WANTED:
Transfer Functions — Experience Needed!

This article is the fifth in a series on the subject of Mechanistic Pavement Design. Previous articles have presented an overview of the subject, a discussion on modeling, aspects of materials characterization, and a discourse on traffic predictions. This article explores the empirical relationships between pavement responses to load and performance. In preparation for the future unveiling of the new 2002 pavement design guide being developed under a National Cooperative Highway Research Program project, it is necessary that the industry gain a working knowledge of the methods used to understand their possible impact on the industry.

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If there is a golden key in mechanistic pavement design, the transfer function is it, the point at which the stresses and strains and traffic predictions are turned into an estimated pavement life. A transfer function is an equation that is used to predict pavement life in terms of a number of repetitions (or loading cycles) to failure, designated as N_f. The most common transfer functions relate pavement responses to either structural rutting, as opposed to surface rutting, and fatigue cracking. Since these are the most devastating asphalt pavement distresses, in terms of the cost of rehabilitation, it makes sense that researchers have focused on them in developing prediction models.

It's All in the Equation

The transfer function is the biggest "empirical" part of mechanistic-empirical pavement design. Other "empirical" parts include the seasonal changes in material properties with time and the characterization of traffic. The transfer function assumes a relationship between the bending strain at the bottom of an asphalt layer and the occurrence of fatigue cracking in that layer, for instance:

$$N_f = k_1(\varepsilon_t)^{k_2}$$

Where: N_f = *Number of load cycles to fatigue failure,*
k_1, k_2 = *constants, and*
ε_t = *tensile strain due to bending at the bottom of the HMA.*

Table 1. Seasonal Changes in Material Properties and the Resulting Pavement Strains.

Season	HMA Modulus, psi	Subgrade Modulus, psi	Tensile Strain at HMA Bottom (ε_t)	Strain at Top of Subgrade (ε_v)
Summer	500,000	20,000	95	201
Fall	750,000	12,000	80	183
Winter	1,000,000	20,000	57	128
Spring	750,000	8,000	87	207

Table 2. Number of Cycles to Failure and Damage for Each Seasonal Condition.

Season	N_f for Fatigue	Fatigue Damage	N_f for Rutting	Rutting Damage
Summer	11,717,000	0.21	12,136,000	0.21
Fall	20,161,000	0.12	17,708,000	0
Winter	58,620,000	0	70,918,000	0
Spring	15,371,000	0.16	10,985,000	0.23
Total Damage		**0.49**		**0.44**

Similarly, the transfer function for the number of load cycles to failure in structural rutting could be related to the vertical strain at the top of the subgrade layer (ε_v) and the constants k_3 and k_4:

$N_f=k_3(\varepsilon_v)^{k_4}$

The importance of this relationship becomes clear when you consider that the adequacy of the thickness design hinges on how representative the equation is of actual pavement performance. If the equation is too conservative, the pavement will be too thick and resources will be wasted in building it, and if the equation is not conservative enough, the pavement may fail early necessitating premature rehabilitation.

Transfer functions, also known as performance equations, performance criteria, or failure criteria, inherently assume that the occurrence of distress in the pavement is directly attributable to a pavement response under load. The transfer function for fatigue is sometimes refined by including a term for the modulus of the material. A higher modulus is usually associated with a lower strain and an improved fatigue life.

It is important to note that because transfer functions are empirical, they are developed for a specific set of circumstances, such as a range of HMA thickness, a given climate, a certain range of material properties, a certain level of distress, etc. Such limitations must be known before applying transfer functions in any given situation.

Transfer functions are used to define the point at which failure occurs under a set of conditions such as temperature, moisture, etc. Therefore, it requires more than merely the calculation of N_f to arrive at an estimate of pavement life. In fact, for each separate condition of load and combination of material properties expected over the life of the pavement, the incremental damage must be calculated. The incremental damage is simply the number of a particular axle load expected during a given seasonal condition divided by the number of load cycles to failure (n_i/N_{fi}). The incremental damage is summed for all the loads and conditions to determine the expected damage over the life of the pavement (D):

$D=\Sigma\frac{n_i}{N_{fi}}$

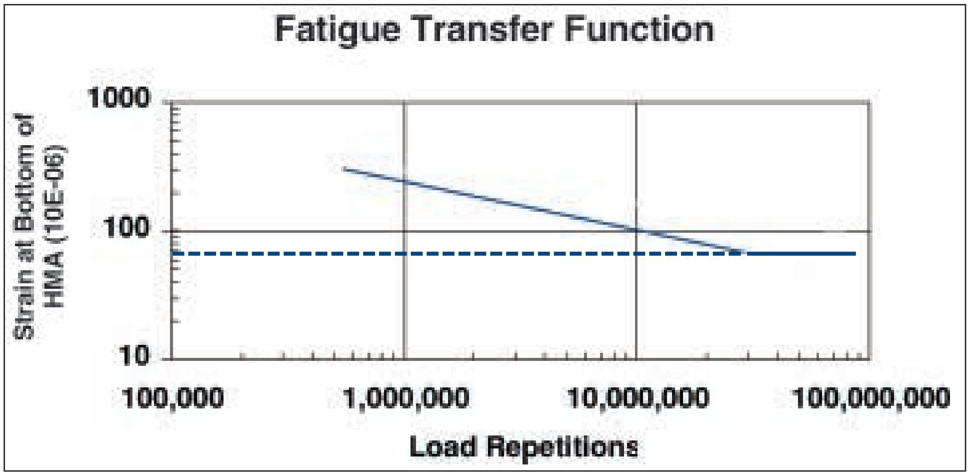
If D is less than a value of one, then the pavement can be expected to exceed its design life. If D is greater than one, then the pavement is expected to fail prematurely. If this value is much less than one, the pavement is probably designed too conservatively.

Two types of transfer functions are shown in Figures 1 and 2. The specific equations in these graphs were taken from results at the Minnesota Road Research Project (Timm, et al., 1999). In these graphs, the strain is on the vertical axis and the corresponding number of cycles to failure is on the horizontal axis. It should be noted that both axes have logarithmic scales. The breaks in the curves, where they flatten, illustrate the thinking that there are thresholds in strain below which damage does not occur to any sensible degree.

Example

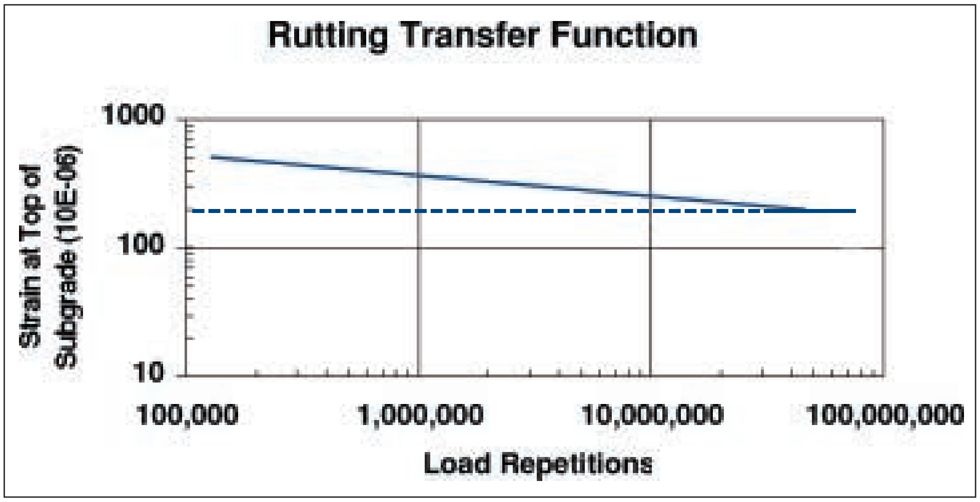
To show how the damage calculation works, let's assume that we have only one axle load (18,000-lb single axle), to simplify things, and it is applied to a 9-inch HMA pavement over a subgrade (Figure 3). The axle load is projected to make 10,000,000 repetitions over the pavement during its life. Now, let's say that we are concerned with four seasons of equal length, and the

Figure 1



Transfer Functions *continued*

Figure 2



material properties change accordingly as shown in Table 1. This means that we will have 2,500,000 repetitions in each season. To determine the N_f value for each season, we will need to know what the tensile strain at the bottom of the pavement is and what the strain at the top of the subgrade is in each case. These values were calculated using a layered elastic computer program, and are shown in Table 1.

Next, using the equations in Figures 1 and 2, the number of cycles to failure in fatigue and rutting are calculated for each season as shown in Table 2. Dividing the value for the amount of traffic expected in each season (n), which is 2,500,000, by the number of repetitions to failure (N_f) for each season, the amount of seasonal damage for fatigue and rutting can be determined. The total damage over the life of the pavement can then be computed by adding the seasonal damage values. As seen at the bottom of Table 2, the fatigue damage is expected to be 0.49 and the rutting damage is 0.44. Both of these are well under the value of 1.00, so the pavement can be expected to serve for its intended traffic without failing, according to this particular approach to mechanistic-empirical design.

How Perpetual Pavements Fit In

With all this talk of failure, do you feel like you're in a rut? Are you feeling fatigued? Running short on load repetitions? Then Perpetual Pavements may be the answer!

Unlike the above example, the idea in a Perpetual Pavement design is to ensure that the strains in the pavement are kept below some threshold value. These threshold values are termed “endurance limits,” and what they imply is that the pavement will not fail from damage deep in the pavement structure. Currently, a tensile strain value of 70 micro-strain is prescribed by researchers such as Carl Monismith

Figure 2

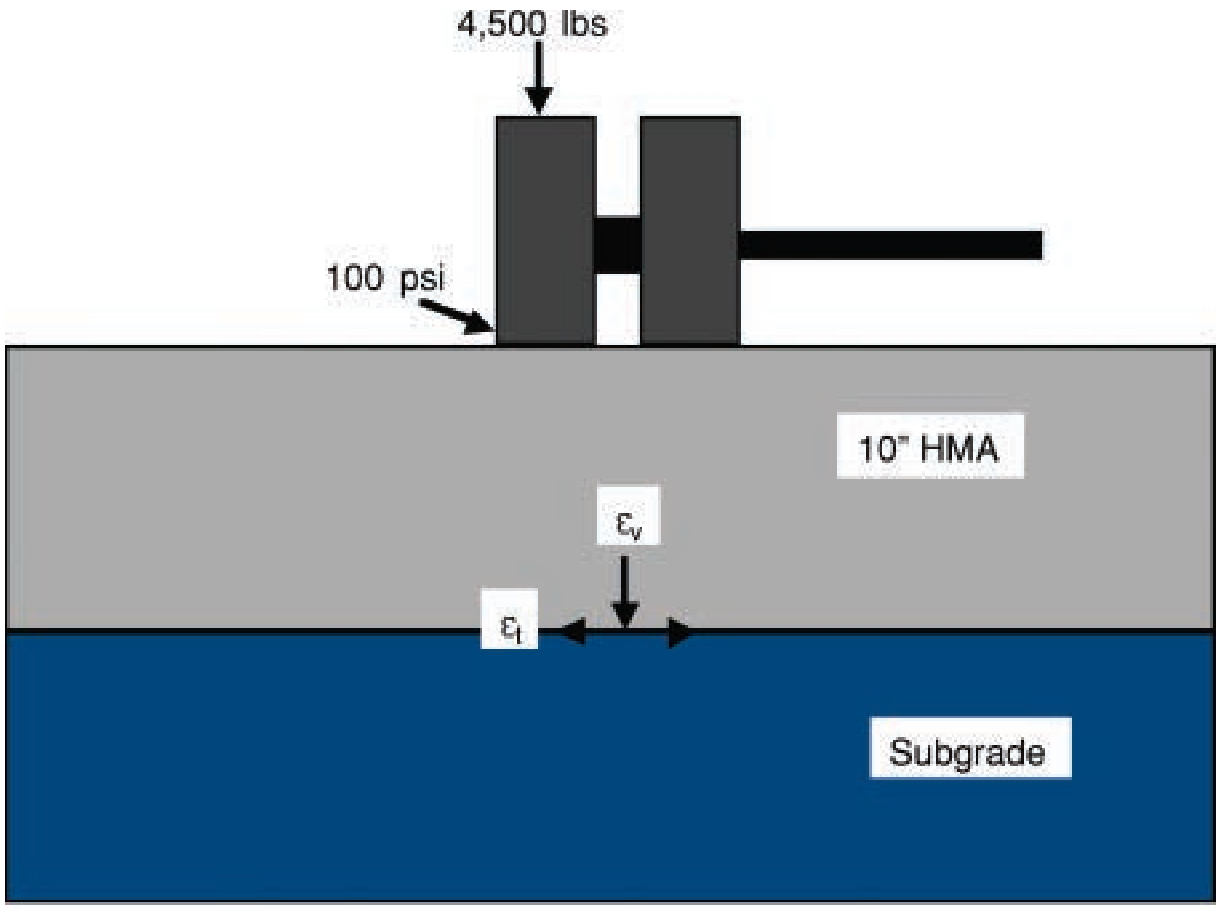


Figure 3. Example Pavement Section.

at the University of California Berkeley used for the bottom of the HMA to preclude bottom-up fatigue cracking, and a limiting vertical compressive strain of 200 microstrain at the top of the subgrade is used for deep structural rutting. The relationships in Figures 1 and 2 have been modified to reflect this change in thinking about long life asphalt pavements. If the analysis is rerun with an HMA thickness of 12 inches, the pavement is not expected to fail due to either bottom-up fatigue cracking or deep structural rutting.

The fatigue endurance limit is being substantiated by laboratory studies at the University of Illinois and the Asphalt Institute. Perpetual Pavement design software is currently under development at the National Center for Asphalt Technology at Auburn University. These efforts, along with those of a growing number of agencies, should provide further refinements in the Perpetual Pavement approach.

Summary

The transfer functions in mechanistic design define the performance of the pavement as a function of pavement responses to loading and environmental conditions. A plan is currently being formulated to calibrate mechanistic models under National Cooperative Highway Research Program (NCHRP) Project 9-30. This project should result in a plan which can be used by agencies to develop models appropriate to specific conditions and regions.

It is of paramount importance that these transfer functions accurately reflect the actual performance of pavements under the expected conditions, because extrapolating them beyond their tested bounds can result in over-designed or under-designed pavement sections. In the former case, the concepts embedded in the Perpetual Pavement should provide a thickness which matches needs of the traffic while efficiently allocating resources.

Reference

Timm, David H., Bjorn Birgisson, and David E. Newcomb, *Mechanistic-Empirical Flexible Pavement Thickness Design: The Minnesota Method*, Report No. MN/RC-P99-10, Minnesota Department of Transportation, St. Paul, January 1999. **HMAT**

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