting. It is obvious that higher load level will cause much more rutting.

Table 7. TxMLS Rutting Depth Results and Typical Temperature.

Load repetition (x1000)	10	40	150	225	300	375	450	525	600	675	750
Temperature, F	72.5	68.0	84.9	95.0	91.0	94.0	96.0	91.0	93.0	77.2	76.0
Left Rutting Depth(mm)	0.32	0.90	1.15	1.94	2.01	2.13	3.26	3.35	3.91	3.74	4.09
Right Rutting Depth(mm)	0.38	0.50	1.12	1.97	2.65	2.93	3.51	4.25	4.32	4.51	4.52
Average (mm)	0.35	0.70	1.13	1.95	2.33	2.53	3.39	3.80	4.12	4.13	4.31

Table 8. Extracted Layer Rutting Results from MDD.

TxMLS load	AC layer		Base layer		Subgrade	
	Rutting	Contribution, %	Rutting	Contribution, %	Rutting	Contribution, %
10000	0.16	46.9	0.19	51.3	0	0
40000	0.44	62.7	0.23	33.5	0.03	3.8
150000	0.73	64.9	0.32	28.3	0.08	6.8
225000	1.38	70.7	0.47	24.0	0.10	5.3
300000	1.73	74.1	0.46	19.7	0.14	6.2
375000	1.82	72.0	0.52	20.4	0.19	7.6
450000	2.47	72.8	0.69	20.4	0.23	6.8
525000	2.57	67.7	0.86	22.5	0.37	9.8
600000	2.92	70.8	0.87	21.0	0.34	8.2
675000	2.92	70.9	0.89	21.7	0.30	7.4
750000	3.10	71.9	0.89	20.7	0.32	7.4
Average		67.8		25.9		6.3

Table 9. Modulus Data.

Temperature, F	AC modulus, psi	Base modulus, psi	Subgrade modulus, psi
72.5	696235	38000	8000
68.0	814388		
84.9	473174		
95.0	359424		
91.0	399308		
94.0	368850		
96.0	350334		
93.0	378627		
77.2	597070		
76.0	620395		

Table 10. Backcalculated α, μ Value.

Temp. °F	AC		Base		Subgrade	
	α	μ	α	μ	α	μ
72.5	0.701	0.260	0.780	0.080	0.760	0.005
68.0	0.712	0.280				
84.9	0.670	0.240				
95.0	0.608	0.210				
91.0	0.628	0.225				
94.0	0.612	0.212				
96.0	0.602	0.208				
93.0	0.616	0.217				
77.2	0.690	0.250				
76.0	0.694	0.262				

Table 11. Surface Rutting Comparison.

Load repetition (x1000)	10	40	150	225	300	375	450	525	600	675	750
Measured (mm)	0.35	0.70	1.13	1.95	2.33	2.53	3.39	3.80	4.12	4.13	4.31
Predicted (mm)	0.51	0.66	1.40	2.26	2.54	2.92	3.30	3.45	3.65	3.65	3.68

Table 12. Layer Rutting Comparison.

TxMLS load	AC Contribution, %		Base Contribution, %		Subgrade Contribution, %	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
10000	46.9	*47.3*	51.3	37.5	0	*15.2*
40000	62.7	*45.0*	33.5	39.6	3.8	*15.4*
150000	64.9	*59.9*	28.3	30.7	6.8	*9.5*
225000	70.7	*71.3*	24.0	22.3	5.3	*6.4*
300000	74.1	*72.6*	19.7	21.4	6.2	*6.0*
375000	72.0	*74.4*	20.4	20.1	7.6	*5.5*
450000	72.8	*76.3*	20.4	18.7	6.8	*5.1*
525000	67.7	*76.5*	22.5	18.5	9.8	*5.0*
600000	70.8	*77.1*	21.0	18.1	8.2	*4.9*
675000	70.9	*76.9*	21.7	18.2	7.4	*4.9*
750000	71.9	*76.7*	20.7	18.3	7.4	*5.0*
Average	**67.8**	***68.5***	**25.9**	**24.0**	**6.3**	***7.5***

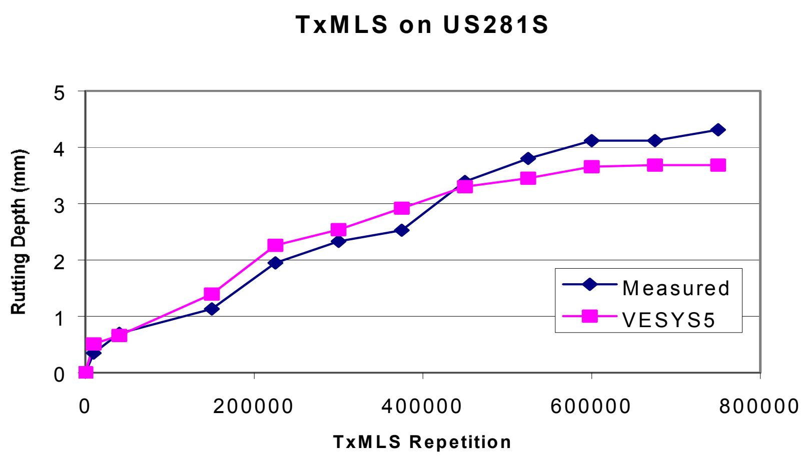


Figure 9. Surface Rutting Comparison on US281S.

Table 13. Shift Factors for α, μ on US281S.

Temp. °F	α_{VESYS5}	μ_{VESYS5}	σ_1	σ_3	σ_D	$\alpha_{Predicted}$	$\mu_{Predicted}$	α_{SF}	μ_{SF}
72.5	0.701	0.260	88.626	5.955	82.671	0.5925	0.4929	1.1831	0.5275
68.0	0.712	0.280	90.368	6.255	84.113	0.6259	0.4871	1.1376	0.5748
84.9	0.670	0.240	84.492	5.382	79.11	0.4841	0.5046	1.3839	0.4756
95.0	0.608	0.210	81.697	5.129	76.568	0.3622	0.5109	1.6786	0.4110
91.0	0.628	0.225	82.751	5.210	77.541	0.4158	0.5087	1.5102	0.4423
94.0	0.612	0.212	81.954	5.147	76.807	0.3764	0.5104	1.6258	0.4154
96.0	0.602	0.208	81.443	5.112	76.331	0.3474	0.5114	1.7330	0.4067
93.0	0.616	0.217	82.216	5.167	77.049	0.3901	0.5099	1.5791	0.4256
77.2	0.690	0.250	86.954	5.698	81.256	0.5549	0.4980	1.2435	0.5020
76.0	0.694	0.252	87.368	5.758	81.61	0.5648	0.4967	1.2287	0.5073

Note: σ_1, σ_3, and σ_D are computed outside edge of tire at the depth of 2 inches.

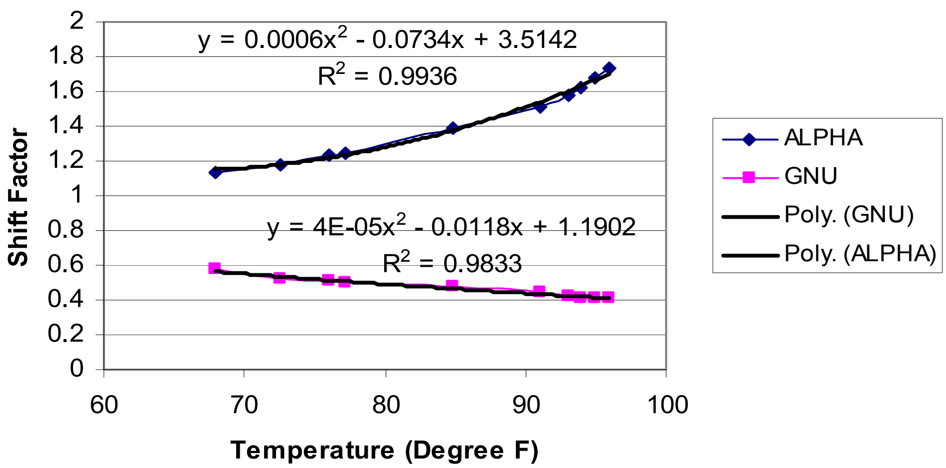


Figure 10. Relationship between Shift Factors of α and μ and Temperatures on US281S.

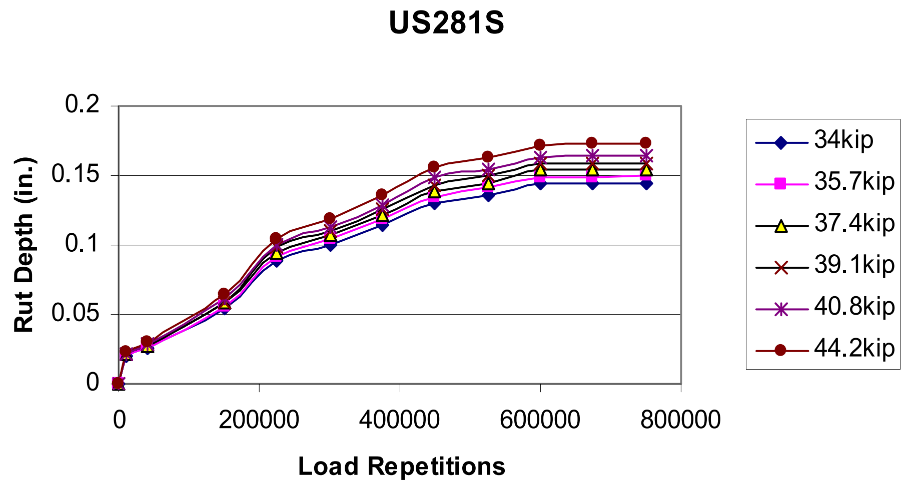


Figure 11. Rutting and Load Repetitions Relationship with Stress-Dependent α, μ Value.

CHAPTER 4

LABORATORY TESTING PROGRAM FOR APT MATERIALS

VERIFICATION OF VESYS TEST METHOD TO CHARACTERIZE THE PERMANENT DEFORMATION OF ASPHALT MIXES

The sensitivity analysis to VESYS5 rutting model showed clearly that the parameters, α and μ, had considerable effect on the predicted rut depth. The values of both parameters are measured from repeated load test (or VESYS test). Therefore, it is crucial to verify the effectiveness of the VESYS test to characterize the permanent deformation of asphalt mixtures.

Fortunately, the SPS-1 sections on US281 in Texas provide a good chance to validate and/or verify the existing test approaches to measure the rutting-resistant property of asphalt mixes. All 20 SPS-1 sections received identical traffic loadings. After approximately three years in service, 14 sections had substantial rutting. At least seven sections had ruts of 15 mm or greater (*5*). The cores taken from six SPS-1 sections were used to evaluate the laboratory test method characterizing the permanent deformation property. These sections had the varied rutting depth that is shown in Figure 12. In Figure 12, S164R means the deeply rutted part of section 164, and non-rutted part of section 164 is designated as S164NR. In addition to the VESYS test method, other test methods, including repeated simple shear test at constant height (RSST-CH), Hamburg wheel track test, Asphalt Pavement Analyzer (APA), and dynamic modulus test, were also evaluated.

Table 14 presents the final ranking for all of these rutting tests, where A represents the best. It can be seen that both RSST-CH and VESYS approaches can differentiate the good mixes from the bad mixes and may be more reasonable than an approach based on the modulus.

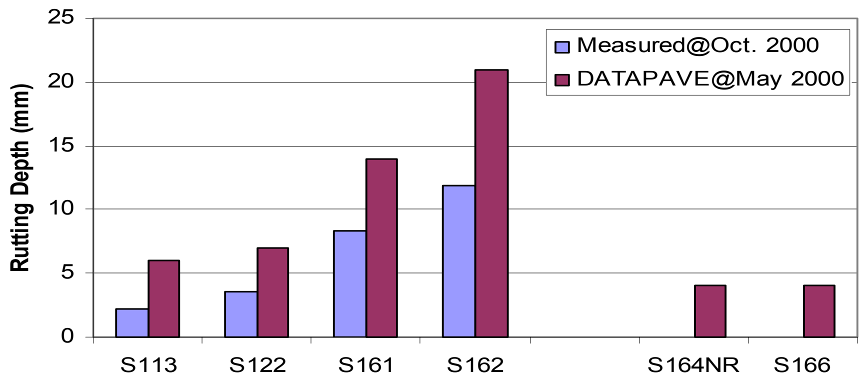


Figure 12. Rut Depths of Six SPS-1 Sections.

Table 14. Summary of Ranking Rut Performance of Asphalt Mixes.

Sections	S166	S164NR	S113	S122	S161	S162	S164R
Field Ranking	A	A	B	C	D	E	F
APA	B	A	*	D	C	E	F
HWTD	B	*	A	A	E	D	C
RSST-CH	A	A	*	B	C	D	E
VESYS	A	A	B	C	D	E	F
Dynamic modulus	B	A	BC	C	DE	DE	D

Note: *: There is no test.

TEST PROTOCOL FOR VESYS5 RUTTING PARAMETERS OF ASPHALT MIXES: μ, α

The results of the above evaluation indicate that the VESYS method (repeated load test) can effectively distinguish the rutting performance of different asphalt mixes. Furthermore, based on the experience from extensive VESYS tests, the VESYS users manual (1977), and Superpave Simple Performance Test (2000), the protocol for input parameters (α, μ) to VESYS5 layer rutting model was developed. The detailed protocol is attached in Appendix B. In addition, the example is presented to calculate the rutting parameters, α and μ.

LABORATORY TEST FOR LOUISIANA ALF EXPERIMENT SITE

- **Cross Sections of Experimental Lanes in Louisiana ALF Test Site**

In the second LA-ALF test the main objective was to evaluate the influence of crumb rubber on pavement performance. Thus, the pavement structures for all three test lanes were same, as shown in Figure 13, which was comprised of 8.5 inches crushed stone base course, 3.5 inches Type 5A base course, 2 inches Type 8 binder course, and 1.5 inches Type 8F wearing course. The only difference among these three lanes was the material of asphalt layer. Lane 2-3 as the control test section used conventional material. Crumb rubber was added in the 1.5 inches wearing course of Lane 2-1, and 3.5 inches base course layer of Lane 2-2.

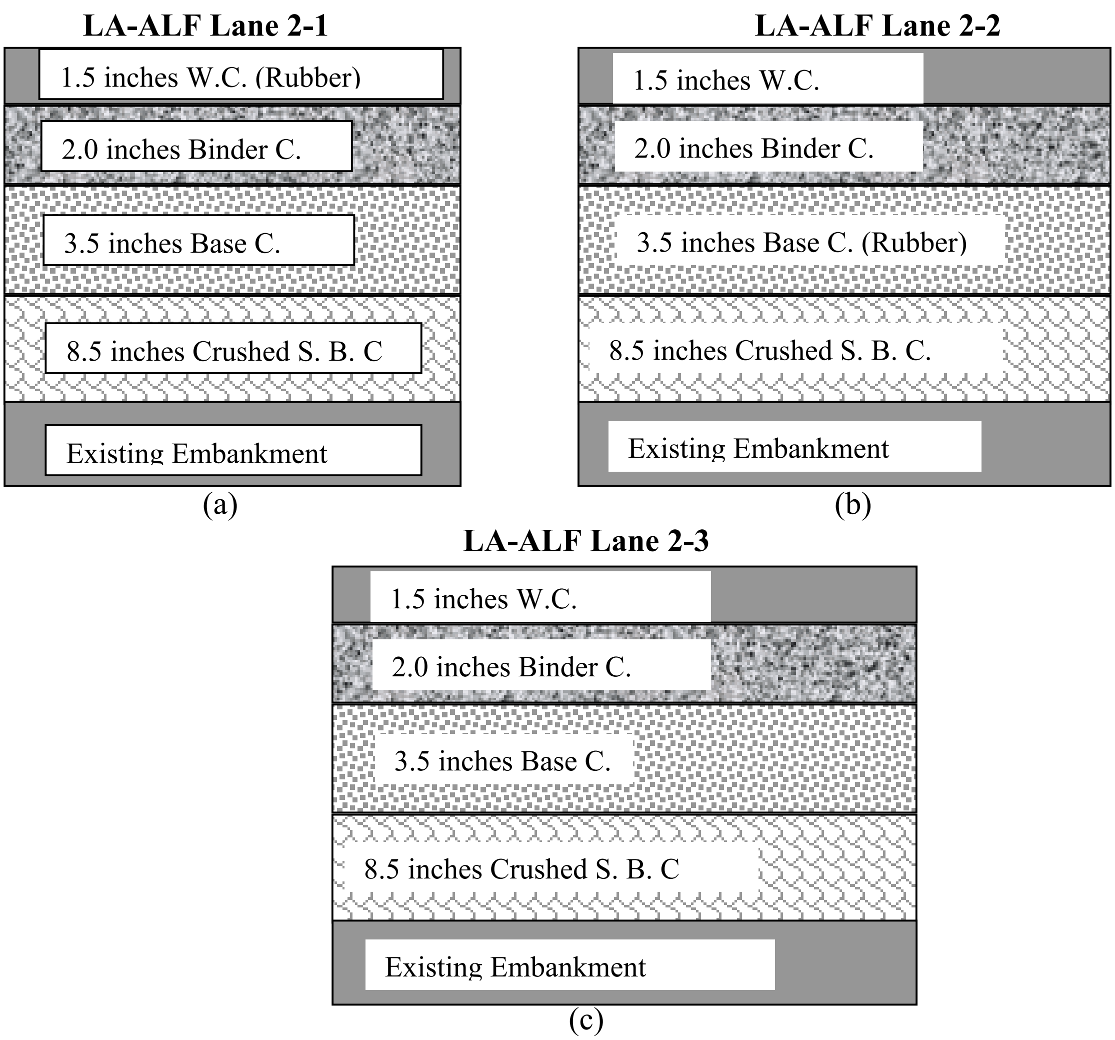


Figure 13. Cross Sections of Experimental Lanes of LA-ALF Test Sites.

- **Laboratory Test Samples of LA-ALF Experimental Lanes**

Several asphalt concrete cores, shown in Figure 14, were taken from each experimental lane and brought to Texas Transportation Institute (TTI) to test. Both modulus (including resilient modulus and dynamic modulus) and permanent deformation tests were performed and discussed as follows.

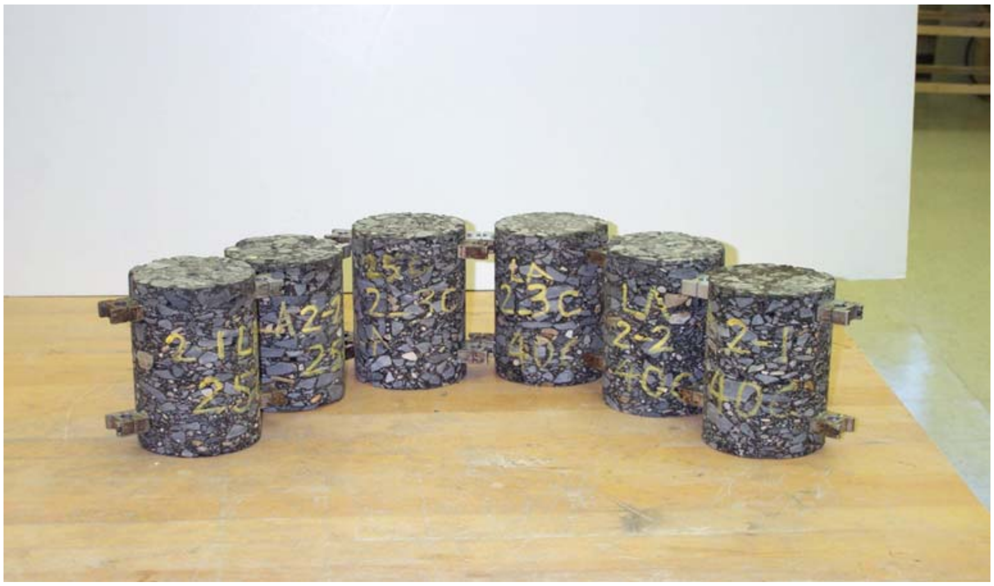


Figure 14. Cores from LA-ALF Experiment Lanes.

MODULUS RESULTS

Two types of modulus tests included;

- dynamic modulus was measured at 25, 40, and 50 °C, as proposed by AASHTO20002; and
- uniaxial resilient modulus, measured from VESYS repeated load test.

Figures 15 and 16 show the dynamic modulus and uniaxial resilient modulus results, respectively. There was no modulus test for Lane 2-3 at 50 °C. In general, it appears that the asphalt mixes of Lane 2-2 have the highest modulus, Lane 2-3 has the lowest modulus, and the modulus of Lane 2-1 is in the middle. These results are consistent with the FWD results.

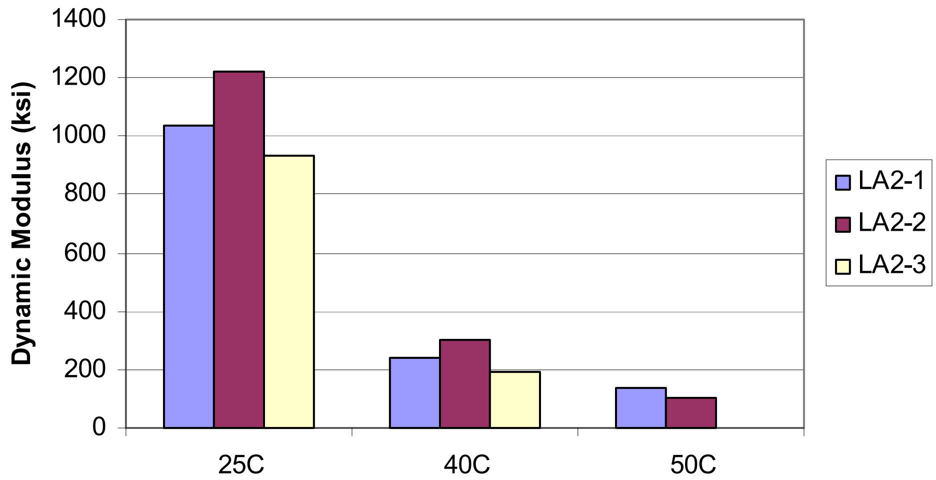


Figure 15. Dynamic Moduli Test Results at 25, 40, and 50 °C.

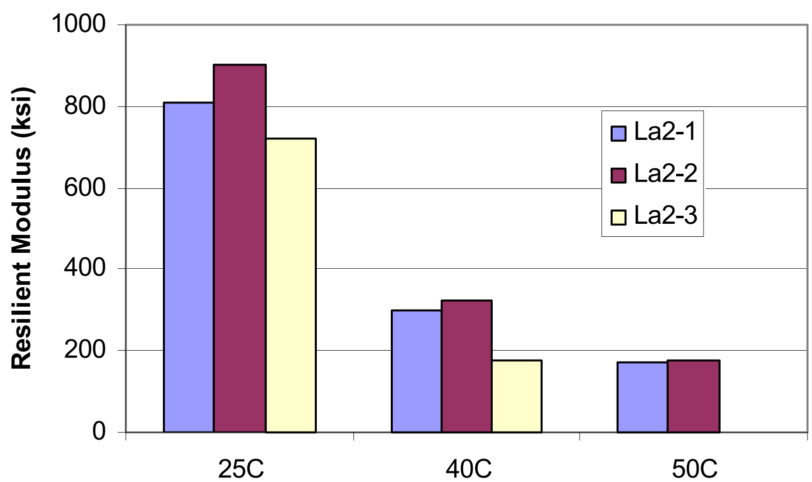


Figure 16. Resilient Moduli Test Results at 25, 40, and 50 °C.

PERMANENT DEFORMATION TEST RESULTS

The permanent deformation tests were performed based on the test protocol above. The load levels used during testing were 30, 20, and 20 psi, corresponding to 25, 40, and 50 °C, respectively.

The permanent deformation test results at 25, 40 and 50° C are presented in Figures 17, 18, and 19, respectively. It is observed that Lane 2-2 shows the strongest resistance to rutting, followed by Lane 2-1. Lane 2-3 has the poorest rutting performance. These results agree with both FWD and modulus results. If all three lanes were tested at the same temperature, Lane 2-2 should have shallow rut depth, followed by Lane 2-1, with Lane 2-3 being the deepest.

Table 15 presents the VESYS layer rutting parameters, μ and α, for all three lanes at different temperatures.

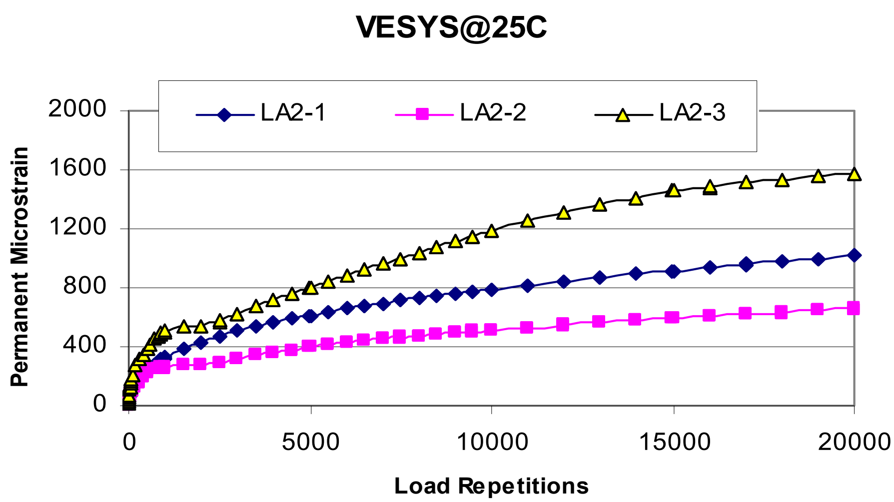


Figure 17. VESYS Test Results at 25 °C.

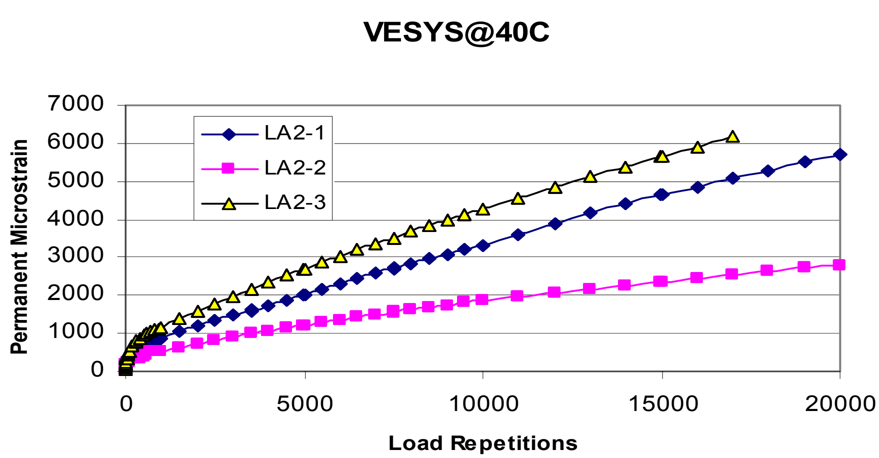


Figure 18. VESYS Test Results at 40 °C.

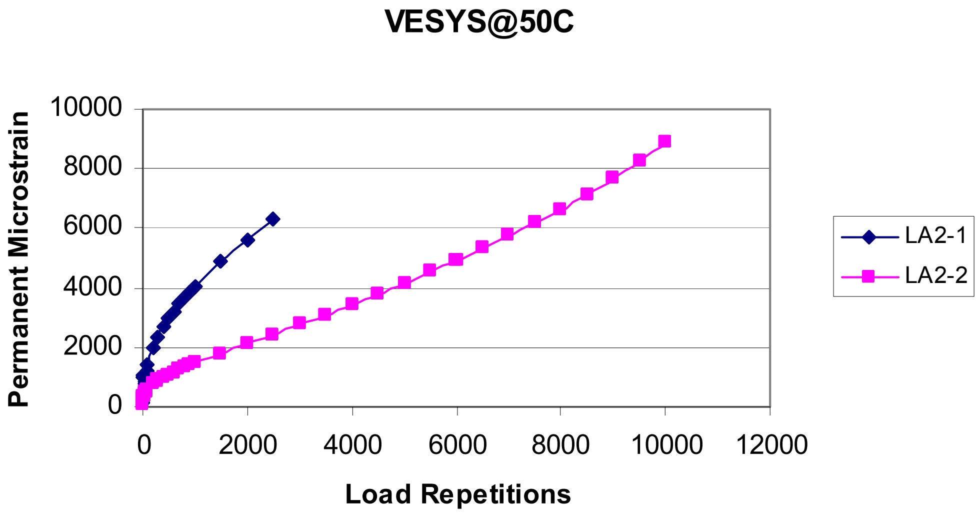


Figure 19. VESYS Test Results at 50 °C.

Table 15. VESYS Rutting Parameters: μ, α.

Temperature	Test Lane	a	b	ε_r	GNU	ALPHA
50 °C	LA2-1	184.46	0.4469	110.6	0.7453	0.5531
	LA2-2	93.839	0.3951	111.3	0.3331	0.6049
	LA2-3	No Test				
40 °C	LA2-1	43.530	0.4188	68.10	0.2677	0.5812
	LA2-2	43.937	0.3641	60.60	0.2640	0.6359
	LA2-3	101.54	0.3585	113.1	0.3219	0.6415
25 °C	LA2-1	19.048	0.4095	37.50	0.2080	0.5905
	LA2-2	27.508	0.3170	34.40	0.2535	0.6830
	LA2-3	51.039	0.3233	43.75	0.3772	0.6767

COMPARISON OF LABORATORY TEST RESULTS WITH LOUISIANA ALF RESULTS

Figure 20 presents the Louisiana ALF test results on Lanes 2-1, 2-2, and 2-3. It is well known that the temperature has considerable effect on the rut development of asphalt pavement. The temperature during ALF test should be same or similar when we make comparison among different asphalt mixtures. The temperature data for three lanes is shown in Figure 21. It is clear that the test temperature of Lane 2-1 was similar to that of Lane 2-2 and considerably higher than that of Lane 2-3 at the initial stage of the ALF test. The estimated difference from Figure 21 is about 25 °F. Thus, it is inappropriate to directly compare the Lane 2-1 with Lane 2-3 without temperature correction. The following comparison will focus on Lane 2-2 with others.

It can be seen from Figure 20 that Lane 2-2, regardless of temperature, has the shallowest rutting depth and performed the best. This is consistent with both modulus and permanent deformation test results shown in Figures 15 through 19.

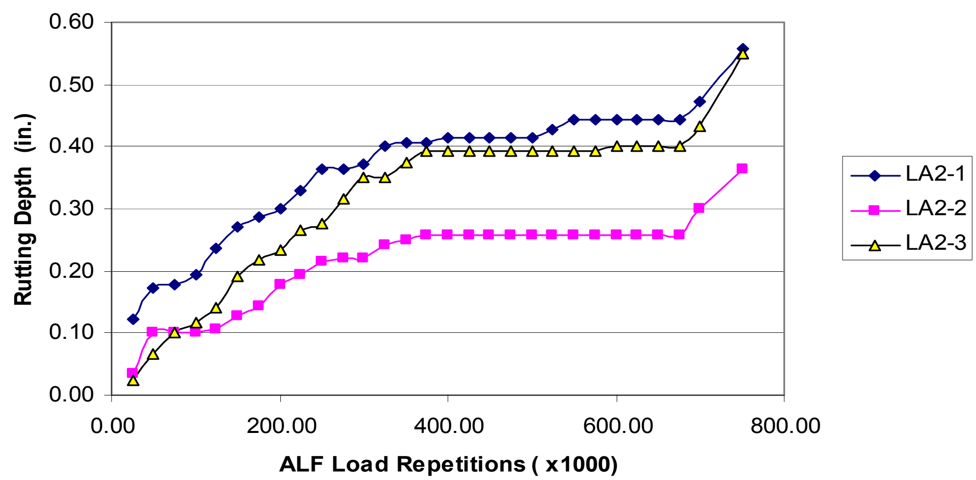


Figure 20. Louisiana ALF Test Results.

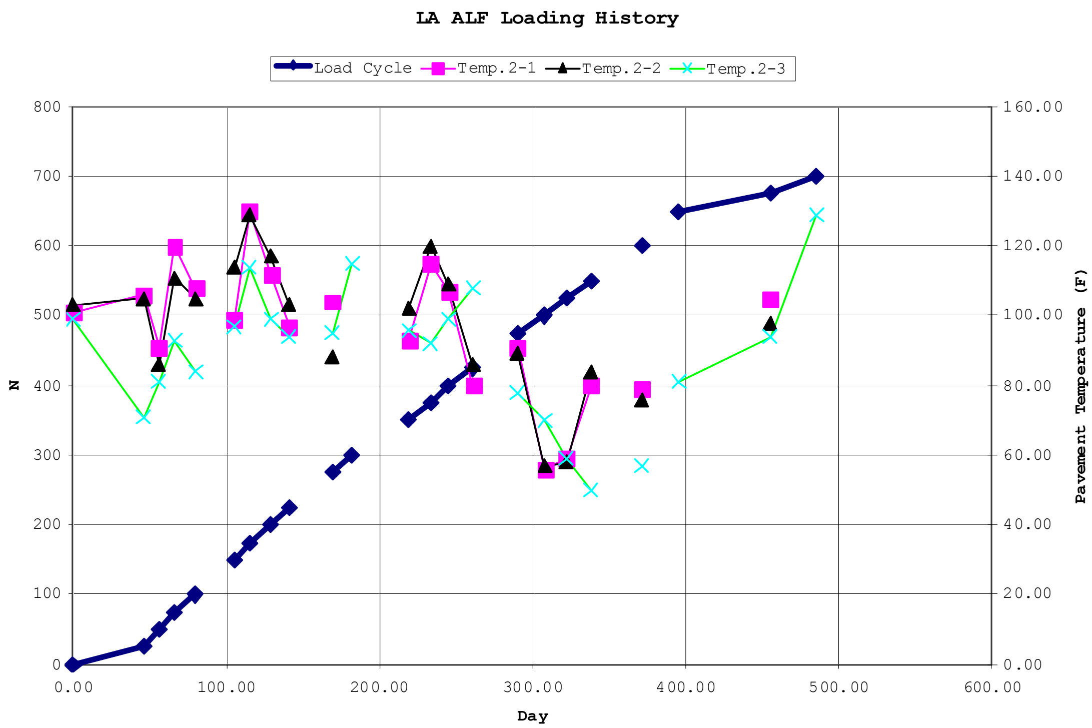


Figure 21. LA-ALF Accumulated Loading Cycles and Pavement Temperature during Test Period.

CHAPTER 5

CASE STUDY: SIMULATION OF THE INFLUENCE OF TRUCKS ON PAVEMENT PERFORMANCE ON US281N

This chapter presents a case study to show the influence of trucks in Texas, Canada, and Mexico on pavement rutting depth. Research shows that the 5-axle tractor-semitrailor (see Figure 1, 1 single axle + 2 tandem axle) is the typical truck traveling on U. S. highways. Therefore, this case study uses this truck. Table 16 presents the truck information (detailed information can be found in Tables 1 and 2).

Pavement structure and material are assumed to be the same as that of TxMLS test pads on US281N (see Figure 4). In this district there are four seasons per year, three months of cold season with 68 °F at the mid-depth of AC, six months of warm season with 89 °F at the mid-depth of AC, and three months of hot season with 95 °F at the mid-depth of AC.

Figure 22 shows the predicted result from VESYS5. It is observed that Mexico's trucks have serious effects on the pavement rutting depth, considerably damaging the pavement. It is clear that both Canada's and Mexico's trucks will induce more damage in the pavement and associated agency cost and user cost. Apparently, more research work should be done in this field.

Table 16. Weight Information of Each Axle for Trucks in Texas, Canada, and Mexico.

Country	Single Axle (kip)	Tandem Axle 1 (kip)	Tandem Axle 2 (kip)	Total (kip)
U. S. (Texas)	12	34	34	80
Canada	12	37.5	37.5	87
Mexico	11	43	43	97

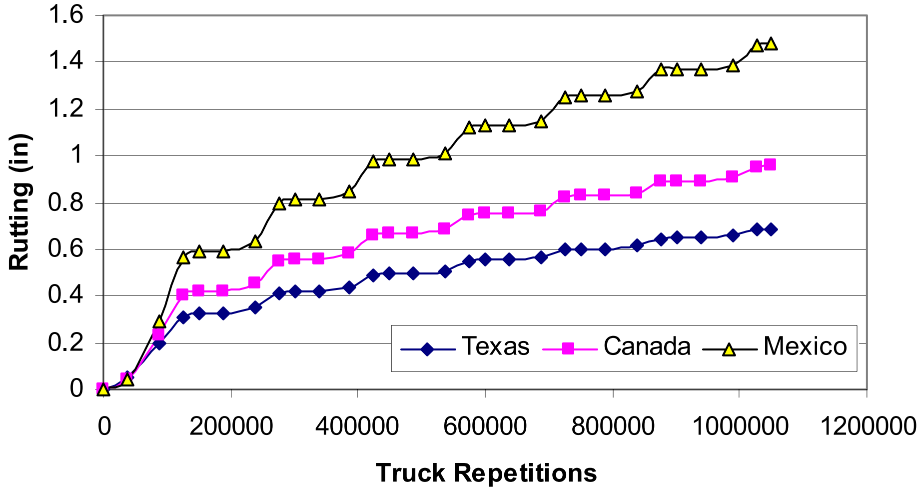


Figure 22. Truck Repetitions vs. Rutting Relationship.

CHAPTER 6
SUMMARY AND CONCLUSIONS

The work and major findings from this project to date are summarized as follows:

- TTI has summarized all data on the various truck types (axle loads and configurations) used in Texas, Canada, and Mexico under the current NAFTA agreement. This information was summarized a technical memorandum.
- A sensitivity analysis of the VESYS5 rutting model was performed. The results were found to be very reasonable. The framework of using the Texas Mobile Load Simulator data to calibrate the VESYS5 layer rutting model has been developed. The rutting prediction from the VESYS5 model correlated well with the TxMLS results on two APT sites in Texas.
- To further evaluate the effectiveness of the VESYS rut prediction approach, TTI compared the field performance of different experimental test sections with the laboratory test results performed on field cores. The sections were part of a SPS-1 site in South Texas with rut depths ranging from 2 to 25 mm. Field studies confirmed that the rutting was primarily in the AC surfacing layer. On cores taken from these sections TTI measured the VESYS rutting parameters (ALPHA and GNU) in a repeated load test procedure. In addition, other recommended test methods used to characterize the permanent deformation properties of asphalt mixes were also performed. These methods included the dynamic modulus, resilient modulus, repeated simple shear test at constant height, asphalt pavement analyzer, and Hamburg wheel tracking test. Based on the laboratory tests, the materials were ranked from best to worst in terms of rutting potential. The VESYS approach was able to rank the sections in an identical order to their actual measured field performance. The VESYS approach was found to be better than the other test methods at matching field performance.
- TTI researchers visited the Louisiana ALF site to take cores from three test sections. Laboratory tests were performed to measure both the modulus and permanent deformation properties at three temperatures. The test results from

the different sections correlated with the ALF test results and the initial FWD measurement.

- A laboratory test protocol for determining the rutting parameters, μ and α, was developed. This test was based on the experience gained from the repeated load test on SPS-1 and Louisiana-ALF materials and from the protocols given in both the VESYS user manual and the Superpave Simple Performance Test.
- As part of this project a comprehensive literature search was also conducted. From published laboratory results researchers found that the VESYS5 rutting parameters, α and μ, were both stress and temperature dependent. Based on the data in the literature, regression equations were developed for α and μ.
- The overall goal of this project is to use calibrated pavement performance models to estimate the impact of different truck loads on overall pavement performance and repair costs. To demonstrate this approach a case study was conducted to evaluate the influence of different NAFTA trucks on pavement performance. The assembled axle load information from Texas, Mexico, and Canada was used in this investigation. This analysis was based on the pavement performance model (VESYS5), from which was calibrated with the accelerated pavement test data collected with the Texas MLS site.

REFERENCES

1. Kenis, W. J. and W. Wang, Calibrating Mechanistic Flexible Pavement Rutting Models from Full Scale Accelerated Tests, Proceedings of the 8th *International Conference on Asphalt Pavements*, Vol. 1, pp. 663-672, Seattle, Washington.
2. Chen, Dar-Hao and Fred Hugo, Comparison of the Two Pavement Rehabilitation Strategies, *Journal of Transportation Engineering*, ASCE, Jan./Feb. 2001, Vol. 127 No.1 pp. 47-58.
3. Chen, Dar-Hao, Huang-Hsiung Lin, and F. Hugo, Application of VESYS3AM in Characterization of Permanent Deformation, *Journal of Pavement Engineering,* 2001.
4. Leahy, Rita, *Permanent Deformation Characteristics of Asphalt Concrete*, Ph.D. Dissertation, University of Maryland, 1989.
5. Chen, Dar-Hao, John Bilyeu, Tom Scullion, Deng-Fong Lin, and Fujie Zhou, "Forensic Evaluation of the Premature Failures of the SPS-1 Sections," Accepted for publication in the *Journal of Performance of Constructed Facility*, ASCE, 2003.
6. Kenis, W. J., *Predictive Design Procedures, VESYS Users Manual*, Report No. FHWA A-RD-77-154, Federal Highway Administration, 1977.
7. *Standard Test Method for Simple Performance Test for Permanent Deformation Based Upon Repeated Load Test of Asphalt Concrete Mixtures*, NCHRP 9-19 Superpave Models Draft Test Method X1 ASU-September 2000.

APPENDIX A

TRUCK INFORMATION UNDER NAFTA

A literature review was conducted to document the types of truck and axle configurations used under NAFTA. In addition to U. S. trucks, both Mexican and Canadian trucks were also documented. All of the information about trucks was summarized and the main information is described as follows.

INFORMATION ON TRUCK SIZE AND WEIGHT REGULATIONS IN TEXAS, MEXICO AND CANADA

Table A1 shows the general comparison of truck size and weight regulations (TS&W) in Texas, Mexico, and Canada. Figure A1 illustrates the typical truck in Texas, Mexico, and Canada. Table A2 presents the detailed comparison of typical truck axle weight and gross vehicle weight. The more detailed truck information is found in Appendix B.

- **Comparison between Texas and Mexico**

There are several important differences between TS&W regulations on both sides of the border that affect trucking in this region. For the most part, regulations on the U. S. side are more restrictive than those on the Mexico side. For that reason, the major TS&W policy issues that exist in this area are U. S.- based.

Width limits (body dimensions) in Mexico and Texas are the same (8.5 ft). In Texas, the length of a semitrailer is restricted to 59 ft, whereas in Mexico, this dimension is not regulated (except as it pertains to overall length). Mexico limits the overall combination length of a tractor semitrailer to 20.8 m (68.2 ft) and in Texas this dimension is not regulated. The 20.8 m length in Mexico permits the use of 53-foot semitrailers with both cab over engine (COE) and cab behind engine (CBE or conventional) tractors but only if the tractor wheelbase is approximately 200 inches (5.08 m). Texas has many long-wheelbase tractors that exceed these limits (as does).

The gross vehicle weight (GVW) governing operations at border crossings in Texas is 80,000 lb, but this can increase to 84,000 lb with the purchase of an annual overweight tolerance permit (off the Interstate system). In Mexico, the maximum allowable GVW for a 3-S2 is significantly greater at 97,020 lb (44 tons). Another example is a six-axle tractor double trailer combination (3-S1-2) with 22 tires, which can operate on Class A2 or A4 Mexican highways at 123,480 lb (56 tons). Again, this same vehicle is allowed 80,000 lb GVW in Texas (or 84,000 lb with the 5 percent overweight tolerance permit). The Mexican GVW limits are increased when the vehicle is equipped with air suspension on all its axles, except the steering axle.

Table A1. General Comparison of Truck Size and Weight Regulations in Texas, Mexico, and Canada.

Item	**Texas (ft and lb)**	**Mexico (ft and lb)**	**Canada (MoU) (ft and lb)**
Dimensions			
Height	14.0	13.9	13.6
Tractor WB (min. to max.)	NR	NR	9.8 to 20.3
Semitrailer length	59.0	NR	53.0
Tractor-Semi length	NR	68.2	75.0
Kingpin to Rear axle for Semi-	NR	NR	20.5 to 41.0[a]
Weight			
Steering Axle	20,000	14,300	12,128
Single axle	20,000	22,045	20,066
Tandem axle	34,000	42,998	37,485
Tridem axle	BFB	49,604	46,305
GVW for 3-S2	80,000[b]	97,020	87,098
Tire pressure (psi)	NR	Manufacturer rating	NR
Tire load/unit width	650 lb/in	NR	559 lb/in
Tire load/tire	NR	NR	6,614 lb
Other considerations			
Spread Tandem Axle	BFB	NR	Ontario&Quebec[d]
Lift axles	NR	NR	Ontario&Quebec[d]
Super single tires	Yes (limited)	No, limited by max	No, limited by
Allowance for powered axles	No	Yes	No
Allowance for suspension type	No	Yes	Yes, varies
Spring bans/winter premiums	No	No	Yes, varies

NP=Not permitted
NR=Not regulated
BFB=Governed by Bridge Formula B.
[a] Measured from kingpin to center of rear axle group.
[b] With weight tolerance permit, off the IH system, can increase to 84,000 lb.
[c] This is for 8.0 ft spacing, for 12 ft spacing, increasing to 52,920 lb.
[d] Other provinces do not allow.

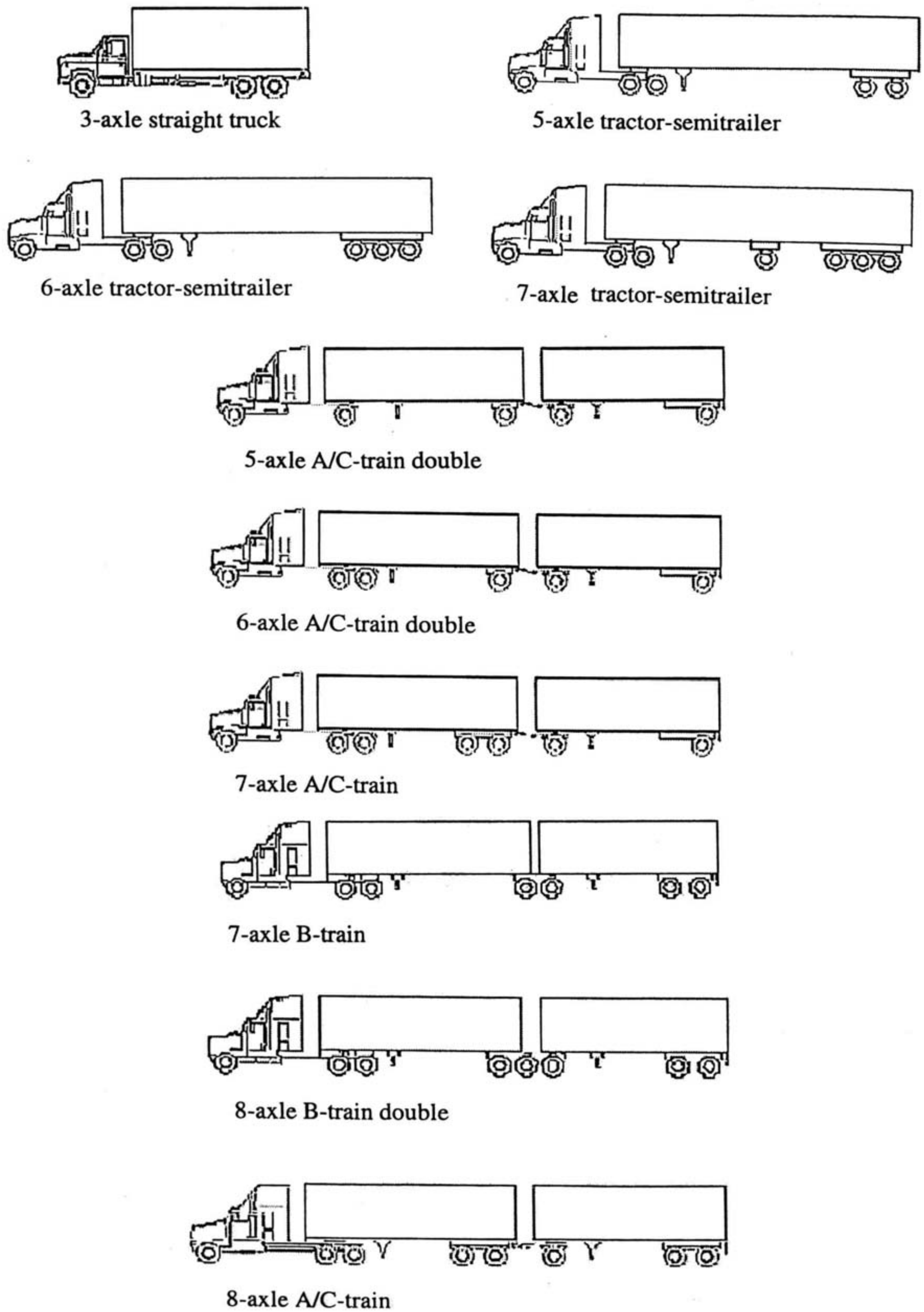


Figure A1. Typical Vehicle Configuration.

Table A2. Basic Maximum Weight Limits in Texas, Mexico, and Canada.

Item	Texas	Mexico	Canada	
			MoU	Ontario/Qu.
Tire loads				
lb/in.	650	NR	560	560
lb/tire	NR	NR	6614	6614
Tire pressure (psi)	NR	Manufacturer rating	NR	NR
Axle loads (lb)				
Steering axle (tractor)	20,000	14,300	12,128	12,128
Steering (straight truck)	NR	NR	15,984	15984
Single (dual tires)	20,000	22,045	20,066	22,045
Tandem (48'' spacing)	34,000	42,988	37,479	37,479
Tandem (72'' spacing)	34,000	42,988	37,479	42,108
Tridem (96'' spacing)	42,000	49,604	46,297	46,958
Tridem (120'' spacing)	43,500	49,604	50,706	50,706
Tridem (144'' spacing)	45,000	49,604	52,911	53,793
Tri-axle (13.1 f. spacing)	NR	NR	NP	61,509
Tri-axle (15.7 ft spacing)	NR	NR	NP	64,155
Quad (100''+60''+60'')	NR	NR	NP	70,548
Quad (100''+72''+72'')	NR	NR	NP	74,957
GVWs (lb)				
3-axle straight truck	NR	57,268	49,604	59,304
5-axle tractor-semitrailer	NR	96,916	87,083	97,003
6-axle tractor-semitrailer	NR	160,828	102,515	119,050
7-axle tractor-semitrailer	NR	NR	NP	124,561
5-axle A-train double	NR	104,625	92,374	100,310
6-axle A-train double	NR	123,348	109,790	120,152
7-axle A-train double	NR	133,260	117,047	136,025
7-axle B-train double	NR	NR	124,561	136,025
8-axle B-train double	NR	132,158	137,789	139,994
7-axle C-train double	NR	NR	120,372	136,025
8-axle C-train double	NR	138,766	128,970	139,970
9-axle train double	NR	146,475	No	No

NR=Not Regulated; NP= Not Permitted.

- **Comparison between Texas and Canada**

The TS&W limits governing trucking operations directly across the Canada-U.S. border (i.e., with first tier states in the U.S.) are very different than the Texas limits (i.e., 80,000-lb GVW, 34,000-lb tandem-axle weight, 20,000-lb single-axle weight, and Bridge Formula B). All but one of the Canada-U.S. border crossings involving a U.S. NHS highway has GVW limits of more than 99,000 lb. Nine of the 11 Interstate highway crossings in the six provinces of interest have GVW limits of more than 105,000 lb. Several crossings between Montana and Alberta, and Ontario and Michigan have GVW limits of close to 140,000 lb.

From the perspective of trucks operating between Texas and Canada, the following difference in TS&W limits are of most importance:

- Weights
  - Major roads in all Canadian provinces permit higher tire loads, higher axle loads, and higher GVWs than Texas.
  - Ontario applies a bridge formula for determining allowable loads among axle groups. The formula is specified in a series of tables showing allowed loads with various numbers of axles and distances between axles. The rest of Canada specifies required axle spacings, axle loads, and GVWs typically by truck type.
  - In all cases, the specified Canadian load limits among axle groups are more liberal than equivalent Texas limits—meaning that a vehicle meeting Texas load limit requirements (assuming dimensional requirements are also in compliance with Canadian regulations) would comply with Canadian weight limits.
- Dimensions
  - Texas allows 14-ft height vehicles. Canada's height limit is restricted to 13.6 ft (4.15 m).
  - Texas allows the use of spread tandem axles. The four western provinces of Manitoba, Saskatchewan, Alberta, and British

Columbia, prohibit the use of these axles, whereas they are allowed in Ontario and Quebec.

- Canada has minimum and maximum inter-axle spacing requirements that are sometimes in conflict with U.S. vehicles.
- Texas allows the use of 59-ft semitrailers. Across Canada, the maximum semitrailer length is 53 ft.
- Western Canada generally prohibits the effective use of lift axles; they are permitted only in Ontario and Quebec.

- **Traffic Load Information in AASHTO2002 Design Guide**

The 2002 Guide applies design and performance models based on the principles of engineering mechanics. These mechanistic models require the estimation of axle loads a pavement is expected to see in service. Consequently, the 2002 Guide eliminates the ESALs approach and uses the full spectra of axle loads applied to a pavement structure by the prevailing or projected traffic stream.

Automatic vehicle classification (AVC) data provide information about the number and types of vehicles, shown in Figure A2. The Class 9 vehicles are responsible for 80-90 percent of traffic loadings on the Interstate system, which corresponds to the 5-axle tractor-semitrailer in Figure A1.

Traffic input requirement is comprised of three levels with the hierarchical approach, shown as follows,

- **Level 1 Input**: Use of volume/classification and axle load spectra data directly related to the project.
- **Level 2 Input**: Use of regional axle load spectra data and project-related volume/classification data.
- **Level 3 Input**: Use of regional or default classification and axle load spectra data.

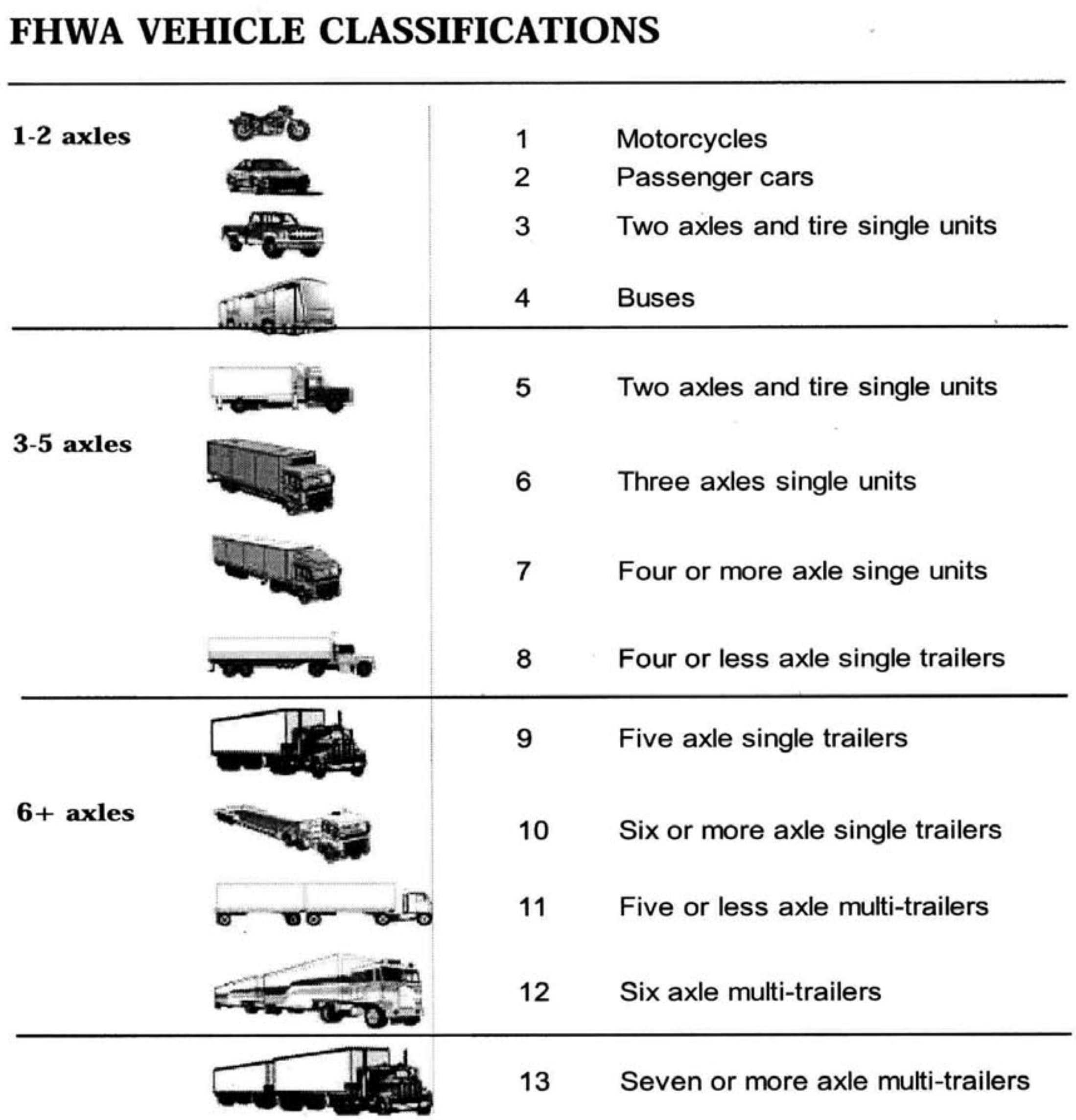


Figure A2. llustration and definitions of the vehicle classes used for collecting the traffic data needed for mechanistic-empirical pavement design. Class 9 vehicles are responsible for 80-90 percent of traffic loadings on the interstate system.

- **Input assumption**

  The 2002 mechanistic design procedure makes three major assumptions in regard to traffic data. The axle load distribution by axle type and vehicle class:

- remains constant from year to year, but the vehicle class distributions can change from year to year;
- does not change throughout the day or over the week (weekday versus weekend and night versus day); however, the vehicle class or truck distributions can change over the time-of-day or day of the week; and
- does not change from site to site within a specific region.

- **Default values for selected variables**

  Default values are provided for each of the elements that describe the details of the tire and axle loads. These default values were developed using the long-term pavement performance (LTPP) traffic database. However, the agency has the option to use site-specific values.

  - *Number of axle type per vehicle for each vehicle class (Table A3)*

    This input is determined from weight in motion (WIM) data by dividing the total number of axles of each type by the total number of trucks weighed. However, these factors were found to be generally independent of site-specific conditions.

Table A3. Default Values for Average Number of Axles per Truck.

Class	**Single**	**Tandem**	**Tridem**
4	1.62	0.39	0.00
5	2.00	0.00	0.00
6	1.02	0.99	0.00
7	1.00	0.26	0.83
8	2.38	0.67	0.00
9	1.13	1.93	0.00
10	1.19	1.09	0.89
11	4.29	0.26	0.06
12	3.52	1.14	0.06
13	2.15	2.13	0.35

- *Axle spacing: 50 inches (1250 mm)*

  The spacing between axles in a tandem, tridem, or quad group of axles must be 50 inches.

- *Dual tire spacing: 11.25 inch (287 mm)*

  Dual tire spacing is the center-to-center spacing of dual tires on the end of a single axle.

- *Tire pressure: Single: 120 psi (827 kPa)*
  Dual: 110 psi (758 kPa)

  The hot inflation pressure should be used in the analysis. The hot inflation pressure is obtained by increasing the cold inflation pressure by 10 to 15 percent. Tire pressure is a function of whether the tire is in single or dual configuration.

APPENDIX B

INFORMATION OF TRUCK SIZE AND WEIGHT REGULATIONS IN TEXAS, MEXICO, AND CANADA

MOTOR CARRIER OPERATIONS IN TEXAS

Texas applies Bridge Formula B to operations on Interstate (IS) highways and requires compliance with the formula from both the inner and outer bridge perspectives, which means that a truck must be legal on all consecutive axle groups. The formula is capped at a gross vehicle weight of 80,000 lb on those highways. However, the state provides an "Annual Overweight Tolerance Permit" (2060 permit) that allows operation at a 5 percent tolerance on GVW and a 10 percent tolerance on axle weights on state and county roads.

- **Maximum vehicle dimensions**

Table B1 presents a summary of selected aspects of the dimensional limits governing truck operations on highways in the state of Texas, also from the Texas Transportation Code.

Table B1. Summary of Truck Dimensional Regulations in Texas.

Item	**Interstate System**	**National Network**	**Other**
Width	8.5 ft (2.6 m)	8.5 ft (2.6 m)	8.5 ft (2.6 m)
Height	14 ft (4.3 m)	14 ft (4.3 m)	14 ft (4.3 m)
Max Length			
Single Unit Truck	45 ft (13.7 m)	45 ft (13.7 m)	45 ft (13.7 m)
Semitrailer	59 ft (48.0 m)	59 ft (48.0 m)	59 ft (48.0 m)
Trailer	NR	NR	NR
Double Trailers	2 x 28.5 ft (2 x 8.7 m)	2 x 28.5 ft (2 x 8.7 m)	2 x 28.5 ft (2 x 8.7 m)
Truck and Trailer	65 ft (19.8 m)	65 ft (19.8 m)	65 ft (19.8 m)
Tractor-semitrailer	NR	NR	NR
Tractor-double Trailer	NR	NR	NR

Source: Texas Transportation Code

NR=Not Regulated

- **Maximum axle and gross vehicle weights**

Table B2 shows a summary of selected aspects of the weight provisions governing truck operations on highways in the state of Texas based on the Texas Transportation Code. These provisions represent the regulatory limits within which trucks can operate legally in Texas.

Table B2. Summary of Truck Weight Regulations in Texas.

Item	**Interstate System**	**National Network**	**Other**
Tire Load (per unit of width)			
Steering	650 lb/in (11.6 kg/mm)	650 lb/in (11.6 kg/mm)	650 lb/in (11.6 kg/mm)
Other	650 lb/in (11.6 kg/mm)	650 lb/in (11.6 kg/mm)	650 lb/in (11.6 kg/mm)
Axle Weight			
Steering	12000 lb (5448 kg)	12000 lb (5448 kg)	12000 lb (5448 kg)
Single	20000 lb (9080 kg)	20000 lb (9080 kg)	20000 lb (9080 kg)
Tandem	34000 lb (15436 kg)	34000 lb (15436 kg)	34000 lb (15436 kg)
Tridem[a]	BFB	BFB	BFB
GVW	80000 lb (36320 kg)	84000 lb (38136 kg)[b]	84000 lb (38136 kg)[b]
Bridge Formula B	yes	modified	Modified

Source: Texas Transportation Code

[a] The maximum weight on a tridem group is governed by Bridge Formula B (BFB).
[b] A 5 percent GVW tolerance policy annual permit is readily available for any vehicle which is otherwise registered for 80,000 lb (36,320 kg) GVW and is capable of operating at the higher GVW authorized by the permit. Within the specially permitted GVW limit of 84,000 lb (38,136 kg), a 10 percent tolerance on individual axle weights (i.e., 34,000 lb on a tandem *1.10 = 37,400 lb (16,980 kg)) is also allowed. This tolerance permit creates a modified Bridge Formula B.

- **Oversize/Overweight Permits**

The TxDOT Motor Carrier Division (MCD) issues oversize/overweight (OS/OW) permits and temporary trip permits for movements of indivisible loads. Permits fees vary by permit type and duration of permit. Commercial motor carriers hauling oversize loads pay a base fee of $30 per trip. The permit fee for portable buildings is $7.50 and for mobile homes is $20. Thirty-day permits for hauling heavy equipment have a base fee of $60. Similar permits for 60 days cost $90, and $120 for permits valid for 90 days. In addition, every load with a GVW that exceeds 80,000 lb (36,320 kg) must pay a highway maintenance fee. A new type of permit is the “Annual Envelope” vehicle permit for weights of up to 120000 lb (54 480 kg) and dimensions 12 ft (3.66 m) wide, 14 ft (4.3 m) high, and 110 ft (33.5 m) long. The fee for this permit is $2,000. All permits, with the exception of portable building and mobile home permits, require a survey bond in the amount of $10,000 or the carrier must have an active Motor Carrier Registration. For weights that exceed 200000 lb (90800 kg), the applicant must also pay a vehicle supervision fee for an amount set by TxDOT. This amount is used to cover costs related to: (1) bridge structural analysis; (2) the monitoring of the trip process; and (3) moving traffic control device.

MOTOR CARRIER OPERATIONS IN MEXICO

- **Maximum vehicle dimensions**

The regulation in Mexico that addresses vehicle size and weight is directly related to the geometric and structural characteristics of the highways. Table B3 shows the maximum vehicle length for highways of Type A and B.

- **Maximum axle and gross vehicle weights**

Vehicles that travel on federal highways in Mexico must comply simultaneously with two conditions in respect to their weight: (1) they must respect maximum weight per axle; and (2) they must not exceed the established gross maximum vehicle weight. The type of vehicle and the highway type determine both conditions of maximum weight. For maximum weight per axle, all vehicles must comply with the specification in Table B4.

Table B5 presents the maximum gross vehicle weight by type of vehicle. These weight limits come from the maximum weight for each axle, then applying other criteria to prevent damage to bridges. The maximum gross vehicle weight limit increases on vehicles with all axles equipped with pneumatic suspensions (except the steer axle) or with mixed suspensions.

Table B3. Maximum Legal Length by Class of Vehicle and Type of Road.

Class of Vehicle	Maximum Legal Length ft/(meters)	
	Type A	Type B
Bus	45.90 (14.00)	45.90 (14.00)
SU Truck w/6 or more tires	45.90 (14.00)	45.90 (14.00)
SU Truck and trailer	93.44 (28.50)	93.44 (28.50)
Tractor semitrailer	68.20 (20.80)	68.20 (20.80)
Tractor semitrailer-trailer	101.60 (31.00)	93.44 (28.50)
Tractor semitrailer- semitrailer	81.97 (25.00)	81.97 (25.00)

Table B4. Maximum Legal Weight by Type and Number of Axles for Highways of Type A and Type B.

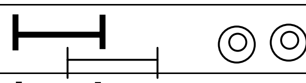
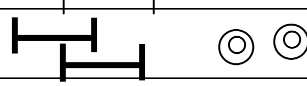
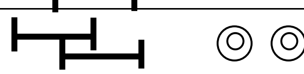
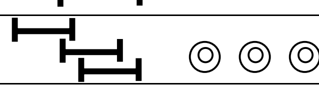
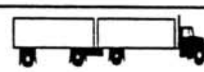
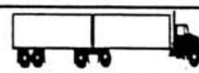
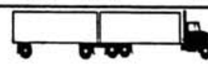
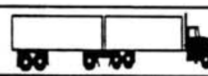
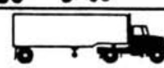
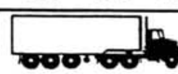
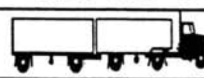
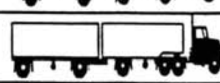
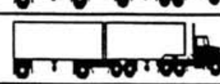
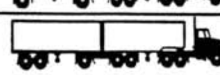
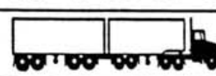
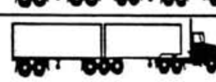
Axle Configuration		Weight lb (metric ton)
Single axle with two tires		14,320 (6.50)
Single axle with four tires		22,026 (10.00)
Power single axle with four tires		24,229 (11.00)
Power double axle or tandem with six tires		34,140 (15.50)
Double or tandem with eight tires		39,647 (18.00)
Power double axle or tandem with eight tires		42,951 (19.50)
Triple or tridem with twelve tires		49,559 (22.50)

Table B5. Maximum Legal Weight by Type of Vehicle for Highways of Type A and Type B

Vehicle Class	Designation		No. of Tires	GVW in lb. *(metric tons)*
Bus (Autobús)	B2		6	38,546 *(17.50)*
	B3		8	48,458 *(22.00)*
	B3		10	57,268 *(26.00)*
	B4		10	67,180 *(30.50)*
Single Unit Truck (Camión Unitario)	C2		6	38,546 *(17.50)*
	C3		8	48,458 *(22.00)*
	C3		10	57,268 *(26.00)*
Truck-Trailer Combination (Camión-Remolque)	C2 – R2		14	82,599 *(37.50)*
	C2 – R3		18	100,220 *(45.50)*
	C3 – R2		18	101,321 *(46.00)*
	C3 – R3		22	118,942 *(54.00)*
Tractor-Semitrailer (Tractocamión-Semirremolque)	T2 – S1		10	60,572 *(27.50)*
	T2 – S2		14	78,193 *(35.50)*
	T3 – S2		18	96,916 *(44.00)*
	T3 – S3		22	160,828 *(48.50)*
Tractor-Semitrailer-Trailer (Tractocamión-Semirremolque-Remolque)	T2 – S1 – R2		18	104,625 *(47.50)*
	T3 – S1 – R2		22	123,348 *(56.00)*
	T3 – S2 – R2		26	133,260 *(60.50)*
	T3 – S2 – R3		30	138,766 *(63.00)*
	T3 – S2 – R4		34	146,475 *(66.50)*
Tractor-Semitrailer-Semitrailer (Tractor-Semirremolque-Semirremolque)	T3 – S3 – S2		30	132,158 *(60.00)*

MOTOR CARRIER OPERATIONS IN CANADA

- **Maximum vehicle dimensions**

Each Canadian province and territory is responsible for administering and enforcing its own truck size and weight regulations. In 1988, the Council of Ministers Responsible for Transportation and Highway Safety signed a Memorandum of Understanding (MoU) on vehicle weights and dimensions. By so doing, they agreed to allow certain vehicles at specified weights and dimensions on certain highway sections of each province's highway system. It was the responsibility of each province to identify its respective designed highway system. The set of size and weight regulations included in the MoU—sometimes called the RTAC regulations—is intended to apply uniformly throughout Canada on most major highways. However, each province has implemented these in slightly different ways, since the agreement allows them to be less restrictive than the MoU for trucks operating within their own jurisdiction. Table B6 illustrates the dimension regulations as prescribed in the RTAC MoU, as well as the variations of these regulations in the provinces of interest.

- **Maximum axle and gross vehicle weights**

Figure B1 shows the different vehicle configurations in Canada. Table B7 presents the key aspects of the basic weight regulations prescribed in the RTAC MoU.

Table B6. Basic Dimension Limits in Canadian Jurisdictions (Imperial Units)

	MoU	PQ	ON	MB	SK	AB	BC
Height [ft.]	13.6	13.6	13.6	13.6	13.6	13.6	13.6
Width [ft.]							
Max of vehicles	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Min of trailer track	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Overall Length [ft.]							
Straight truck	41.0	41.0	41.0	41.0	41.0	41.0	41.0
Semitrailer	53.1	53.1	53.1	53.1	53.1	53.1	53.1
Truck and trailer combination	75.5	75.5	75.5	75.5	75.5	75.5	75.5
Tractor-semitrailer combination	75.5	75.5	75.5	75.5	75.5	75.5	75.5
Double trailer combination	82.0	82.0	82.0	82.0	82.0	82.0	82.0
LCVs (length > 82 ft)	NP	Permit	NP	Permit	Permit	Permit	NP
Box Length [ft.]							
Truck and trailer combination	65.6	NR	NR	65.6	65.6	65.6	65.6
A-train	60.7	60.7	60.7	60.7	60.7	65.6	60.7
B-train	65.6	65.6	65.6	65.6	65.6	65.6	65.6
C-train	65.6	65.6	65.6	65.6	65.6	65.6	65.6
Wheelbase [ft.]							
Straight truck	NR	NR	NR	NR	NR	NR	NR
Full trailer (minimum)	20.5	NR	NR	20.5	20.5	20.5	20.5
Semitrailer (minimum)	20.5	NR	NR	20.5	20.5	20.5	20.5
Semitrailer (maximum)	41.0	41.0	NR	41.0	41.0	41.0	41.0
Tractor (maximum)	20.3	20.3	20.3	20.3	20.3	20.3	20.3

NP = not permitted NR = not regulated

Note 1: in all jurisdictions, the min distance between steering axle and first drive axle for MoU vehicles is 9.8 ft.

Note 2: the sum of the wheelbases on both semitrailers of a B-train cannot exceed 55.8 ft.

Note 3: in ON, the min track width of 8.2 ft., the max overall length of 82.0 ft., and the wheelbase limit of 20.3 ft. apply to MoU trucks only.

Source: F. Nix, 1999 Canadian Size and Weight Chart, and regulations from individual provinces

Table B7. Basic Maximum Weight Limits in Canadian Jurisdictions (Imperial Units)

	MoU	PQ	ON	MB	SK	AB	BC
Tire Loads							
Lb./in	560	616	560	560	560	560	560
Lb./tire	6614	NR	6614	6614	6614	8047	6614
Axle Loads [lb.]							
Steering (tractor)	12,125	12,125	19,842	12,125	12,125	12,125	19,842
Steering (straight truck)	15,984	15,984	19,842	16,094	15,984	16,094	19,842
Single (dual tires)	20,062	22,046	22,046	20,062	20,062	20,062	20,062
Tandem (4.0 ft. spacing)	37,479	39,683	37,479	37,479	37,479	37,479	37,479
Tandem (6.0 ft. spacing)	37,479	39,683	42,108	37,479	37,479	37,479	37,479
Sprd tandem (10.0 ft. spc)	NP	39,683	42,108	NP	NP	NP	NP
Tridem (8.0 ft. spacing)	46,297	46,297	46,958	46,297	46,297	46,297	52,911
Tridem (10.0 ft. spacing)	50,706	52,911	50,706	50,706	50,706	50,706	52,911
Tridem (12.0 ft. spacing)	52,911	57,320	53,793	52,911	52,911	52,911	52,911
Tri-axle (13.1 ft. spacing)	NP	39,683	61,509	NP	NP	NP	50,706
Tri-axle (15.7 ft. spacing)	NP	39,683	64,155	NP	NP	NP	55,116
GVWs [lb.]							
3-axle straight truck	49,604	55,777	59,304	53,572	53,572	53,572	57,320
5-axle tractor-semitrailer	87,083	91,492	97,003	87,083	87,083	87,083	87,083
6-axle tractor-semitrailer	102,515	109,129	119,050	102,515	102,515	102,515	102,515
5-axle A-train double	92,374	100,310	100,310	92,374	92,374	92,374	92,374
6-axle A-train double	109,790	117,947	120,152	107,586	109,790	109,790	109,790
7-axle A-train double	117,947	117,947	136,025	117,947	117,947	117,947	117,947
7-axle B-train double	124,561	130,073	136,025	124,561	124,561	124,561	124,561
8-axle B-train double	137,789	137,789	139,994	137,789	137,789	137,789	139,994
7-axle C-train double	120,372	122,357	136,025	120,372	120,372	127,207	120,372
8-axle C-train double	128,970	128,970	139,994	133,380	128,970	133,380	133,380

* Refers to the road networks described above NP = not permitted NR = not restricted

Note 1: A tri-axle is a tandem plus a single axle. The single axle is often a lift axle. Similar to spread tandems, tri-axles are not recognized under the RTAC MoU.

Note 2: The GVWs shown for Ontario are valid under a specific set of assumptions: (e.g., a practical maximum of 15,432 lb. for a steering axle of tractor-semitrailers, a tandem-drive spread of 60 inches). Theoretically higher GVWs are attainable. Also in Ontario, the 6,614 lb./tire limit applies only to MoU vehicles.

Source: F. Nix, 1999 Canadian Size and Weight Chart; Regulations from individual provinces; and J.J. Keller Truck License and Tax Manual: A Guide to Canadian Regulations, 2000.

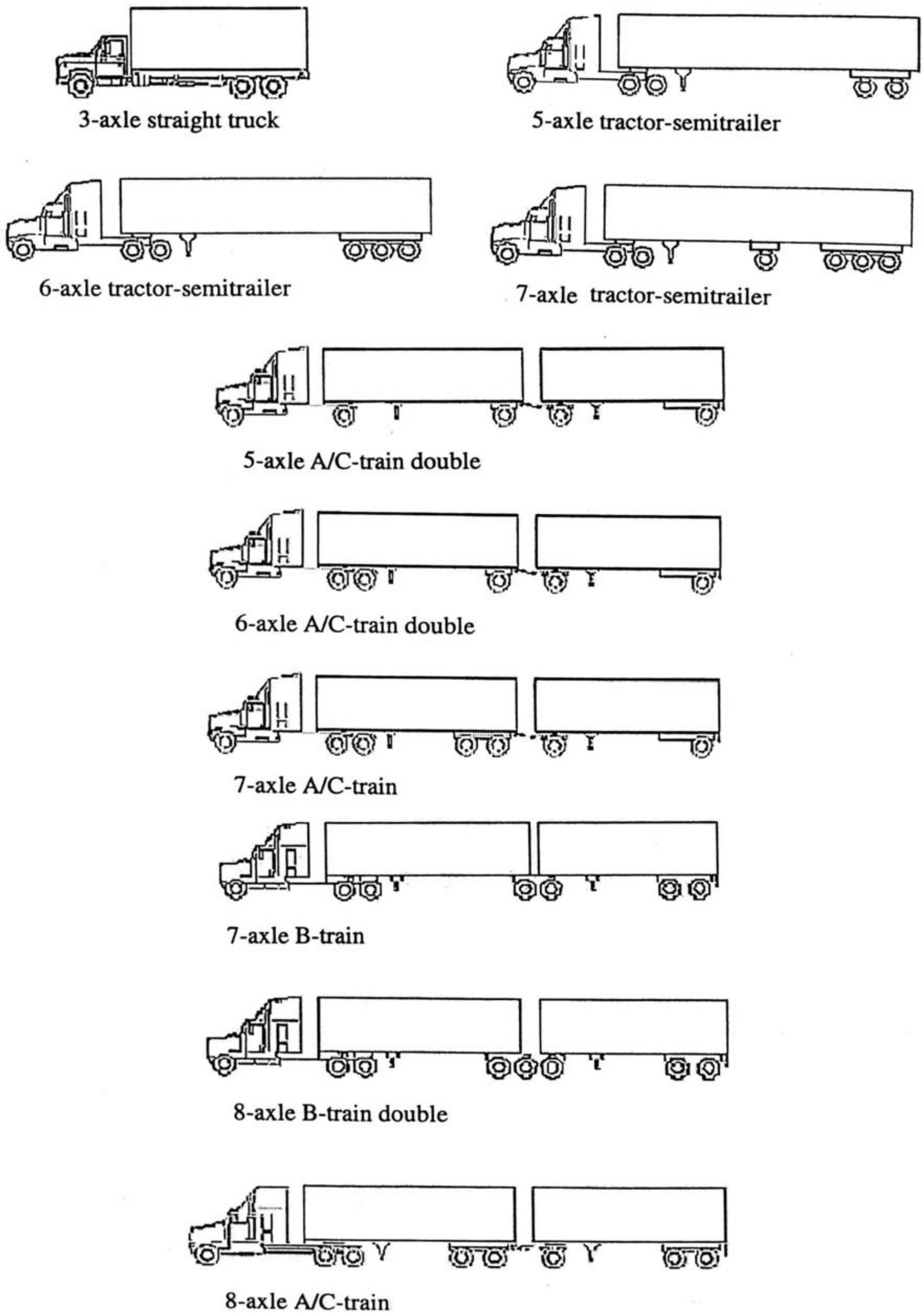


Figure B1. Commercial Motor Vehicle Configurations Used in Canada.

APPENDIX C

VESYS TEST PROTOCOL FOR ASPHALT MIXES

TEST SAMPLES

Size

Testing shall be performed on 100 mm (4 inch) diameter by 150 mm (6 inch) or more high test samples from laboratory or cores from field.

Aging

For laboratory compacted samples, mixture shall be aged in accordance with the short-term oven aging procedure in AASHTO PP2.

Gyratory Specimens

For laboratory compacted samples, prepare 150 mm (6 inch) high samples to the required air void content in accordance with AASHTO TP-4. Gyratory compactor is shown in Figure C1.

End Preparation

The ends of all test samples shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the samples by milling with a single- or double-bladed saw. To ensure that the sawed samples have parallel ends, the sample ends shall have a cut surface waviness height within a tolerance of ±0.05 mm across any diameter.

Air Void Content

Determine the air void content of the final test sample in accordance with AASHTO T269. Reject samples with air voids that differ by more than 0.5 percent from the target air voids.

Replicates

The number of test samples required depends on the number of axial strain measurements made per sample and the desired accuracy of the average permanent deformation. Normally, two replicates are OK for each sample with two linear variable differential transformers (LVDTs).

TEST SAMPLE INSTRUMENTATION

Attach mounting studs for the axial LVDTs to both sides of the sample with 180° intervals (in plan view) using epoxy cement (shown in Figure C2). Make sure the studs are the alignment.

The gauge length for measuring axial deformations shall be 100 mm ±1 mm. The gauge length is normally measured between the stud centers.

TEST PROCEDURES

The recommended test protocol for ALPHA and GNU used in the VESYS program consists of testing the asphalt mix at two temperatures with specified stress level. Table C1 shows the recommended test temperatures and associated stress level.

Table C1. Recommended Test Temperatures and Associated Stress Level.

Test Temperature (°F)	Test Stress Level (psi)
77	30
104	20

Place the test sample in the environmental chamber and allow it to equilibrate to the specified testing temperature. A dummy specimen with a temperature sensor mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, Table C2 provides recommended temperature equilibrium times for samples starting from room temperature (77 °F).

Table C2. Recommended Equilibrium Times.

Test Temperature (°F)	Time (min.)
77	10
104	30

After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the sample on top of the lower end treatment, and mount the axial LVDTs to the studs glued to the sample. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

Place the upper friction reducing end treatment and platen on top of the sample. Center the specimen with the load actuator visually in order to avoid eccentric loading.

Apply a contact load equal to 5 percent of the total load level that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., check for proper direction sensing for all LVDTs).

Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber.

After the sample reaches the testing temperature, apply the haversine load, which yields the desired stress on the specimen. The procedure uses a loading cycle of 1.0 Hz frequency, which consists of applying 0.1-second haversine load followed by 0.9-second rest period. The maximum applied load (P_{max}) is the maximum total load applied to the sample, including the contact and cyclic load: $P_{max}=P_{contact} + P_{cyclic}$.

The contact load ($P_{contact}$) is the vertical load placed on the sample to maintain a positive contact between loading strip and the sample: $P_{contact} = 0.05 \times P_{max}$. The cyclic load ($P_{cyclic}$) is the load applied to the test sample, which is used to calculated the permanent deformation parameters: $P_{cyclic}=P_{max} + P_{contact}$.

Apply the haversine loading (P_{cyclic}) and continue until 5000 cycles is reached or until the sample fails and results in excessive tertiary deformation to the sample, whichever comes first.

During the load applications, record the load applied and the axial deflection measured from all LVDTs through the data acquisition system. All data should be collected in real time and collected so as to minimize phase errors due to sequential channel sampling. It is recommended to use the data acquisition of the cycles shown in Table C3.

Table C3. Suggested Data Collection for VESYS Rutting Test.

Data collected during cycles	Data collected during cycles	Data collected during cycles
1 through 10	598 through 600	2723 through 2725
18 through 20	698 through 700	2998 through 3000
28 through 30	798 through 800	3248 through 3250
48 through 50	898 through 900	3498 through 3500
78 through 80	998 through 1000	3723 through 3725
98 through 100	1248 through 1250	3998 through 4000
148 through 150	1498 through 1500	4248 through 4250
198 through 200	1723 through 1725	4498 through 4500
298 through 300	1998 through 2000	4723 through 4725
398 through 400	2248 through 2250	4998 through 5000
498 through 500	2498 through 2500	

CALCULATIONS

Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to total axial strain by dividing by the gauge length (100 mm (4 inches)).

Compute the cumulative axial permanent strain and resilient strain (ε_r) at 100th load repetition.

Plot the cumulative axial permanent strain versus number of loading cycles in log-log space, which is shown in Figure C4. Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve, which is demonstrated on Figure C5.

Compute the rutting parameters: ALPHA, GNU

$$\mu = \frac{ab}{\varepsilon_r}$$

$$\alpha = 1 - b$$

REPORT

Report all sample information including mix identification, dates of manufacturing (or cored) and testing, sample diameter and length, volumetric properties, stress levels used, and axial permanent deformation parameters: α, μ (or ε_r, a, and b).

Figure C1. Superpave Gyratory Compactor.

Figure C2. Samples with Studs.

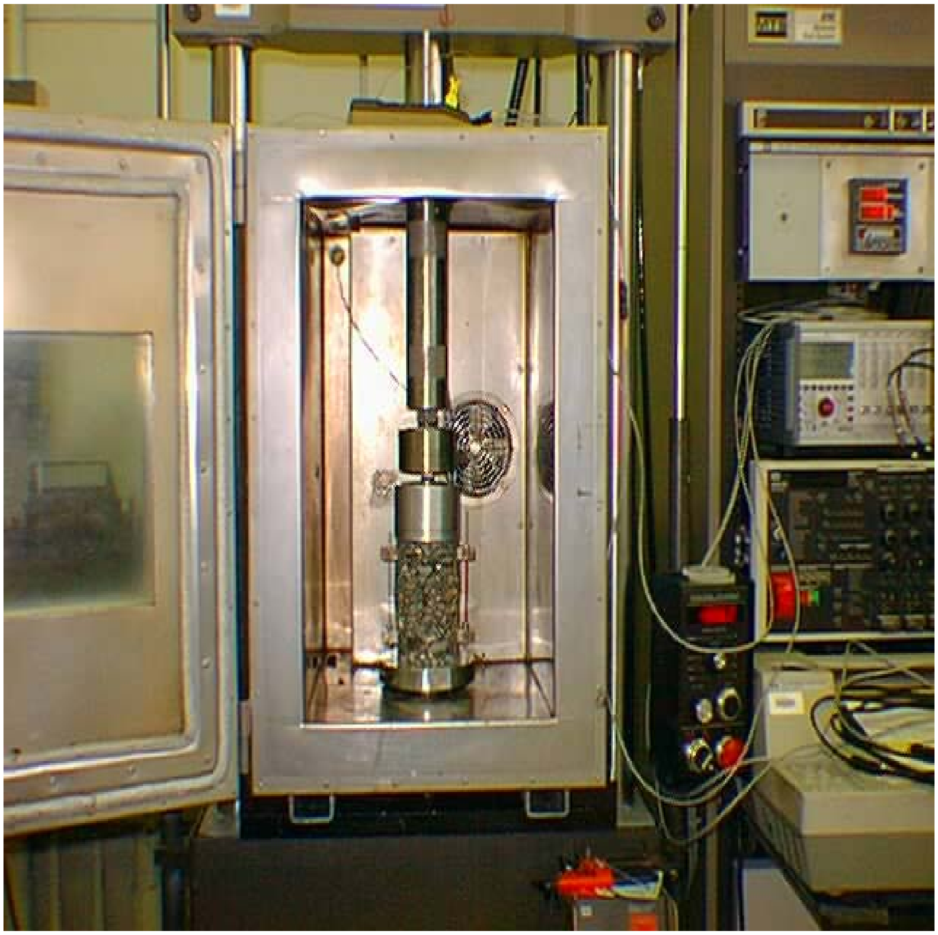


Figure C3. Schematic of Repeated Load Permanent Deformation Test.

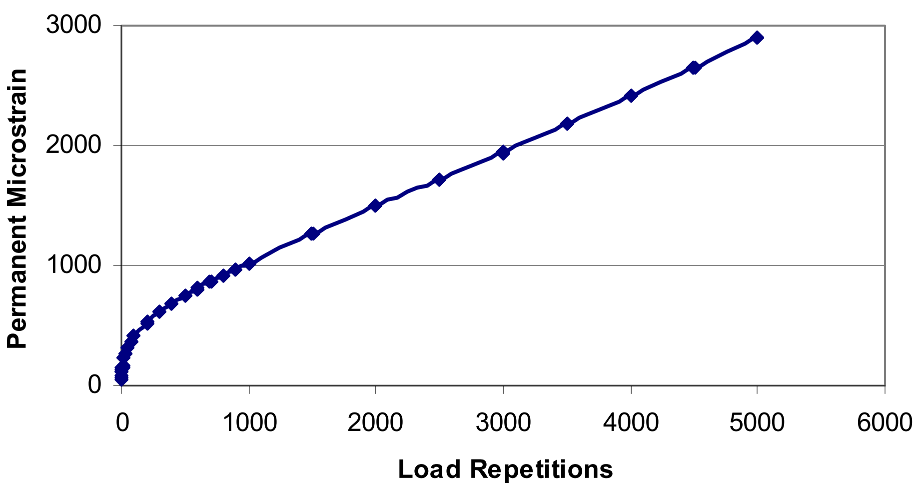


Figure C4. Cumulative Permanent Strain vs. Loading Cycles from a Repeated Load Permanent Deformation Test.

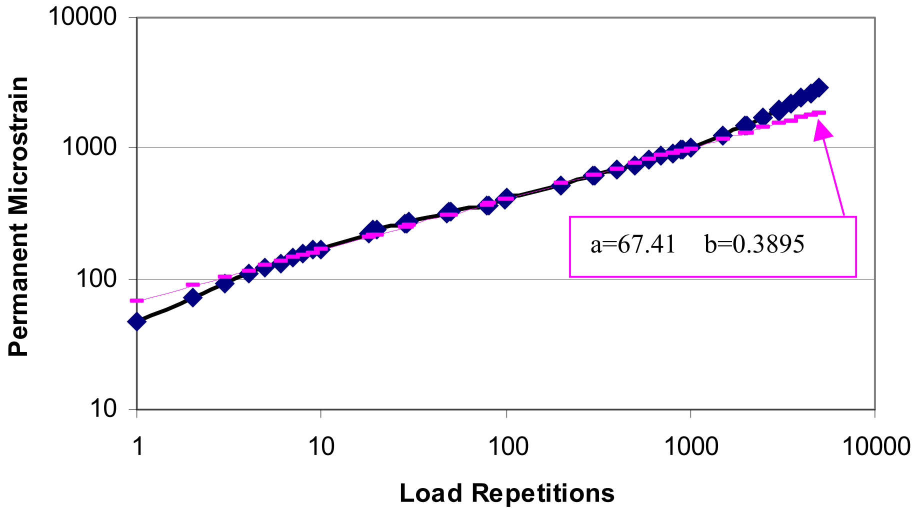


Figure C5. Plot of Regression Constants "a" and "b" from Log Permanent Strain – Log Number of Loading Cycles.

Example: ALPHA and GNU Calculation

ε_r=88.1250

a=67.4100

b=0.3895

$\mu = a*b/\varepsilon_r = 67.41*0.3895/88.125 = 0.2979$

$\alpha = 1-b = 1-0.3895 = 0.6105$