Background
Research and development in the structural design of hot mix asphalt (HMA) pavements over the past fifty years has focused on a shift from empirical design equations to a more powerful and adaptive design scheme. Mechanistic-empirical (M-E) design has been developed to utilize the mechanical properties of the pavement structure along with information on traffic, climate, and observed performance, to more accurately model the pavement structure and predict its life.

The M-E design process integrates the environmental conditions and material properties of the HMA and underlying layers into the pavement structure. The structure is then modeled using a mechanical analysis program, and the pavement response is calculated given the axle load and tire configuration. The pavement response is then correlated to performance, or cycles to failure, through empirically derived transfer functions.

The most challenging piece of the design process is developing the transfer function, or performance equation, that is needed to relate the calculated pavement response (stress, strain) to performance (amount of cracking, rut depth). This research focuses on accurately modeling fatigue distress and developing fatigue transfer functions. The transfer function is the key to a successful M-E pavement design, and much effort has been devoted to developing useful transfer functions (1-3). Transfer functions are somewhat mix specific and dependant on the climate; therefore, local calibration or development is required to account for local materials and conditions.

Most fatigue transfer functions are developed using laboratory fatigue tests that are then calibrated or shifted to match observed field performance. This process accurately measures the response in the loaded specimen, but is often shifted based on limited field data. Further, the performance equations developed in the lab are dependant on the mode of loading, rest periods, and type of apparatus.

Objectives
Given the above concerns, eight test sections of the National Center for Asphalt Technology (NCAT) Test Track were devoted to a structural experiment to investigate the many integral parts of M-E design. Within the main objectives of the 2003 NCAT Structural Study, the goal of this research was to develop fatigue performance equations for use in M-E flexible pavement design. This included the following tasks and objectives:

- Develop a procedure for gathering, processing, and storing dynamic response data from embedded instrumentation in a useful and concise manner.
• Gather and store environmental data.
• Accurately monitor and quantify field performance.
• Characterize the material properties of the structure including seasonal trends.
• Develop a procedure for incorporating the above efforts into the development of a useful fatigue transfer function that will accurately predict fatigue life to be used in design and analysis procedures.
• Describe the effect of modified binders and thickness on fatigue performance.

Scope
The 2003 NCAT Structural Study consisted of eight test sections including three different HMA thicknesses and different asphalt mixtures and binders. Instrumentation, including strain gauges, earth pressure cells, and thermistors, was installed in the pavement structure to measure the pavement response and condition directly. The test sections were trafficked with a fleet of heavily loaded triple-trailers (gross vehicle weight = 152 kips) and one legally loaded box trailer, both shown in Figure 1. Similar wheel wander and traffic conditions were applied to the Test Track as open-access highways since real drivers were used.

One million vehicle repetitions (equivalent to approximately 10 million ESAL) were applied over a 2-year test cycle which began October 2003. Dynamic response data and field performance data were collected on a weekly basis, and environmental data were collected and stored continuously. The test sections were designed to develop fatigue distress during the testing cycle so that a relationship between damage and response could be developed.

The structural study allowed for a direct relationship between measured mechanical response and observed field performance. One of the shortcomings of the experiment was that the sections were heavily trafficked under an accelerated loading schedule so the pavement likely did not age as it might on the highway. Further, the experiment is somewhat specific to the climate of the NCAT Test Track and the materials used. Thus, the equations and relationships developed are specific, yet useful, to the applicable conditions. The transfer functions developed from the 2003 test cycle will aid Alabama Department of Transportation (ALDOT), and surrounding states, in adopting an accurate M-E design procedure.

General M-E Design Procedure
The major components that must be quantified for design are the expected traffic over the design life including volume, configuration, and load; specific seasonal material properties for the HMA and unbound pavement layers; a mechanical model to accurately calculate the pavement response; a transfer function with local calibration for the specific distress mode; and the distress criteria considered “failure”. Many M-E procedures utilize load spectra that describes the modeled traffic data by axle type, frequency of load magnitude, and tire pressure. One of the important parts of the NCAT Structural Study was the embedded instrumentation in the pavement structure to measure pavement response to various loading conditions.
Fatigue Failure Mechanism

Fatigue cracking is one of the major modes of distress in flexible pavements along with rutting and thermal cracking. It is a significant distress because fatigue cracking propagates through the entire HMA layer which then allows water infiltration to the unbound layers. This causes accelerated surface and structural deterioration, and pumping of the unbound materials and rutting. The textbook definition of fatigue theory states that fatigue cracking initiates at the bottom of the flexible layer due to repeated and excessive loading, and it is associated with the tensile strains at the bottom of the HMA layer (4). Shook et al. (2) explains that the M-E structural design process must limit the tensile strain in the HMA layer in order to control or design against fatigue cracking. Further, the Asphalt Institute MS-1 development manual (5) refers to ten different M-E design procedures that use the tensile strain at the bottom of the HMA layer as the critical design criteria in regards to fatigue cracking. Fatigue cracking is also referred to as alligator cracking due to its distinctive pattern; the cracking often looks like the back of an alligator (Figure 2).

The Strategic Highway Research Program (SHRP) Distress Identification Manual for the Long-Term Pavement Performance Project (6) gives a standard on how to measure and categorize fatigue cracking, but it does not recommend a specific failure criteria. It is important in fatigue transfer development to determine at what extent cracking is considered failure. It is also important when using established fatigue transfer functions to know what level of damage the functions were calibrated to in order to gauge expected performance.
The transfer functions developed from NCHRP 1-10B were calibrated using data from the American Association of Highway Officials (AASHO) Road Test, conducted in the late 1950’s, and considered two levels of cracking as failure. The first calibrated function considered cracking of 10 percent of the wheelpath as failure, and the second considered greater than 45 percent of the wheelpath. The AI transfer functions (an adaptation of NCHRP 1-10B) were also calibrated using AASHO Road Test data and considered an area greater than 45 percent of the wheelpath or an equivalent 20 percent of the total lane as failure (1-2).

The 2002 Design Guide used Long-Term Pavement Performance (LTPP) test sections to calibrate performance models, and 50 percent cracking of the total lane was considered failure. It is important to note that the calibration for the 2002 Design Guide included all severities of fatigue cracking equally without any weight to the higher severities (7).

Fatigue Performance
Asphalt fatigue research has shown that HMA fatigue life is related to the horizontal tensile strain. Further developments included the HMA mixture stiffness in the fatigue life relationship to account for varying temperature and loading frequency. The HMA stiffness is an important parameter in the fatigue performance, and it must be considered in conjunction with the expected in situ HMA thickness and failure mode.

General Model Development Procedure
For the most part, fatigue life relationships or performance equations are developed in the laboratory using some form of fatigue testing apparatus. Typically, HMA samples are cut into beams and subjected to repeated flexural loading either in a controlled strain or controlled stress mode. The most common apparatus is simple flexure with third-point loading. Much research and debate has been devoted to determining whether controlled stress or controlled strain is the most appropriate. Most do agree that it depends on the conditions (mainly thickness) of the in situ pavement. Controlled stress more closely simulates the mode of loading for thicker HMA layers, while controlled strain is more appropriate for thin (less than 2 in.) asphalt pavements (7).

One of the main discrepancies between the two tests is the effect of mixture stiffness on
the fatigue life. For testing under controlled stress, stiffer mixes will have a higher fatigue life, while controlled strain will show that stiffer mixes have lower fatigue life. Because of the discrepancies, the mode of loading should be carefully considered and reported with beam fatigue results. Further, the observation drives the recommendation that controlled stress should be used for thicker, more robust pavements, where high stiffness is beneficial. It should also be noted that controlled stress loading will result in a more conservative fatigue life than controlled strain loading for identical mixes (8).

Either way, laboratory-developed performance equations do not accurately predict the fatigue life of asphalt pavements in the field (9). Due to the differences in the laboratory and the field, fatigue life relationships must be calibrated or shifted to observed field performance. This is the empirical part of M-E design. The calibration process, or developed shift functions, is one of the more problematic elements of M-E design. SHRP Project A-003A (10) warned that “established correlations between laboratory data and field response are weak, and the project further reported that the range of shift factors proposed by a variety of researchers ranged from slightly over 1 to over 400.

Field calibration is necessary in defining useful transfer functions, but as mentioned above, the process can be very difficult and often inexact. As an improvement to earlier efforts, the 2002 Design Guide calibrated the fatigue transfer function using data from the LTPP database from different pavement sections all over the U.S. (7). A total of 82 new LTPP sections were included in the analysis, and the 2002 Design Guide Software was run at a full matrix of assumed shift factors. The set that most closely matched the performance data was selected to calibrate the model. Another shift factor was then developed to mathematically shift the thinner asphalt sections (less than 4 in. thick).

**NCAT Structural Study**

The Structural Study, sponsored by ALDOT, Indiana DOT (InDOT) and FHWA, consisted of eight test sections with three different HMA thicknesses and two different binder types (PG 67-22 and an SBS modified PG 76-22). All eight sections had an underlying 6 in. crushed granite granular base over fill material which was constructed over the existing embankment. Figure 3 shows the cross sections of the structural study sections, N1-N8. Notice that the sections were a full factorial experiment with N7 serving as a duplicate to N6 with an SMA surface, and N8 is a duplicate of N7 with an asphalt-rich bottom layer.

The sections were designed structurally using the 1993 AASHTO Design Guide (11), and the mix design was performed according to ALDOT specifications. The sections were designed to show a variety of distresses over the life of the experiment, and it was intended that at least the 5 and 7 in. sections would exhibit fairly extensive structural distress in order to correlate performance to field-measured pavement responses. The thin sections (N1 and N2) were designed for about 1.1 million ESAL, the medium sections (N5-N8) for 2.9 million ESAL and the thick sections (N3 and N4) for 7.8 million ESAL.
Instrumentation

The test sections of the NCAT Structural Study were instrumented to measure the in situ conditions (i.e., temperature, moisture) of the pavement as well as the dynamic pavement response under traffic (i.e., stress, strain). To measure the condition of the pavement structure, thermistors and time domain reflectometry (TDR) probes were installed to measure the pavement temperature profile and the subgrade moisture content, respectively. The thermistor bundle measured the pavement temperature at three depths: near the surface, 2, 4 and 10 in. deep. The TDR probes were installed 3 in. deep into the fill layer and measured gravimetric and volumetric moisture contents of the soil. As suggested by the manufacturer, specific calibration functions were developed for the TDRs using the subgrade soil.

The temperature and TDR probes were sampled using a Campbell Scientific CR10X datalogger located at each test section in the roadside box. The datalogger sampled the gauges every minute and recorded the hourly average and maximum and minimum readings. Hourly readings were transmitted through a radio modem to the data storage computer throughout the two-year testing cycle to continuously monitor the pavement environmental condition.

Dynamic Pavement Response

The dynamic pavement response gauges required a much higher sampling frequency than did the in situ condition gauges; therefore, a separate data acquisition scheme was developed. A portable DATAQ highspeed dynamic data acquisition system (Figure 4) was used to connect to the roadside box through the slow/highspeed interface and collect dynamic data. The signal conditioning cards within the acquisition system are gauge
specific and supplied the needed excitation voltage to the gauge and performed needed amplification to the signal. The data were then streamed, real time, to the acquisition software on a laptop computer. Because the system was portable, only one data acquisition system was needed to sample all eight test sections.

**Figure 4: Dynamic Data Acquisition System (19)**

**FWD Testing**

On a monthly basis, ALDOT performed FWD testing on all the test sections at the Test Track. FWD testing was conducted at three predetermined locations per test section in both the inside and outside wheelpaths, and each testing location was thumped twice. At the beginning of the testing cycle, three random locations were determined for each of the eight test sections. FWD testing, transverse profiles and density measurements were taken at these three locations for the extent of the two-year test cycle. The deflection data were then used in a backcalculation procedure to determine the stiffnesses of the pavement layers. This was critical to the Structural Study because the monthly deflection data provided in situ material properties for the pavement layers at a variety of seasons and temperatures.

**Strain Trace Investigation**

Figure 5 shows the longitudinal strain trace for the steer, tandem, and five trailing single axles. Notice for the longitudinal gauges there is a compression wave (compression is negative) as the tire approaches the gauge prior to the tensile peak. Also notice that there is a full strain reversal between every axle, even within the tandem axle configuration.
Lateral Distribution of Traffic Loads

The lateral distribution of the axle loads, or wheel wander, was measured and investigated at the NCAT Test Track for two main reasons: to determine if the wheel wander was comparable to other open-access highways and to better understand the dynamic strain data. The lateral position of the outside tire was measured using axle-sensing strips installed in a pattern such that the lateral offset of the tire could be calculated. The distribution was observed to be normal and have a comparable standard deviation, although at the low end, to other open-access highways. The distribution of loads greatly affects field performance, so verifying that the Test Track traffic was similar to open-access roadways allowed for the direct application of results from the Test Track to open facilities.

Strain Response Characterization

General Trends

As with the HMA stiffness data, seasonal trends and damage were observed with the strain data over time. The induced strain is a function of the stiffness of the mix, which is in turn a function of temperature. As a result, the strain response is strongly correlated with the temperature of the HMA layer. Unlike the stiffness data, the strain data is also a function of the thickness of the HMA layer. The load bearing capacity of the HMA increases with thickness; thus, the induced strains at the bottom of the layer are reduced with thicker HMA sections. The thickness effect is the central concept behind M-E design: determine the needed layer thicknesses to control the critical responses, such as horizontal strain at the bottom of the HMA layer, given the traffic and seasonal data. The
thickness effect is especially evident for the two 5 in. sections, N1 and N2, which have much higher strain levels than the other sections. Also, strain values for N1 and N2 were especially high after the first spring, when the sections began to show fatigue cracking. Strain data collected after visible cracking were not included in the fatigue models for the same reasons as the stiffness data. One, the readings are especially variable and erratic, and two, it is common practice that fatigue models or transfer functions assume an intact pavement structure.

For this research, both longitudinal and transverse strain was measured. As shown in Figure 6, the longitudinal strain is greater for approximately 80 percent of the data. Rather than averaging the two strain values, it was decided to use the most severe response in the analysis. As a result, only the longitudinal strain was considered in the development of the fatigue transfer functions.

![Figure 6: Transverse vs. Longitudinal Strain](image)

**Fatigue Performance Characterization**

*Observed Fatigue Distress*

Sections N1, N2 and N8 showed excessive fatigue failure, and the distress of all three sections progressed in a similar fashion. First, small transverse cracks appeared in the wheelpath. Then the cracks progressed to the end of the wheelpath and often arched in the direction of traffic. Later, the individual transverse cracks became interconnected into the classical alligator pattern fatigue cracking. Pumping of the fines from the unbound aggregate base through the cracks was also observed in the individual transverse cracks.
as well as the alligator cracked areas. The pumping proved that the cracks propagated all the way through the HMA layer. Cores were also taken in the cracking area to verify that the cracks were in fact bottom-up cracking.

Once the first cracks appeared, after approximately 2.6 million ESAL, the progression of failure was fairly rapid, especially once pumping began. The granular base was easily pumped as water infiltrated through the cracks and into the structure, and the base support was lost. This led to further deterioration and rutting.

As explained above, once the first cracks appeared, the fatigue distress progressed rapidly. After a month the individual cracks became interconnected, and within four months, both wheelpaths had full fatigue cracking with pumping.

**FATIGUE MODEL DEVELOPMENT**

At the time of this report, three test sections had reached the fatigue cracking failure criteria. Recall that cracking covering 20 percent of the total lane area was considered failure. Sections N1 and N2 reached failure in the summer of 2004, and section N8 reached failure in the summer of 2005. It should be noted that all three sections survived past their initial design life of 1.1 million ESAL for N1/N2 and 2.9 million ESAL for section N8.

Final fatigue transfer functions were developed using the data from the three failed test sections, and preliminary transfer functions were developed for the other sections based on the traffic and performance data, to date. Revisions will need to be conducted on these models after the sections deteriorate further.

**Methodology**

The hourly temperature data collected continuously throughout the two-year test cycle was the critical link between the traffic data and the HMA stiffness and strain data. For each hourly temperature, the in situ HMA stiffness and strain magnitude were calculated for each test section and vehicle type. With the applied loads, stiffness and strain values, the cycles to failure, $N_{fi}$, was calculated assuming a fatigue transfer function. From this, the incremental damage, $D_i$, was computed each hour using Miner’s hypothesis:

$$D_i = \frac{n_i}{N_{fi}}$$

where,

- $D_i$ = incremental damage for hour $i$
- $n_i$ = number of cycles for hour $i$
- $N_{fi}$ = number of cycles until failure under conditions of hour $i$

It is important to note that the effort of this research was to calibrate models previously developed using full-scale field response, material and performance data. The exact models followed and the calibration results are discussed below.
Fatigue Model
The current state of practice for fatigue transfer functions, including AI MS-1, Shell Oil Design Guide and the 2002 Design Guide, is in the form of:

\[ N_f = k_1 \left( \frac{1}{\varepsilon_t} \right)^{k_2} \left( \frac{1}{E} \right)^{k_3} \] (2)

where,
- \( N_f \) = Number of load cycles until fatigue failure
- \( \varepsilon_t \) = Applied horizontal tensile strain
- \( E \) = HMA mixture stiffness
- \( k_1, k_2, k_3 \) = Regression constants

In the development of the 2002 Design Guide, all three regression constants were tweaked to better match LTPP performance data (12). In a similar manner to the 2002 Design Guide, all three regression constants were calibrated to fit the data collected at the NCAT Test Track for the models presented here. Also following the 2002 Design Guide and accepted practice, the AI MS-1 equation was used as the base model and guide to the calibrated functions. The equation was simplified to:

\[ N_f = 0.0795 \ast \left( \frac{1}{\varepsilon_t} \right)^{3.29} \left( \frac{1}{E} \right)^{0.854} \] (3)

The above equation served as the base model that was then calibrated using the field data to create the final transfer functions.

The two 5 in. sections, N1 and N2, reached their terminal life within the span of the 2003 research cycle as well as one of the 7 in. sections, N8. Section N8 included the rich bottom layer consisting of 2 in. of HMA with an additional 0.5 percent asphalt content. It was found that this section behaved differently in fatigue than did sections N1 and N2. Consequently, one fatigue function could not be developed that explained the performance of both the 5 in. sections and section N8. Upon further investigation, it was determined that section N8 performed differently than the other 7 in. and 9 in. test sections, also. Therefore, three transfer functions are presented here. One function for the 5 in. test sections was developed, termed the thin model. This model is separate because the data set is complete. Further, it is widely accepted (8,10,12) that thin asphalt pavements are subjected to a different loading mechanism than are thicker pavements. Although sources do not agree with what is considered “thin”, the range is typically less than 2 in. to 5 in. The second transfer function developed was for section N8 and termed the rich bottom model. And finally, the third model presented, termed the thick model, was a first attempt at a calibrated model for the remaining test sections, N3-N7, based on data up to August 2, 2005. The three models are presented below followed by discussion of the calibration and section performance.

Thin Model
The response, material property and performance data from both sections N1 and N2
were considered to develop the fatigue transfer function given below in units of strain (in./in.) and psi:

\[
N_f = 0.4875 * \left( \frac{1}{\varepsilon_i} \right)^{3.0312} \left( \frac{1}{E} \right)^{0.6529}
\]  
(4)

Both test sections failed in a very similar manner and within two months of each other. Section N1 failed prior to section N2, which was expected because the strain values of N1 were statistically higher, and N2 was slightly stiffer than N1. Both of these effects are quantified in the above equation.

Rich Bottom Model
Recall, that a study conducted by Harvey et al. (9) investigated the rich bottom concept. They not only predicted an increase in stiffness of the rich layer, which may be reason for the lower strain values found here, they also reported an increase in fatigue life by a factor of 2.18. From this structural study, the rich bottom concept did not hold true. As a result, further investigation into the rich bottom concept should be pursued at NCAT and elsewhere, both in the laboratory and the field, before it is widely accepted as a viable pavement design option.

Thick Model
In order to calibrate a fatigue model using the data from sections N3-N7, a current damage ratio was assumed. In the calibration of the thin and rich bottom models, the damage was set equal to 1 at the time of failure. In calibration of the thick model, hourly temperature and traffic data until August 2, 2005 were used, and a current damage ratio was assigned to each test section. Section N6 had the highest amounts of cracking and was the only section with areas of interconnected cracks; therefore, it was assigned a damage of 0.7. Section N5 had a small amount of cracking in both wheelpaths, and there were some transverse cracks in section N7; consequently, section N5 and N7 were assigned damage ratio values of 0.4 and 0.5, respectively. The two 9 in. sections (N3 and N4) had no observed cracking prior to August 2, 2005 and were assigned a value of 0.2.

Using the data from the five sections and the damage assumptions, the general model developed is given below:

\[
N_f = 0.4801 * \left( \frac{1}{\varepsilon_i} \right)^{3.143} \left( \frac{1}{E} \right)^{0.4834}
\]  
(5)

The increase in damage and cracking during the warmer months may contradict some conventional understanding of cracking damage in flexible pavements. For example, temperature-induced surface cracking is a major distress in many areas of the U.S., which occurs during the winter months due to daily temperature fluctuations. This is not the same mechanism that occurs in bottom-up fatigue cracking. The thick fatigue transfer function is based on assumptions regarding the current state of distress of the test
sections. Further improvements should be made as the test sections are further trafficked and show further distress and subsequent failure. The plans for the 2006 Test Track testing cycle include leaving these sections in-place for further traffic and observation. Although the function may be updated, it is predicted that one function can be developed to describe the performance of all five test sections, including both thicknesses (7 and 9 in.).

**Concluding Remarks on Model Development**

The fatigue transfer functions presented here were developed to aid ALDOT and other states in adopting M-E design procedures. The models are applicable to public highway analysis and design for similar conditions of the NCAT Test Track. The test sections were designed using ALDOT materials and specifications; therefore, they are directly applicable to the State of Alabama and other states with similar mixture designs and climatic conditions. Further, two separate models were presented for thick and thin HMA pavements, avoiding any necessary shift factors. The rich bottom model was developed using only one test section, so further investigation is warranted, especially considering the section did not perform as expected.

**REFERENCES**


