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KENTRACK 4.0: A RAILWAY TRACKBED STRUCTURAL DESIGN PROGRAM

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ABSTRACT

The KENTRACK program is a finite element based railway trackbed structural design program that can be utilized to analyze trackbeds having various combinations of all-granular and asphalt-bound layered support. It is applicable for calculating compressive stresses at the top of subgrade, indicative of potential long-term trackbed settlement failure. Furthermore, for trackbeds containing an asphalt layer, it is applicable for calculating tensile strains at the bottom of the asphalt layer, indicative of potential fatigue cracking. The program was recently expanded to include both English and international units. A procedure has been incorporated to provide a path to save results in a text formation in post-Windows XP operating systems. More importantly, properties of performance graded (PG) asphalt binders and the Witczak E* predictive model have been incorporated in the 4.0 Version of the program. Component layers of typical trackbed support systems are analyzed while evaluating the significance of layer thicknesses and material properties on design and predicted performance. The effect of various material parameters and loading magnitudes on trackbed design and evaluation, as determined and predicted by the computer program, are presented. Variances in subgrade modulus and axle loads and the incorporation of a layer of asphalt within the track structure have significant effects on subgrade vertical compressive stresses and predicted trackbed service lives. The parameter assessments are presented and evaluated using sensitivity analysis.

INTRODUCTION

Railroads have been a primary mode of transportation in the United States for over 180 years. During this period, train speeds, annual gross ton-miles, and axle loads have increased significantly. Hot Mix Asphalt trackbeds have been developed mainly for freight lines. The main attributes are to provide increased support, accommodate heavier axle loads, and reduce trackbed maintenance costs, thereby favorably impacting train operations *(1)*. Asphalt trackbeds are used extensively in Europe and Asia for new high-speed passenger lines to provide high quality track geometric features for safe operations at high speeds *(2)*. Asphalt dynamic modulus is the most important asphalt property influencing the structural response for asphalt-bound layered trackbeds. Numerous dynamic modulus (E*) predictive models and related equations have been developed over 50 years. Significant E* predictive models developed over the last 50 years include the Shell Oil, Shook and Kallas, Hirsh and Witczak Models *(3,4)*.

Research has been conducted in order to develop a structural design and analysis procedure for railroad trackbeds. Computer models were developed utilizing combinations of finite element analysis and layered systems. These include FEART *(5)*, ILLITRACK *(6)*, and GEOTRACK *(7)*. These can only be used for the analysis of all-granular ballast trackbeds and are not applicable to asphalt trackbeds and slab trackbeds. Therefore, it was necessary to develop a scientific rational analysis procedure to determine the stress distribution for both asphalt and all-granular trackbeds. KENTRACK (*8)* was developed for that purpose.

In the previous KENTRACK versions, asphalt dynamic modulus was predicted using the method developed by the Asphalt Institute *(9)*. Asphalt dynamic modulus is a function of temperature, viscosity at 135°F, loading frequency, mix volumetric properties and aggregate gradation. However, a shortcoming of the model was that viscosity is extremely sensitive to temperature. Viscosity increases when temperature decreases. Thus, using a constant value for viscosity at 135°F may lead to an underestimate asphalt dynamic moduli. Further, since Superpave has improved the performance of asphalt due to new asphalt mix design and Performance Grade (PG) System for asphalt binders, the old asphalt dynamic modulus predictive model existing in KENTRACK 3.0 (the latest version released) may not be sufficiently accurate to predict dynamic modulus of PG asphalt binders. Therefore, updating the predictive model was desirable to include asphalt dynamic modulus. This is appropriate for both the AC (Asphalt Cement) system based asphalt binders that were used in old trackbeds, and PG system based (Superpave) asphalt binders that are used in newly constructed trackbeds.

DEVELOPMENT OF KENTRACK

KENTRACK was developed by Huang, Rose, Lin and Deng of University of Kentucky in 1984. It is a layer elastic finite element based computer program that can be utilized for a performance-based structural design and analysis of railroad trackbeds *(8)*. It was written initially in FORTRAN on the Disk Operating System (DOS) and developed to analyze traditional all-granular layered trackbeds as well as asphalt layered trackbeds.

In 2006, KENTRACK 2.0.1 provided an update from the DOS system to a windows platform with a Graphic User Interface (GUI) which allowed users to easily change various parameters *(10)*. However, the program did not have default set of values; this limited the usage of KENTRACK.

In order to expand user friendly capabilities and developments, KENTRACK 3.0 changed from FORTRAN to C# and was developed entirely on .Net framework. Meanwhile, the program set up default sets of values, added a help manual to the program *(11)*, and expanded the program to analyze combination trackbeds. KENTRACK 4.0 is a derivative of KENTRACK 3.0. It retained the same format, but the structure is an improvement to the previous version.

KENTRACK 4.0 includes a myriad of updates and fixes. Most notably, Witczak E* predictive model is incorporated to estimate asphalt dynamic modulus. Provisions to use the PG asphalt binders are available. Also, users may now make adjustments in data entry without restarting the program, thereby retaining parameter values from previous runs. Further, users can also tweak parameters and reprocess the data. For ease of comparison, these results are presented in a new Windows form. Meanwhile, this latest version solves a critical problem from the previous versions where calculated results could not be saved in any post-Windows XP operating system. It addresses the problem by prompting users for a path to save results in a text format. Saved files include user input data for future reference. In addition to English unit system, this update includes International unit system as an alternative to input parameters. All defaults are adjusted accordingly, as well as associated unit labels. Calculated outputs provide results based on the unit system selected at configuration time.

KENTRACK THEORY

Trackbed Type

Three types of trackbeds, as depicted in Figure 1, are included in KENTRACK – All-Granular trackbed, Asphalt

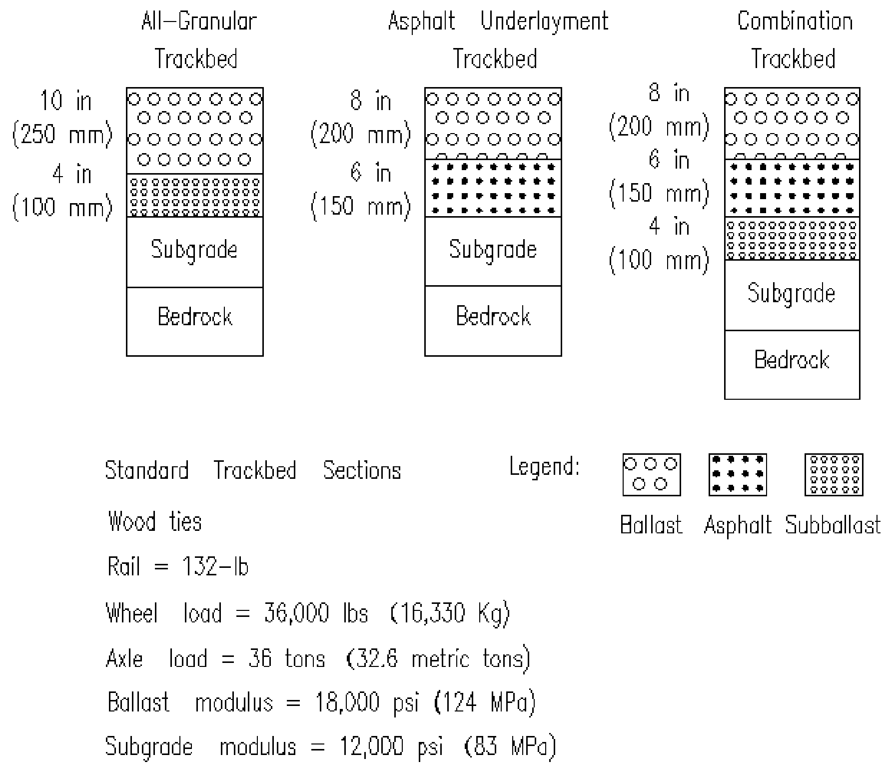


Figure 1 Standard Default Trackbed Sections

Underlayment trackbed, and Combination trackbed.

The all-granular trackbed is a traditional trackbed which is composed of ballast, subballast, subgrade and bedrock.

In the asphalt underlayment trackbed, an asphalt layer is substituted for the subballast layer in the all-granular trackbed. The asphalt underlayment trackbed has been widely accepted not only because it can reduce subgrade stress; it has shown to enhance waterproofing to control subgrade moisture contents, and provide a high level of confinement for ballast enhancing the shear strength of the ballast *(12, 13, 14)*.

The combination trackbed has both an asphalt layer and a granular subballast layer. It is composed of ballast, asphalt, subballast, subgrade and bedrock. Subballast is considered as an improved subgrade.

Trackbed Model

The model divides the track system into the following components from top to bottom: rails, springs (tie plates/pads), ties, and layered support system. Rails and ties, considered as beam elements, are orthogonal to each other. Spring connections between rails and ties are used to account for looseness between rail and tie. A linear spring constant is specified to indicate the rigidity of the connections. A wheel load is converted to a circular load applied on the top layer. Burmister multi-layer system theory is applied to calculate stresses and strains in the trackbed. Stresses and strains at subgrade or asphalt layer under multiple wheel loads are obtained by load superposition theory *(11)*.

Material Properties

Subballast and subgrade are considered as linear elastic materials. The bedrock is assumed incompressible with a Poisson’s ratio of 0.5.

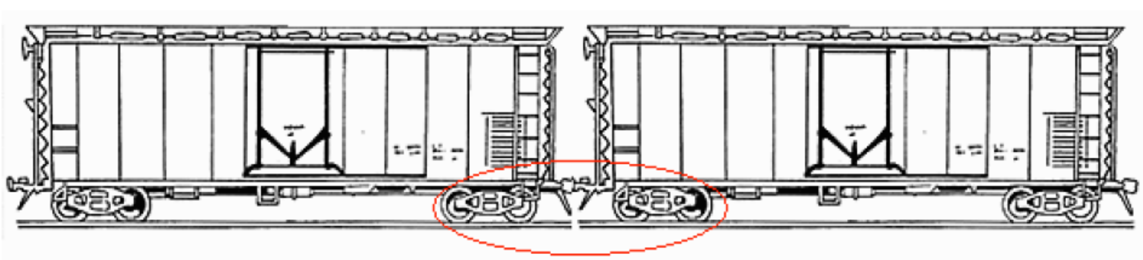
Ballast in a newly constructed trackbed behaves non-linearly while in an aged trackbed it behaves linearly due to being well compacted. The elastic modulus of nonlinear materials is determined as Eq.1. When

θ= bulk stress, or the sum of three principal stresses
including geostatic stresses, psi;

$$N_a = 0.0795 \varepsilon_t^{-3.291} E_a^{-0.853} \qquad \text{(Eq.4)}$$

where,

N_a = the allowable number of load repetitions in asphalt;



Wheel load	= 36,000 lb/wheel
For one car the total weight	= 36,000 lb/wheel x 8 = 286,000 lb/rep
	= 143 ton/rep
The number of repetitions assumed per year	= 200,000 rep/yr
The traffic per year	= 200,000 rep/yr x 143 ton/rep
	= 28,600,000 GT/yr
	= 28.6 MGT/yr

CASE STUDY

It is necessary to understand the effects of the various track components to develop a rational structural design method for railroad trackbeds. These factors include axle load, subgrade modulus, etc. A trackbed that has strong load bearing capacity of subgrade should be able to support heavy tonnage and wheel loads without excessive deformation.

KENTRACK is applicable for calculating stresses and strains in the trackbed and predicting associated design lives for a specific set of design parameters. In addition, selected parameters can be varied in magnitude and the relative influences evaluated. Based on the standard input parameters, all-granular, asphalt underlayment, and combination trackbeds can be analyzed by varying parameters such as axle load, subgrade modulus, layer thickness, etc.

Standard Input Parameters

Standard scenarios for typical designs use PG 64-22 asphalt binders. The default parameters are shown in Tables 2 and 3 and Figure 1. Table 2 presents the standard default design parameters for All-Granular, Asphalt Underlayment, and Combination trackbeds used in the United States. The asphalt modulus varies depending on seasons. The modulus in each season is calculated by Witczak E* predictive model. Table 2 shows the detailed information for the track model and properties of the asphalt binders.

Example outputs calculated by KENTRACK 4.0 using default parameters for the standard all-granular, asphalt underlayment and combination trackbeds are listed in Table 4. The advantage of trackbeds with asphalt can be noted. For example, the all-granular trackbed provides the highest calculated subgrade compressive stress and shortest predicted service life. The combination trackbed has the lowest predicted subgrade compressive stress and asphalt tensile strain and longest predicted service lives.

TABLE 2 Layer Properties for Default Case

Layers	All-Granular trackbed		Asphalt Underlayment Trackbed			Combination Trackbed		
	Thickness (in)	Modulus (psi)	Thickness (in)	Modulus (psi)		Thickness (in)	Modulus (psi)	
Ballast	10	18,000	8	18,000		8	18,000	
Asphalt	n/a		6	Spring	1.86	6	Spring	1.86
				Summer	0.91		Summer	0.91
				Fall	3.39		Fall	3.39E
				Winter	4.84		Winter	4.84
Subballast	4	31,000	N/A	N/A		4	31,000	
Subgrade	200	12,000	200	12,000		200	12,000	
Bedrock	N/A	1.00	N/A			N/A	1.00	

TABLE 3 Standard Input Parameters

Rail Type	RE 136
Type of Tie	Wood
Tie Spacing (in)	20
Temperature for Asphalt (° F)	Spring 50
	Summer 67
	Fall 33
	Winter 20
Wheel Load (lbs)	2 @ 36,000
% Passing #200 Sieve	4
Cumulative % Retained on #4 Sieve	56
Cumulative % Retained on 3/8 Sieve	40
Cumulative % Retained on 3/4 Sieve	16
% Air Voids	4
% Effective Binder Content by Volume	10
Loading Frequency (Hz)	1

Table 4 Example Outputs for All-Granular, Asphalt Underlayment, and Combination Trackbeds with Wood Ties Using Default Parameters

Trackbed Type	Calculated Subgrade Compressive Stress (psi)	Predicted Subgrade Service Life (yrs)	Calculated Asphalt Tensile Strain	Predicted Asphalt Service Life (yrs)
All-Granular Trackbed	13.52	6.0	n/a	n/a
Asphalt Underlayment Trackbed	10.84	21.4	1.48E-04	25.0
Combination Trackbed	9.82	28.5	1.29E04	34.0

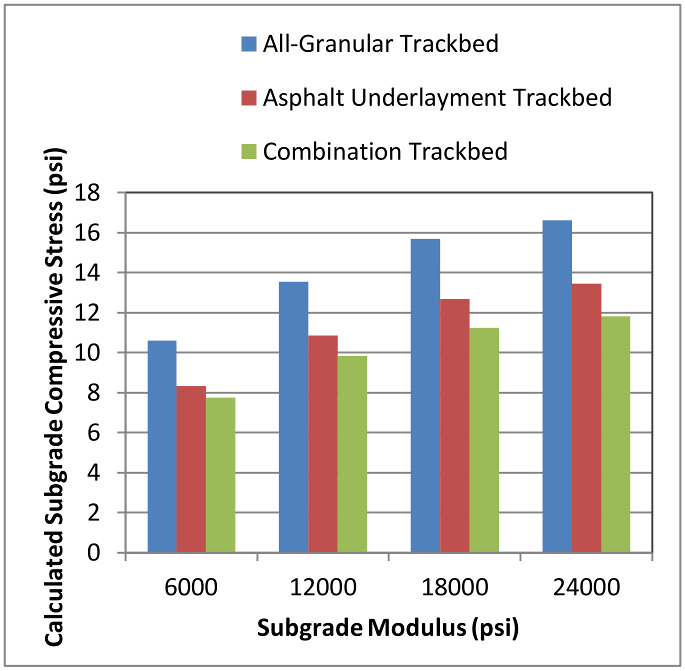
Varying Subgrade Modulus

Figure 3 shows the effect of varying subgrade modulus on all-granular, asphalt underlayment, and combination trackbeds. An interesting finding is that as subgrade modulus increases, subgrade compressive stresses also slightly increase, as shown in Figure 3(a), together with a significant increase in predicted subgrade service life, as shown in Figure 3(b). This is because the increase in subgrade modulus leads to higher bearing capacity. The increment of the bearing capacity of the subgrade is always greater than the increment of the subgrade compressive stress. Therefore, even if the pressure on the top of subgrade increases, the higher modulus subgrade will still perform satisfactorily for an extended period.

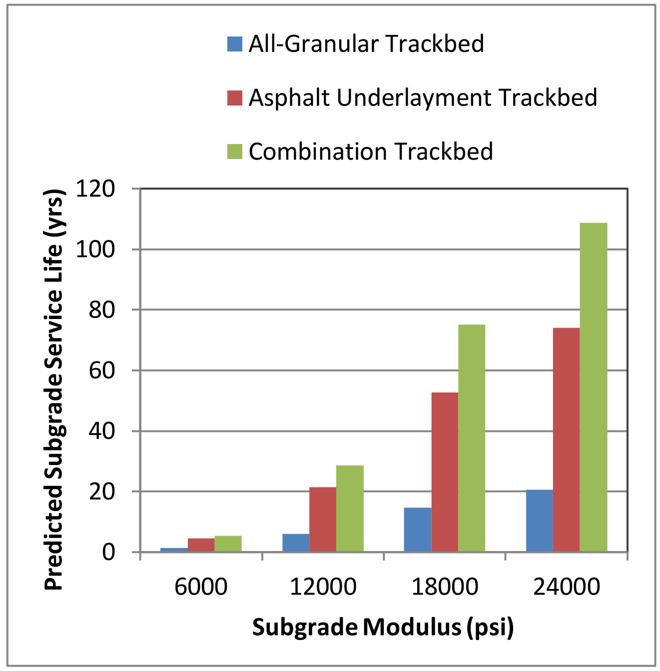
Figure 3(c) shows the effects of varying subgrade modulus on tensile strains at the bottom of the asphalt layer. The tensile strain decreases as subgrade modulus increases. For low subgrade moduli, the subgrade cannot adequately support the loadings on the asphalt layer. In this case, with the same load on the asphalt layer, deformation of the asphalt increases on the soft subgrade, producing higher tensile strains on the bottom of the asphalt layer due to excessive bending strains.

The predicted service lives of subgrade and asphalt with different subgrade moduli are presented in Figures 3(b) and 3(d). Note that subgrade modulus has a significant effect on the predicted service lives for all three types of trackbeds. For example, increasing the subgrade modulus from 6,000 psi to 24,000 psi (4 fold increase) under 36-ton axle load, will increase the predicted asphalt service life by a factor of 5 and the subgrade live by a factor of 15.

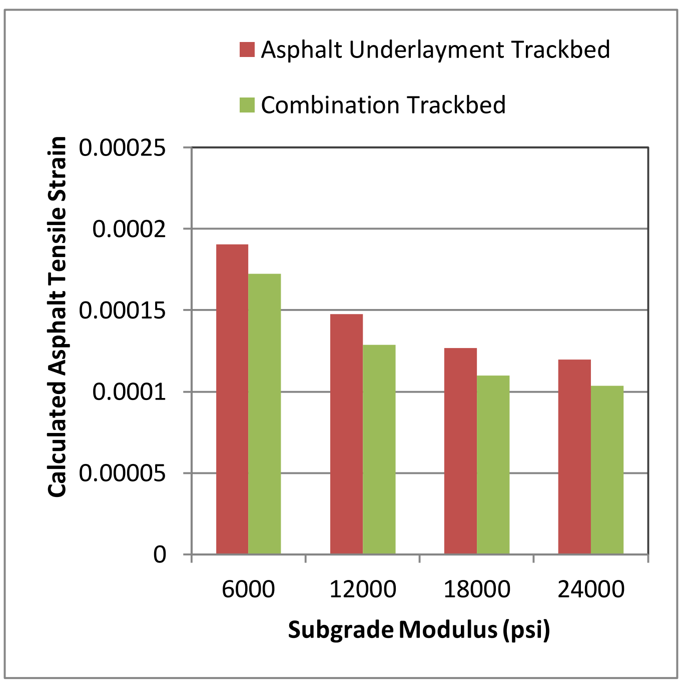
Also, comparing the effects on asphalt trackbeds with all-granular trackbeds, the predicted subgrade service life for an asphalt trackbed is typically increased by 100% over that of an all-granular trackbed. A combination trackbed has longer predicted service lives of the subgrade and asphalt layers than asphalt underlayment trackbed. Therefore, it is desirable to have a stiffer trackbed foundations with high moduli. A soft subgrade may have issues with track geometry maintenance due to settlement and excessive deflection.



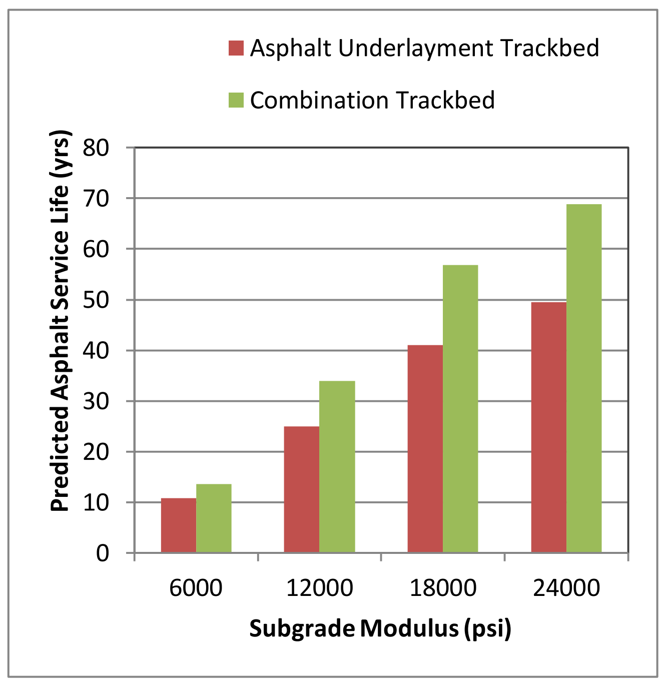
a. Subgrade Compressive Stress



b. Subgrade Service Life



c. Asphalt Tensile Strain



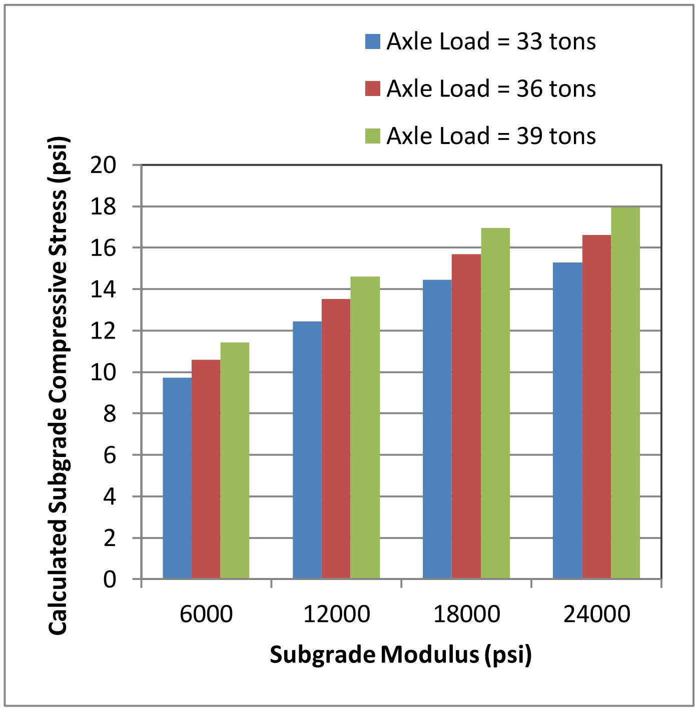
d. Asphalt Service Life

Figure 3 Effects of Varying Subgrade Modulus (Axle Load = 36 tons)

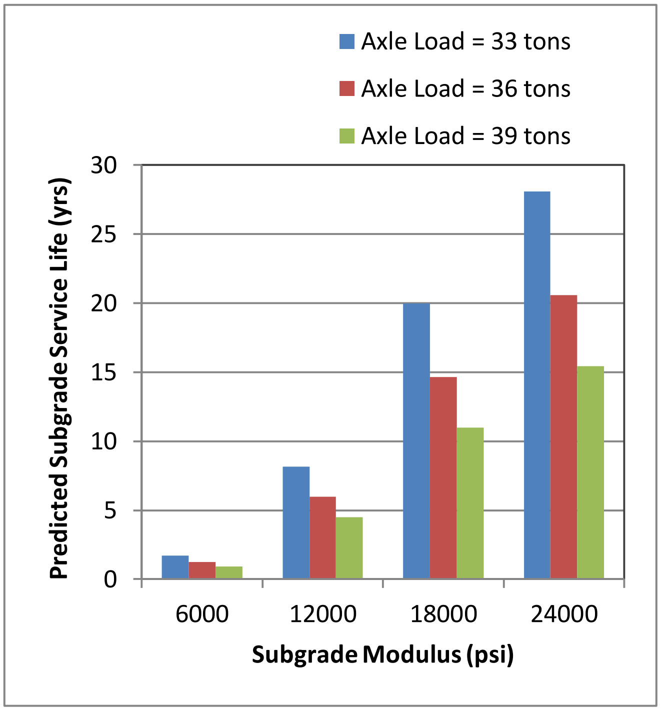
Varying Axle Load

Figures 4-6 show the effects of varying axle load (33 tons, 36 tons and 39 tons) on compressive stresses at the top of the subgrade layer, tensile strains at the bottom of the asphalt layer, and predicted subgrade and asphalt service lives for the three types of trackbeds. As expected, with increases in the magnitude of the axle load, subgrade compressive stresses and asphalt tensile strains increase, while predicted service lives of subgrade and asphalt layer decrease.

For an asphalt underlayment trackbed, if a heavy axle load (39 tons) is applied on a weak trackbed with a subgrade modulus of 6,000 psi, the predicted subgrade service life is reduced to 3 years, as shown in Figure 5 (b). Comparing that with a well-supported trackbed with a subgrade modulus of 24,000 psi and an applied 39-ton load, the subgrade compressive stress is reduced by one-half and the predicted subgrade service life is increased by 15 times. Also, the same trend is apparent relative to predicted asphalt service life. Heavy loads applied on a subgrade with high modulus can produce less asphalt tensile strain and longer predicted service life than heavy loads applied on a weak subgrade. Therefore, it is implied that if the trackbed is subjected to heavy wheel loads, it is desirable to strengthen the subgrade and maintain a high subgrade modulus.

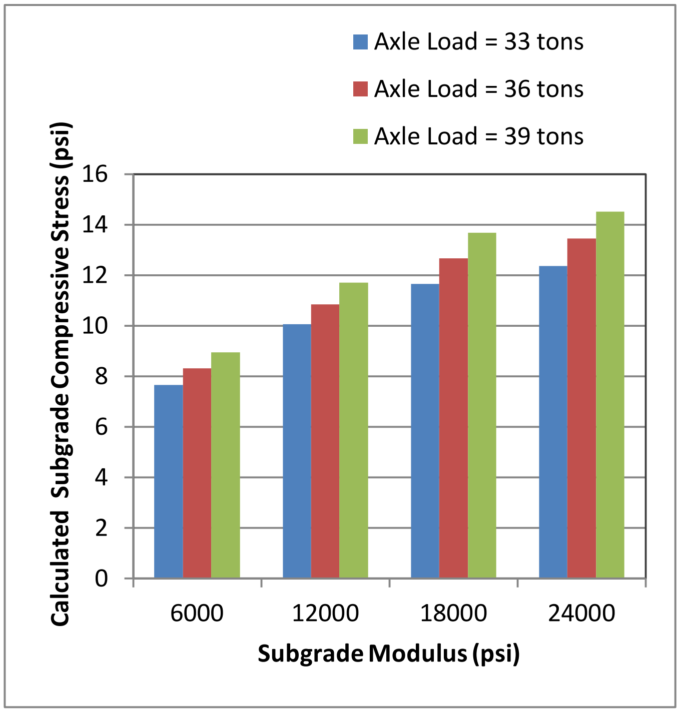


a. Subgrade Compressive Stress

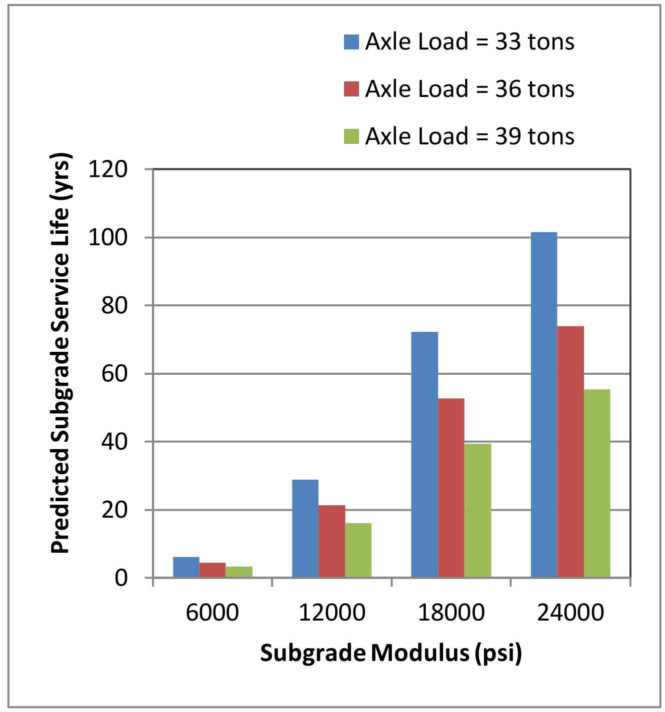


b. Subgrade Service Life

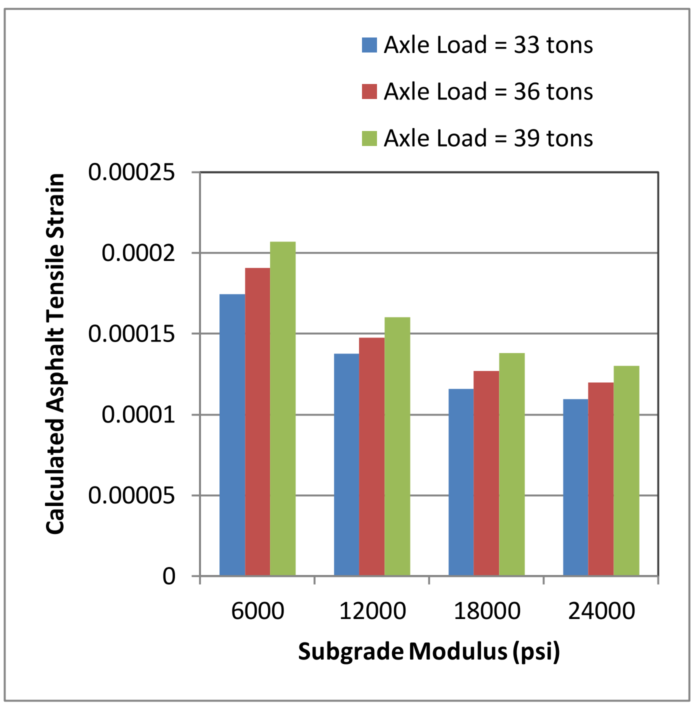
Figure 4 Effects of Varying Axle Load and Subgrade Modulus for All-Granular Trackbed



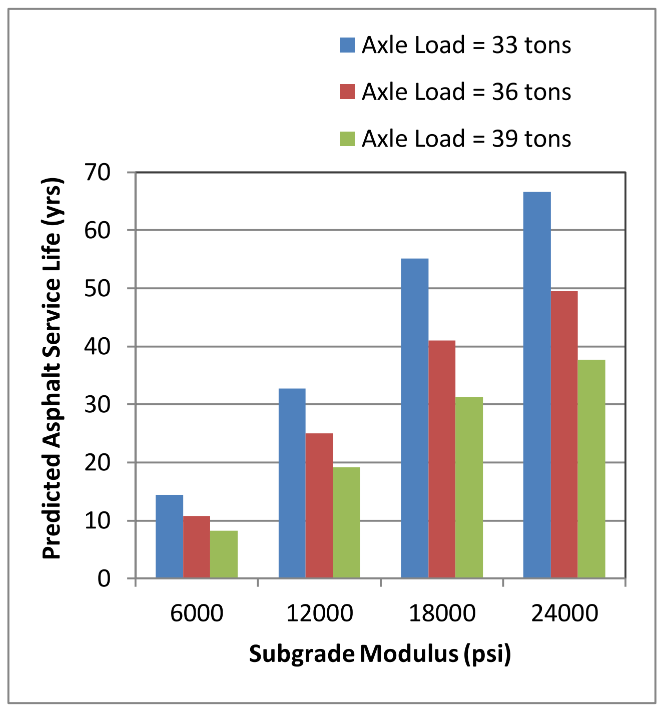
a. Subgrade Compressive Stress



b. Subgrade Service Life

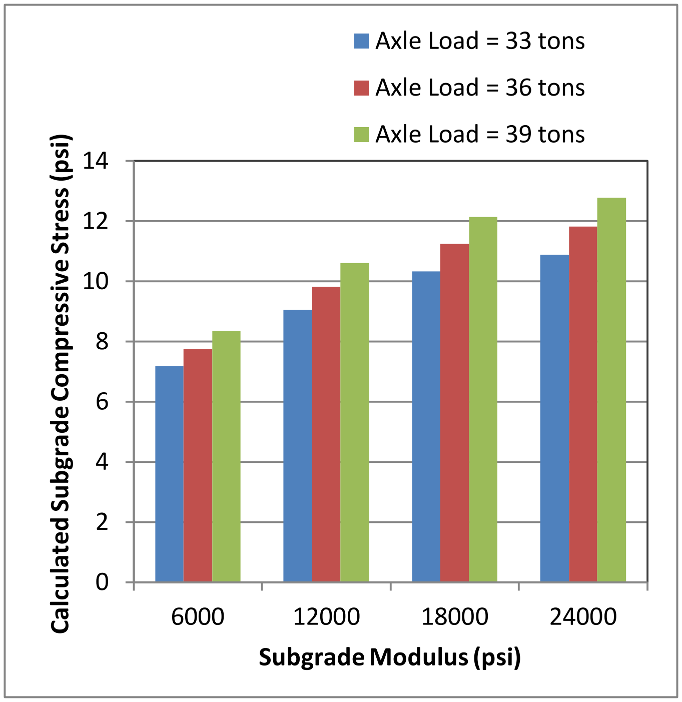


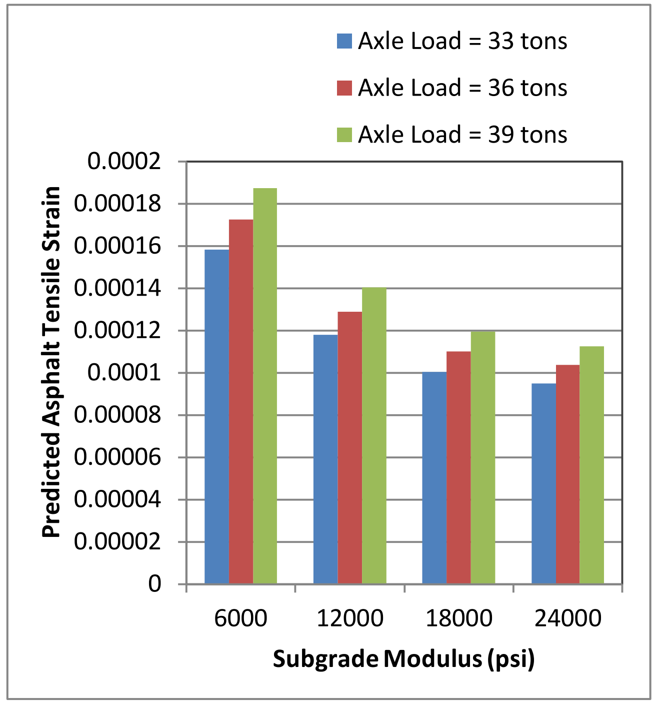
c. Asphalt Tensile Strain



d. Asphalt Service Life

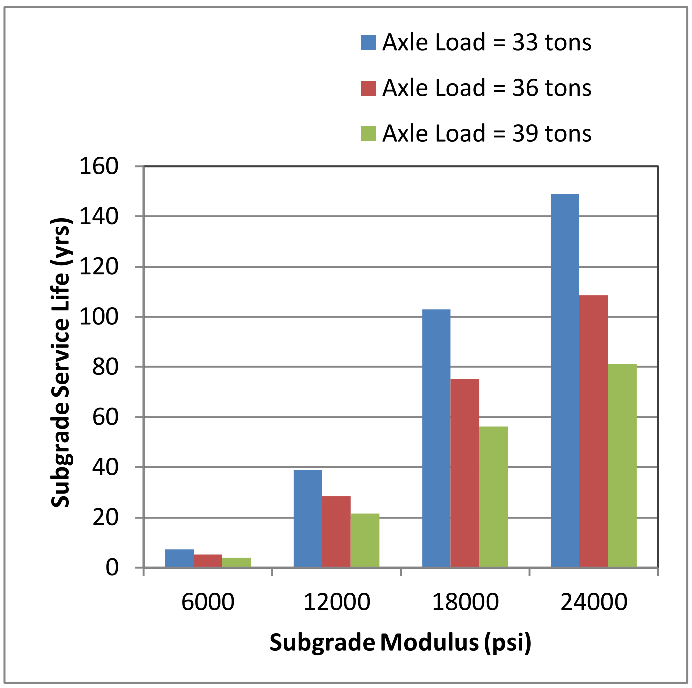
Figure 5 Effects of Varying Axle Load and Subgrade Modulus for Asphalt Underlayment Trackbed

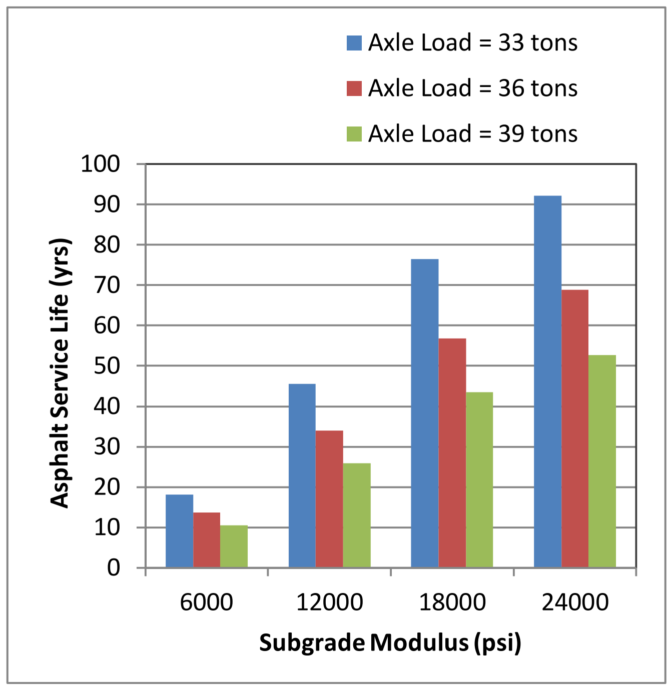




a. Subgrade Compressive Stress

b. Subgrade Service Life





c. Asphalt Tensile Strain

d. Asphalt Service Life

Figure 6 Effects of Varying Axle Load and Subgrade Modulus for Combination Trackbed

COMPARISON

In order to evaluate the improvement from the current KENTRACK 3.0 version to the revised KENTRACK 4.0 version, comparisons of calculation results using two versions are presented in Table 5. The results using the same type of asphalt binder, AC-20, in KENTRACK 4.0 were compared to KENTRACK 3.0. Also, analyses in KENTRACK 4.0 using AC-20, PG 64-22, and PG 76-22 were conducted to evaluate the effect of different types of asphalt binders. All of the calculations followed the standard default trackbed designs, i.e. typical values for material parameters and an axle load of 36 tons, as described in Tables 2 and 3 and Figure 1.

The core of the KENTRACK 4.0 Version is incorporating the asphalt E* predictive model, thus, for the all-granular trackbed, no asphalt layers are included, all the analyses for all-granular trackbed by KENTRACK 3.0 and 4.0 are identical, as indicated in Table 5.

Evaluating the same asphalt binder, AC-20, for the two versions reveals that subgrade compressive stresses differ insignificantly, but tensile strains are reduced by 10 percent and the predicted service lives of subgrade and asphalt layers are increased using KENTRACK 4.0. The dynamic modulus predictive model used in KENTRACK 3.0 tends to be conservative due to viscosity underestimation. By incorporating the Witczak E* predictive model into KENTRACK 4.0, the procedure for predicting asphalt dynamic modulus is more reasonable. The modulus increases using the new E* predictive model, thus asphalt becomes stiffer, leading to the decreases in asphalt tensile strains and increases in predicted service lives.

Considering the various asphalt binders in KENTRACK 4.0, it is apparent that the differences of trackbed performance using AC-20 and PG 64-20 are subtle, because the properties of two asphalt binders are essentially identical. When the grade (quality) of the asphalt binder increases from PG 64-22 to PG 76-22, the subgrade compressive stresses and asphalt tensile strains decrease, and the predicted service lives of asphalt and subgrade increase as expected. The grade of asphalt binder is selected based on the severity of the environment. The larger the number of the upper/lower grade, the more severe environment the asphalt binder can satisfactorily endure, thus the predicted asphalt tensile strains are decreased and the predicted service lives of the asphalt are increased.

Table 5 Comparisons of Calculation Results for Different Asphalt Binder Grades in Different KENTRACK Versions*

Trackbed Type	KENTRACK Version	Asphalt Binder Grade	Calculated Subgrade Compressive Stress (psi)	Predicted Subgrade Service Life (yrs)	Calculated Asphalt Tensile Strain	Predicted Asphalt Service Life (yrs)
All-Granular Trackbed	3.0	AC-20	13.52	6.0	n/a	n/a
	4.0	AC-20	13.52	6.0	n/a	n/a
		PG 64-22	13.52	6.0	n/a	n/a
		PG 76-22	13.52	6.0	n/a	n/a
Asphalt Underlayment Trackbed	3.0	AC-20	11.36	17.3	1.73E-04	20.4
	4.0	AC-20	10.86	21.3	1.50E-04	24.9
		PG 64-22	10.84	21.4	1.48E-04	25.0
		PG 76-22	10.52	23.1	1.34E-04	26.5
Combination Trackbed	3.0	AC-20	10.18	24.1	1.47E-04	30.1
	4.0	AC-20	9.86	28.2	1.33E-04	33.6
		PG 64-22	9.82	28.5	1.29E-04	34.0
		PG 76-22	9.58	30.3	1.18E-04	35.6

** Subgrade modulus = 12,000 psi*

CLOSURE

The KENTRACK program is a finite element based railroad trackbed design program. The Witczak E* predictive model for asphalt was applied in Version 4.0. Asphalt binders, classified in either AC system or PG system, can be used in KENTRACK 4.0. The program was expanded to include the SI international unit system. The program is applicable for determining relative effects of varying parameters and effects on design considerations.

For a given type of trackbed, the effect of subgrade stiffness (modulus) is the most significant factor influencing the design. For a given loading configuration, stiffer subgrades produce slightly higher subgrade stresses, but the predicted service lives for the stiffer subgrades are increased by several orders of magnitude. Asphalt tensile stresses are lower for the stiffer subgrades and the predicted service lives are increased proportionally. This indicates that selecting and maintaining a stiff high resilient modulus subgrade is extremely important.

Increasing axle loadings result in increased subgrade stresses and reduced predicted subgrade lives for all three types of trackbeds. Asphalt tensile strains are marginally increased and the predicted asphalt lives are marginally reduced with increased loadings. The detrimental effects of the higher axle loads can be offset by increasing the effective stiffness of the subgrade.

An asphalt trackbed results in lower subgrade stress than a similar thickness of all-granular trackbed. This is more pronounced when subballast is added to the asphalt trackbed forming a combination trackbed. For a given level of subgrade stiffness and axle loading, predicted subgrade design lives are higher for both the asphalt and combination trackbeds as compared to an all-granular design.

SOURCES

This paper was largely adapted from a recently completed MSCE Thesis entitled "KENTRACK 4.0: A Railway Trackbed Structural Design Program" authored by Shushu Liu in the Department of Civil Engineering at the University of Kentucky, December, 2013.

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