

PERPETUAL PAVEMENT DESIGN IN CHINA

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ABSTRACT

Flexible perpetual pavements have proven to be a viable option in the U.S. for agencies needing high-performance, low-maintenance and long-life highway structures. Projects in California, Oregon and Texas are examples of high-traffic interstate perpetual pavements in a variety of environmental conditions. More recently, three perpetual pavement test sections, along with two control sections, were built during the summer of 2005 as part of a perpetual pavement experiment on a newly constructed expressway in Shandong Province, China. A unique feature of the experiment is the heavy traffic loads typical of China (e.g., average single axle weights exceeding 20 kip (9 tonnes)) but not commonly found in the U.S. Central to the experiment are a weigh-in-motion facility and embedded pavement response gauges to document the types and weights of vehicles and corresponding pavement responses. This paper documents the design process used to develop the perpetual pavement sections using the design software, PerRoad. Material property and load spectra data provided by the Shandong Highway Bureau and Shandong Research Institute were utilized in PerRoad to develop three perpetual pavement cross sections. A conservative fatigue threshold of $70 \mu\epsilon$ resulted in the first test section, a 20 in. (500 mm) full-depth asphalt pavement. The second test section, a 15 in (380 mm) full-depth pavement, used a less conservative threshold of $125 \mu\epsilon$. The third test section duplicated the second, but with a higher performance graded binder in the bottom 3 in. (75 mm) lift. The two remaining sections are representative of typical expressway design in China: thin HMA layers on a pozzolanic-treated base. One section has 13 in (330 mm) of HMA on 16 in. (400 mm) of lime-flyash treated base, and the other section, more typical of pavements in Shandong Province, has 6 in. (150 mm) of HMA on 21.5 in. (560 mm) of lime-flyash treated base. The expressway opened to traffic in December 2005 and experiments with control vehicles and live traffic are currently underway. The testing protocol is described and representative response data collected in December 2005 are also presented.

INTRODUCTION

The rapid economic growth in China over the past years has facilitated an emphasis on developing the national infrastructure. With this growth, road building has been an important component as a reliable inter-provincial transportation network is vital to continued growth of China. From 2005 to 2010, China's Ministry of Communication plans to increase the expressway network by 108,000 miles (173,809 km) to complete a 1.4 million mile (2.3 million km) road system, connecting most major cities (*1*).

While construction of these roadways is a major undertaking, there is an added challenge of designing the pavements to withstand the vehicle weights prevalent in China. Compared to the U.S., traffic loads on Chinese expressways are significantly heavier. Figure 1 illustrates the gross vehicle weights obtained from a weigh-in-motion (WIM) facility on the Bin-Bo expressway, the highway in Shandong Province that is the focus of this paper. As shown in the figure, the average weights of the larger trucks (4+ axles) exceed 70,000 lb (32 tonnes). Of particular interest is the S1.2.2 vehicles (a standard 5-axle semi-trailer), comparable to Class 9 vehicles in the U.S., as they represent 33% of the heavy traffic volume and have an average gross vehicle weight of 122,000 lb (55 tonnes). This is nearly double the gross vehicle legal limit in the U.S. Clearly, the traffic demands in China are extreme, and the pavement structures must be carefully designed to meet the demand.

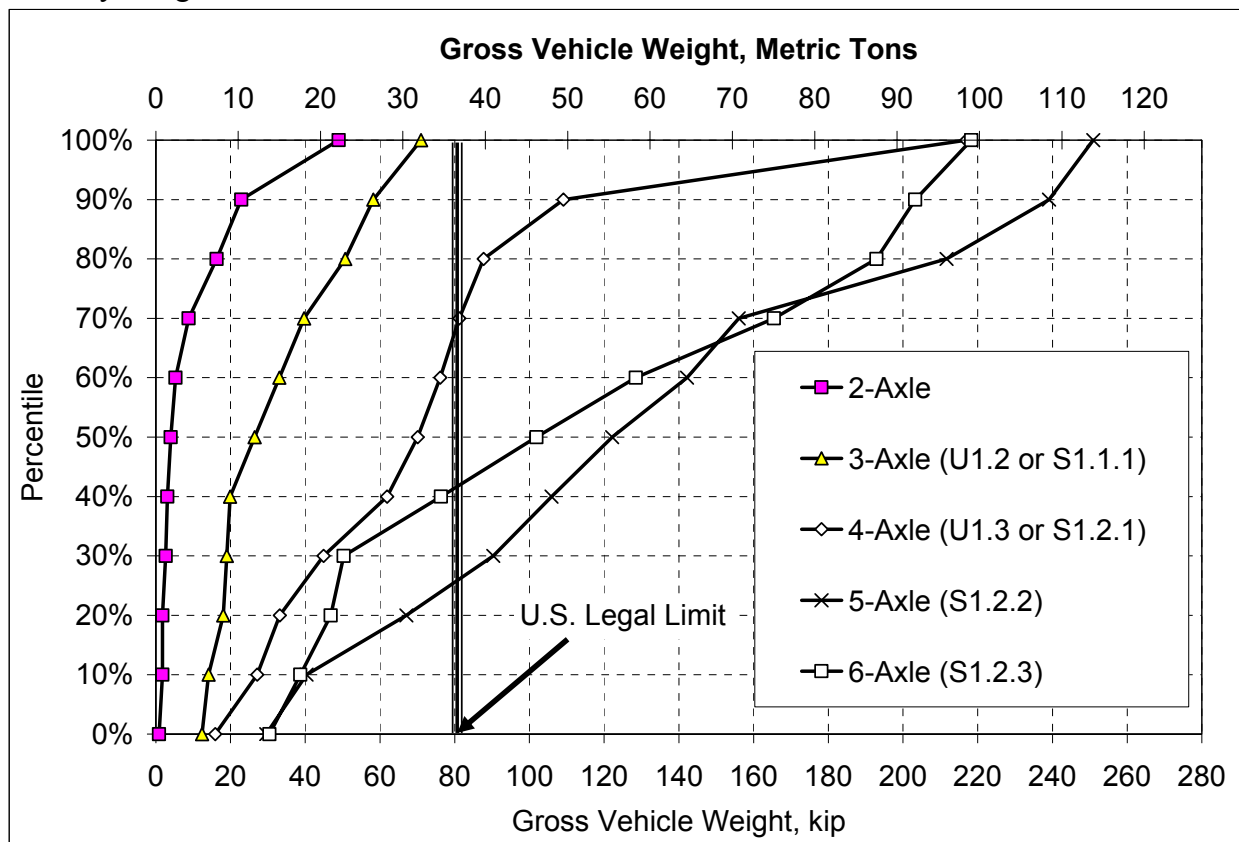


FIGURE 1 Gross Vehicle Weight from Bin-Bo Expressway.

The typical design on an expressway in Shandong Province consists of 6 to 8 inches (150 to 200 mm) of hot-mix asphalt (HMA) over 14 to 24 inches (355 to 610 mm) of cement-bound stabilized granular material on top of 8 to 12 inches (200 to 305 mm) of stabilized soil on the

untreated embankment. A unique feature of most Chinese expressways is that they are built on 10 ft (3 m) high embankments serving as the pavement foundation. The resulting pavement structure has guardrails on each side and down the median, and access is controlled through toll-gates. While this design has been used throughout China for expressway routes, there have been cases of early pavement deterioration. To help investigate, a team of Chinese and U.S. engineers met in Shandong Province in November, 2004 to collaborate with the Shandong Highway Bureau and the Shandong Transportation Research Institute (2).

Given the need for high-performing, long-lasting pavement structures, the perpetual pavement concept was presented as the best approach. Central to perpetual pavement design is calculating the mechanistic response of the pavement structure under expected traffic and designing the layers to maintain stresses and deformation below prescribed limits. This design approach prevents deep structural problems, such as fatigue cracking and base or subgrade rutting (2). To investigate this approach, and its impact on long-term performance, it was jointly decided to construct a number of perpetual pavement test sections on the Bin-Bo expressway currently under construction in Shandong Province.

OBJECTIVES

The overall objective of the research project in Shandong is to develop a set of recommendations regarding perpetual pavement design under extreme traffic conditions. Because the project is still in its early stages, having only been subjected to 7 months of traffic, the objectives of this paper are necessarily limited to the following:

1. Documentation of the structural design process.
2. Presentation of pavement sections.
3. Presentation of testing and data collection plan.

PROJECT LOCATION AND GENERAL SITE CONDITIONS

Shandong Province is located in the east central part of China. Beijing is about 250 miles (400 km) north of Jinan, the capitol of Shandong Province. For the most part, Shandong is low-lying with an elevation less than 330 ft (100 meters) above sea level, except for a highland area in the center of the province and another on the peninsula into the sea. A motorway on the west side of Binzhou (Figure 2) is about 5 km west of the city. When completed, this new motorway will connect Shanghai and Tianjin, a major port east of Beijing. Part of this expressway in the city of Binzhou was dedicated to the research project documented here.

The pavement test sections are located a few kilometers north of the Huang-He River. The terrain is flat, and the soil is composed of river-deposited silt. The silt has a plasticity index of approximately 8 to 10 and CBR of 8. The water table in the area is very high. Ditches along local roads in the area show a water table about 5 to 6.5 ft (1.5 to 2.0 m) below the ground surface. The high water table in combination with the silty soil causes consolidation to occur under the weight of the 10 to 20 ft (3 to 6 m) embankment fill. Consolidation is typically 4 to 8 in. (10 to 20 cm). Current density specifications for the subgrade call for 95% of standard Proctor density in the top 31 in. (80 cm), 93% in the 20 in. (50 cm) below that and 90% in the lower layers.

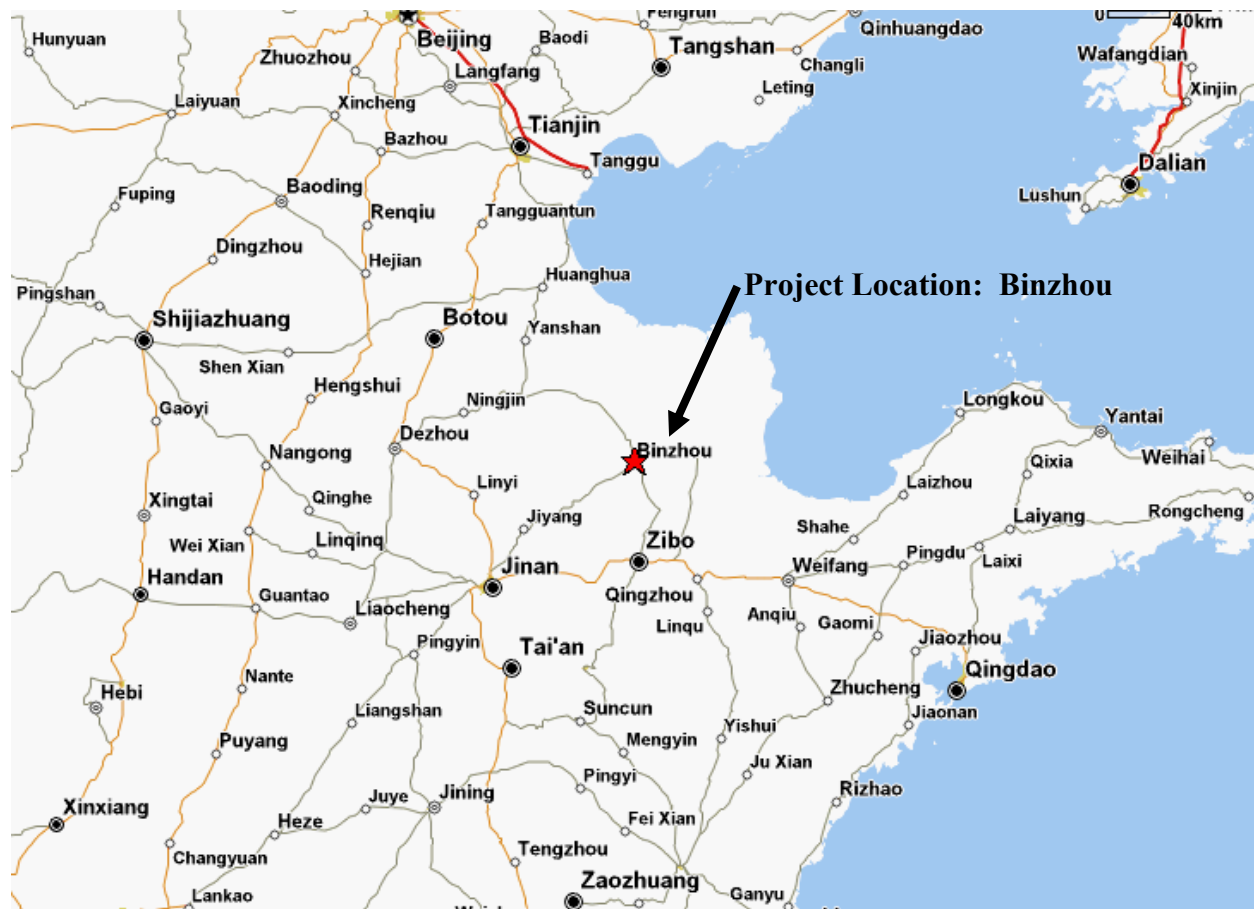


FIGURE 2 Project Location (3).

CONTROL SECTIONS

Two structural cross-sections commonly used in China on expressways were proposed as control sections in the experiment and are shown in Figure 3. Both sections have a stone-matrix (SMA) surface with performance grade (PG) 76-22 binder. The underlying hot mix asphalt (HMA) layers were designed according to Superpave standards with 19 and 25 mm nominal maximum aggregate sizes (NMAS) in layers two and three, respectively. Both sections utilize a lime-kiln dust-fly ash cement-stabilized granular base layer (CSGL), but Section 4 contains a large stone mixture (25 mm NMAS) between the HMA and CSGL. Based upon investigation and discussion, it was hypothesized that the primary cause of early pavement deterioration in sections of this type was overstressing of the CSGL causing cracks to propagate through the HMA layers to the surface. Once cracks were present, water infiltration further accelerated the pavement deterioration. It follows, then, that Section 4 should perform better than Section 5 since the CSGL is 7 in. (175 mm) deeper in the structure. Both control sections also utilized stabilized soil layers as shown in Figure 3.

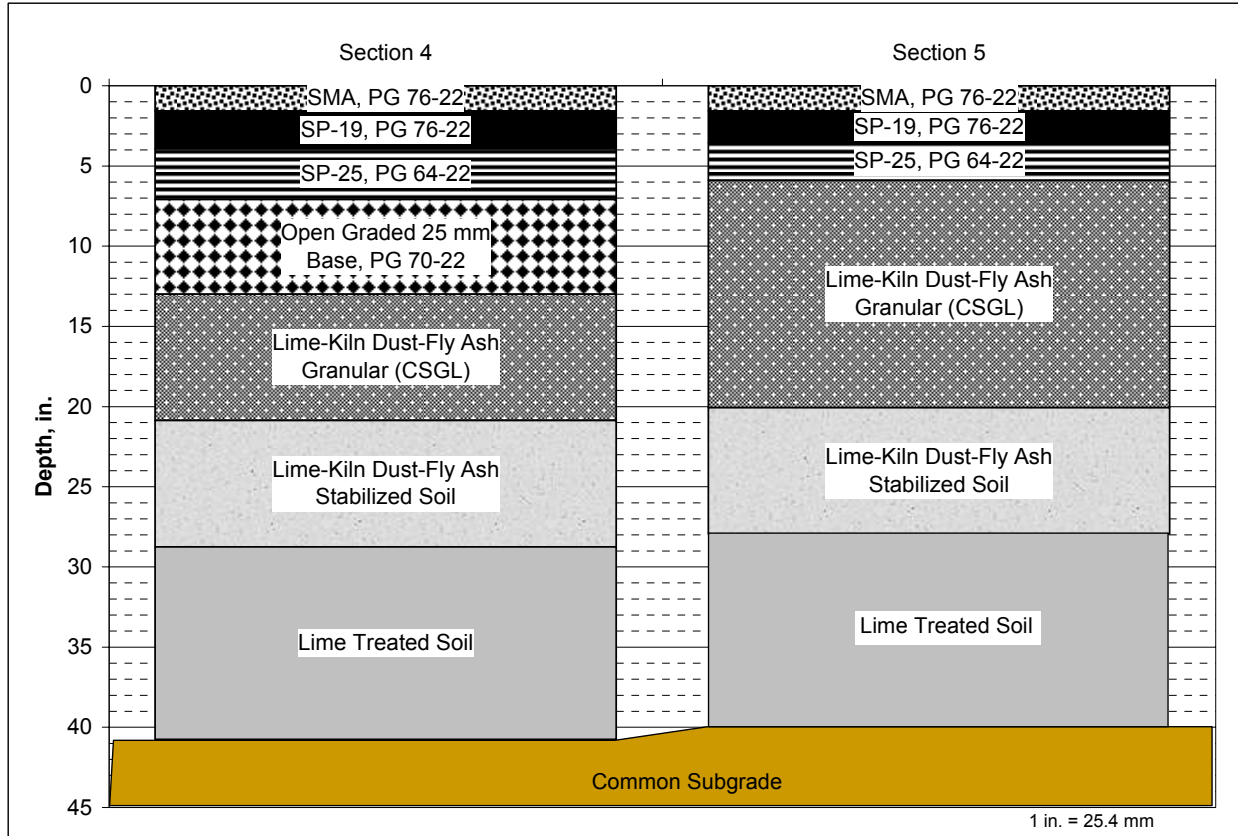


FIGURE 3 Control Sections.

DESIGN OF EXPERIMENTAL SECTIONS

As discussed previously, there was consensus among team members to develop perpetual pavement designs to meet the high traffic demands of this project. Additionally, it was decided to eliminate the CSGL and the lime-flyash treated soil as structural components since it was believed to be the root cause of early pavement deterioration experienced in China. The following sub-sections detail how the designs were developed using the design software, PerRoad.

Traffic Characterization

Regardless of the pavement design approach, traffic must be accurately represented to achieve a successful design. Since this was a new expressway, site-specific traffic data were not available. WIM data from another site, thought to be representative of the Bin-Bo expressway, were used to develop the necessary load spectra information required for design. Now that the project has been opened to traffic, data from the on-site WIM have been collected and comparisons between the design and measured load spectra are presented in Figure 4. It must be noted that the measured axle weight data represent only a 24-hour period and more data will be collected to fully judge the accuracy of the design load distribution. Preliminarily, however, the data indicate relatively good agreement between measured and design load spectra. The steer and single axle load spectra used in design appear to be conservative at the 90th percentile. However, the design load spectra for the tandem and tridem axles appear unconservative at the

90th percentile and more data must be evaluated to ascertain the effect of these heavier axle loadings.

As discussed above regarding gross-vehicle weight, it is certainly important to comprehend the magnitude of loadings applied to the pavement. For example, the average single axle load is approximately 19,000 lb (8 tonnes), which is nearly the legal limit for U.S. federal routes. Even more significant is the average tandem axle load of 43,000 lb (19.5 tonnes) which is 9,000 lb (4 tonnes) heavier than the U.S. legal limit. Translated into damage using the generalized 4th power rule (4), the average tandem axle in China would cause 2.7 times more damage than the maximum legal tandem axle in the U.S. Looking at it another way, consider the measured 90th percentile tandem axle weight (100,000 lb (45 tonnes)) shown in Figure 4c. This value compares to a 90th percentile in the U.S. of approximately 36,000 lb (16 tonnes). Again computing damage using the 4th power rule, this translates into approximately 60 times more damage for the same percentile axle weight. The Chinese load spectra is one of the unique aspects of this project, pushing traditional western pavement design and allowing for performance evaluation under extreme loading.

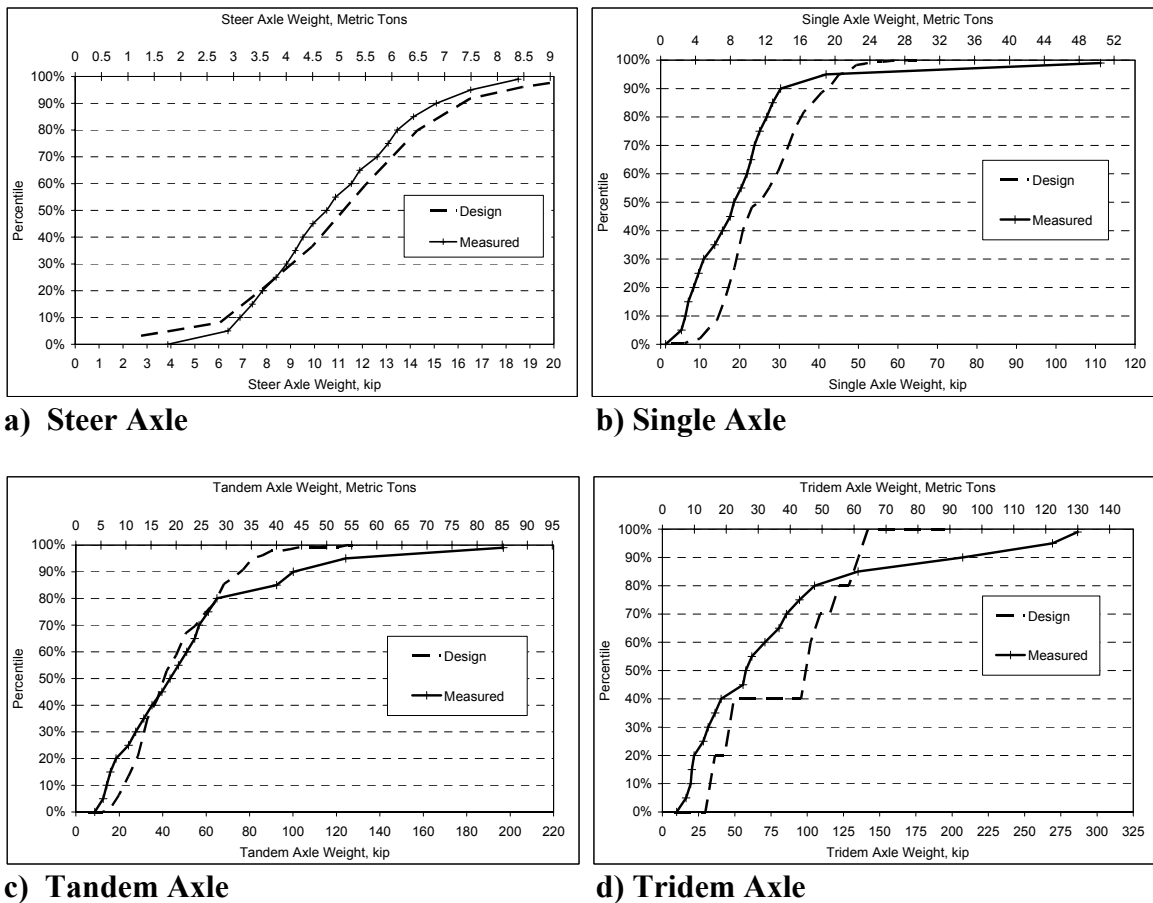


FIGURE 4 Axle Load Spectra.

Materials Characterization

Material characterization began by examining a limited amount of falling weight deflectometer (FWD) data provided by the Shandong Research Institute. Testing was conducted directly on the prepared embankment at loads ranging from 2,000 to 8,000 lb (8.8 to 35.6 kN).

The standard AASHTO (5) approach using the outermost deflection to estimate soil stiffness (M_r) was employed, and the results are summarized in Figure 5. The data followed an approximately normal distribution with an average of 19,179 psi (132 MPa). Since the data were from one testing date and no information regarding seasonal changes was available, a number of potential designs were developed using various soil stiffnesses. Specifically, designs were developed for 7,000, and 15,000 psi (48 MPa and 103 MPa) soil.

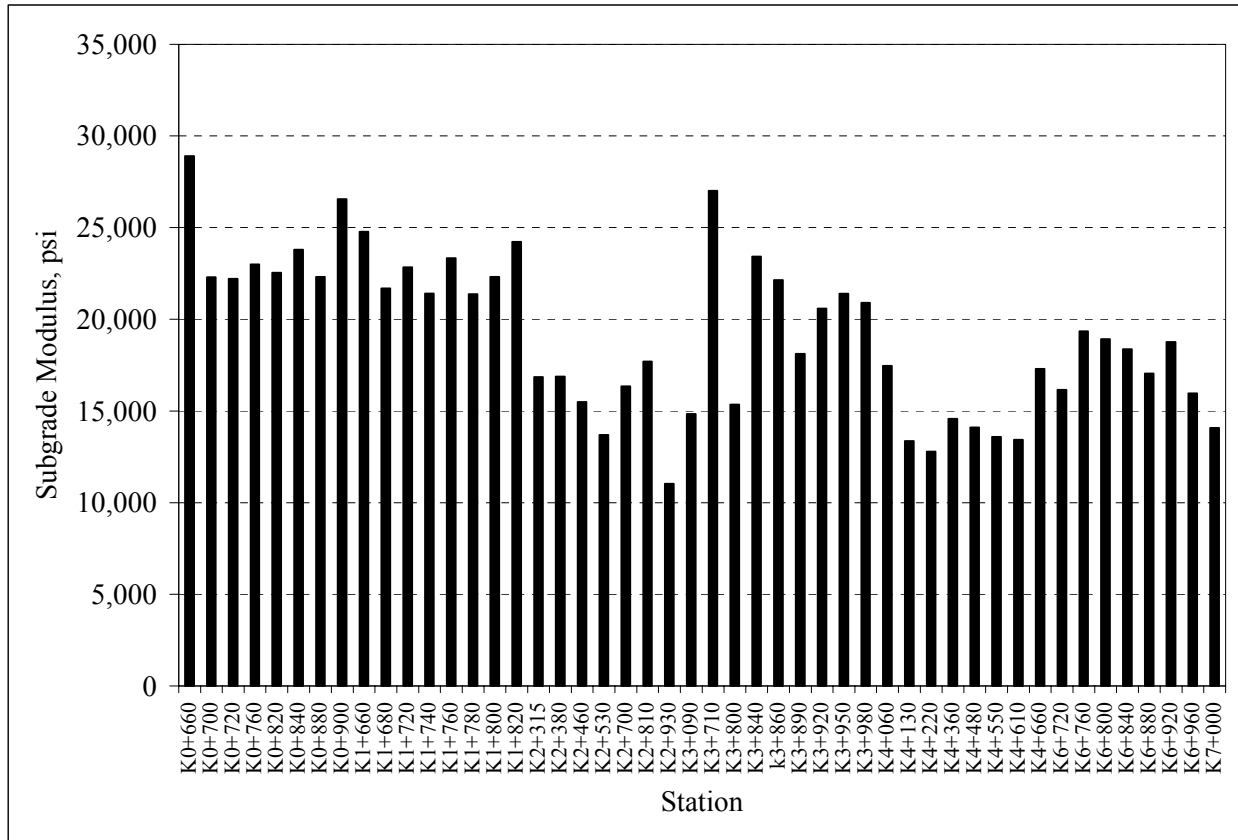


FIGURE 5 Embankment Soil Stiffness.

Though a comprehensive laboratory testing plan is currently underway for the asphalt materials used in the project, very little information regarding the stiffness was available during the design phase. Therefore, assumptions were necessary. Through team discussions and review of relevant data sets such as those from the National Center for Asphalt Technology (NCAT) Test Track, the design stiffness for HMA was set at 700,000 psi (4,826 MPa). This value is reasonable given similar materials tested at the NCAT Test Track (6) that yielded average stiffnesses, from backcalculation, of approximately 850,000 psi (5,860 MPa) at 68F (20C). Given that the average annual temperature at the project location is 58.6F (14.8C) (7), the design value can be considered conservative yet reasonable.

Performance Criteria

Central to the concept of perpetual pavement design is establishing the threshold pavement responses below which structural damage will not occur. Traditionally, fatigue cracking has been controlled through limiting the horizontal strain at the bottom of the HMA layer while structural rutting has been controlled by limiting the vertical strain at the top of the

subgrade (8). Previous laboratory and field research have conservatively estimated fatigue and rutting thresholds of 70 $\mu\epsilon$ and 200 $\mu\epsilon$, respectively (9, 10). Other studies have suggested that the fatigue threshold may be significantly higher; horizontal tensile microstrain exceeding 150 $\mu\epsilon$ (11). Based upon these previous efforts, it was decided to develop designs at two theoretical fatigue strain thresholds, 70 $\mu\epsilon$ and 125 $\mu\epsilon$, and use the results of the experiment to help guide future perpetual pavement designs. The vertical strain criterion was set at 200 $\mu\epsilon$; consistent with a previous field study (10).

PerRoad Design and HMA Sub-Layer Selection

The data described above were used in the perpetual pavement design software, PerRoad 2.4. This mechanistic-empirical (M-E) pavement design program utilizes layered elastic analysis and Monte Carlo simulation to develop stochastic pavement designs. The computational algorithms within PerRoad are beyond the scope of this paper, but can be found in other literature (12, 13, 14).

Using PerRoad 2.4, multiple designs were developed to keep the critical pavement responses below the respective thresholds 90% of the time. In other words, a small percentage of “overloads” were allowed in the design. It should be noted that a laboratory fatigue study conducted by Thompson and Carpenter (15) indicated that a small proportion of overloads exceeding the strain threshold did not alter the existence of the strain threshold.

Two sets of material properties and failure criteria were used in developing the designs. The first set was a conservative design using a soil stiffness of 7,000 psi (48 MPa) with the fatigue threshold at 70 $\mu\epsilon$. The second set was less conservative considering 15,000 psi (103 MPa) soil and a fatigue threshold of 125 $\mu\epsilon$. The resulting thicknesses are illustrated in Figure 6 where the conservative design is represented by “70 $\mu\epsilon$ ” and the less conservative designs are designated by “125 $\mu\epsilon$.” The rutting criteria of less than 200 $\mu\epsilon$ was met in each case, and did not control the design of these sections.

As shown in Figure 6, the conservative design resulted in approximately 20 in. (508 mm) of HMA materials above the lime-stabilized soil while the less conservative design consisted of 15 in. (380 mm) of HMA. In comparison, the control sections were considerably thinner; HMA thicknesses were 6 to 7 in. (150 to 180 mm).

The sublayers within the HMA were selected to achieve rut resistance in the upper portions of the pavement and fatigue resistance in the lower portions. To that end, SMA and dense-graded Superpave layers were used in the upper sublayers. An open graded drainage layer was used within each section to help remove moisture and mitigate stripping problems. Moisture damage (stripping of asphalt binder from the aggregate) has been observed in several failure investigations of pavements in Shandong Province that had been in service for 5 to 8 years. Reducing moisture infiltration or providing an outlet for internal pavement drainage has shown benefit in reducing moisture related distress. Therefore, the drainage layer was included in the perpetual pavement sections. It should be noted that one of the control sections (Section 4 in Figure 3) also included an open-graded drainage layer. The open-graded drainage layers are daylighted to the outside shoulder rather than the typical U.S. method of utilizing pipe underdrains.

Each experimental section featured a bottom HMA layer as a fatigue-resistant dense-graded material with an asphalt content 0.6% above optimum. Based upon previous studies (8), it is believed that the added asphalt content will improve the density and overall fatigue

resistance of the pavement where the tensile strains are the highest. The “125 $\mu\epsilon$ (Modified)” section has a polymer modified-binder that is expected to further improve the fatigue resistance.

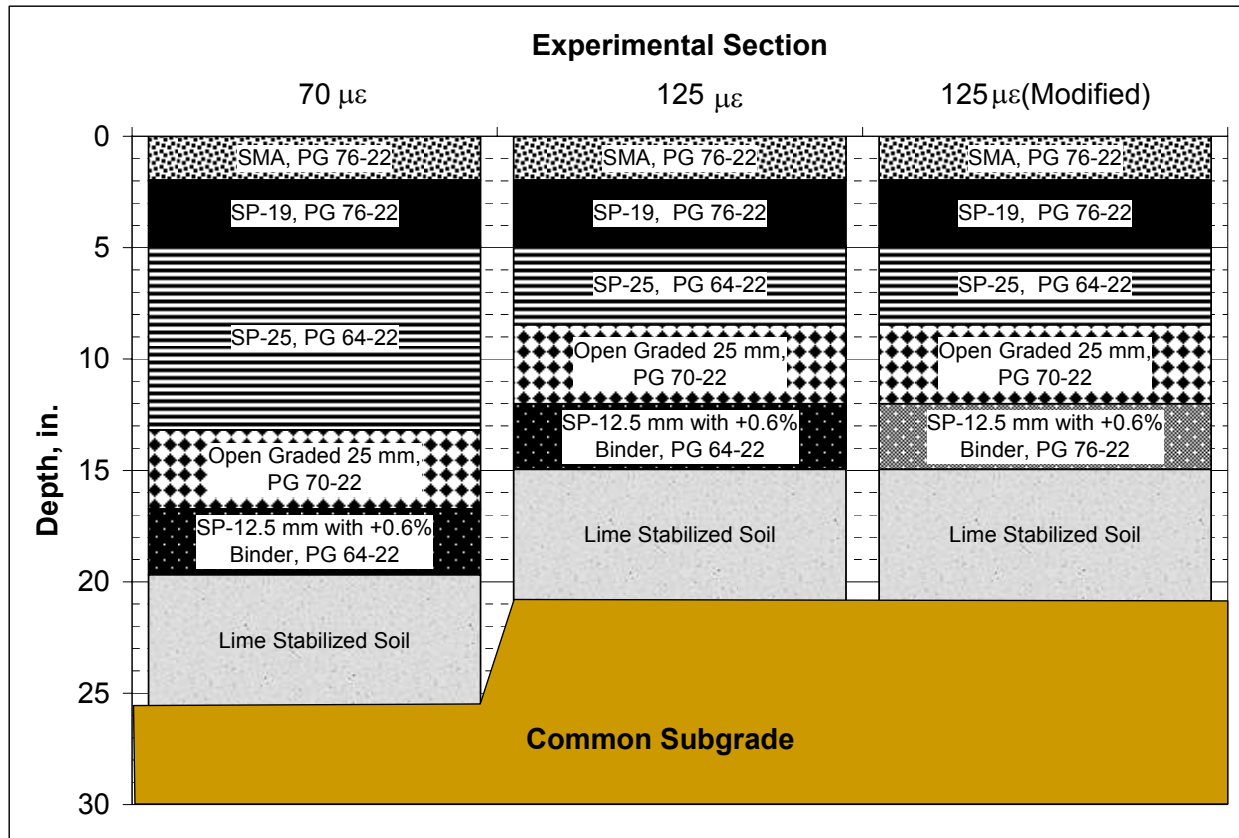


FIGURE 6 Perpetual Pavement Test Sections.

INSTRUMENTATION AND CONSTRUCTION

Instrumentation was embedded in the roadway to enable pavement response measurements under the expressway traffic. The instrumentation layout is shown schematically in Figure 7 and was patterned after the scheme used at the NCAT Test Track (16). Axle sensors are used to pinpoint the location of loads as they move across the gauge array in the outside wheelpath (OWP). The earth pressure cell measures vertical stresses on top of the lime-stabilized soil (experimental sections) and CSGL (control sections) and will support efforts to characterize limiting stress/strain criteria. The asphalt strain gauges measure horizontal strain, in the lateral and transverse directions, at the bottom of the HMA and are spaced to capture the natural wander of vehicles. These gauges are important to establishing critical strain thresholds for fatigue and evaluating the design methodology. A temperature probe was installed vertically in the pavement to capture temperature at the top, middle and bottom of the HMA, which helps develop relationships between environmental parameters, material properties and pavement response. Not shown in Figure 7 is a WIM station that was installed at the end of the project to document live traffic volume, weights, and axle configurations.

Construction of the test sections occurred in June 2005. The HMA mixtures were produced at a new batch plant located near the test sections. Rolling patterns were established on trial mixes and two pavers were used in tandem to pave widths up to 40 ft (12.2 m). During

construction, HMA samples were obtained from the delivery trucks and shipped to the U.S. for further testing.

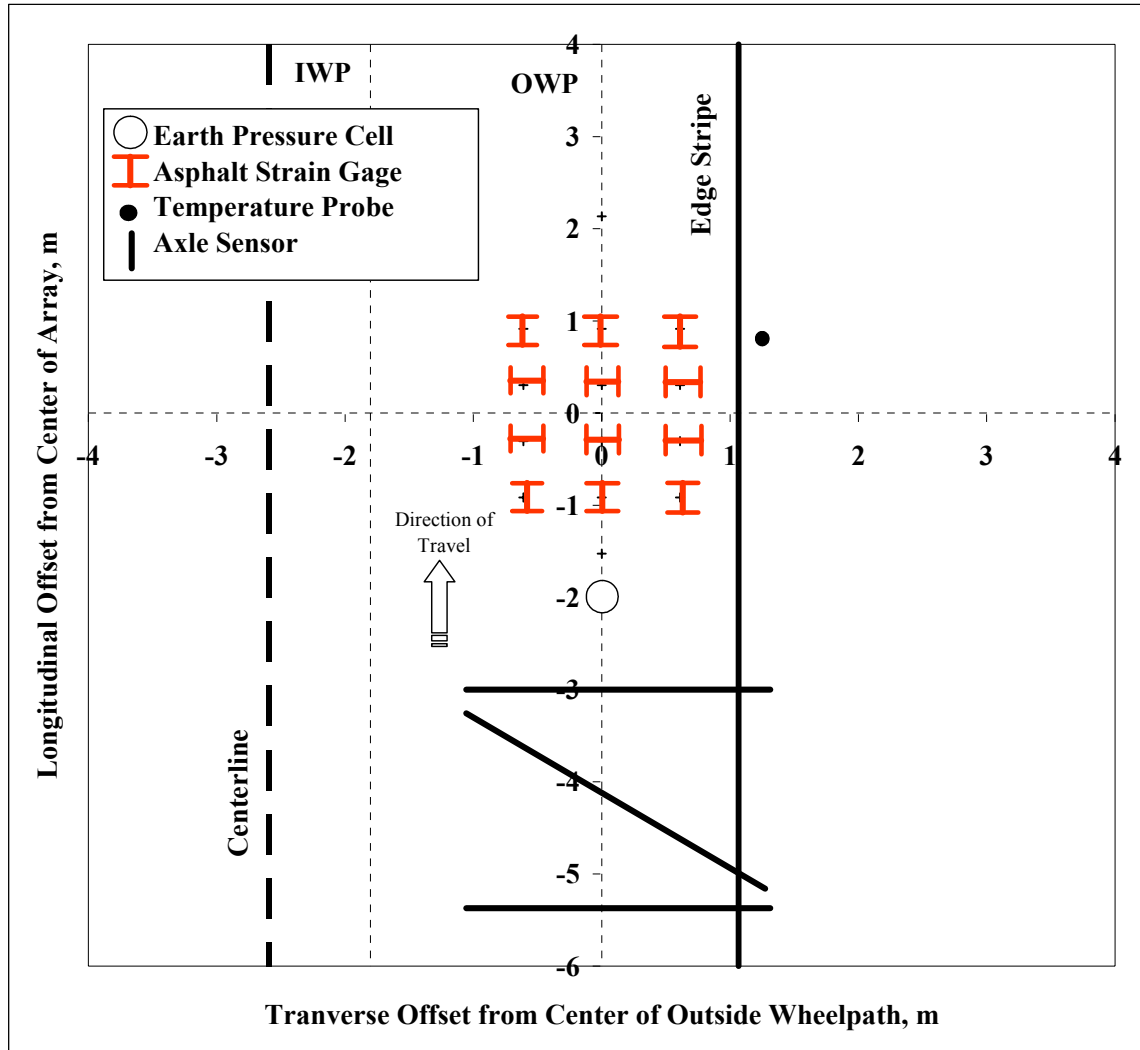


FIGURE 7 Embedded Pavement Instrumentation.

DATA COLLECTION EFFORTS

Due to the nature and length of this experiment, the data collection efforts are a massive undertaking. Collection and analysis of WIM, FWD and dynamic response data through the life of the test sections (or sensors) is a major component of the study. Laboratory material testing, continuous pavement performance monitoring, and forensic investigations as the sections begin to show distress are also vital. Further, all of the mentioned collection efforts are particularly challenging because the experimental sections are segments of a public access expressway.

Traffic load characterization from WIM data was briefly presented above, and the material characterization testing has not been fully completed, to date. FWD testing was conducted on all the test sections prior to trafficking and will be conducted on a seasonal basis to monitor the test sections. Although all the collection efforts are essential to the overall success of the experiment, the dynamic response data collection plan will be the focus of this section.

Dynamic pavement instrumentation is a powerful tool used to measure the in situ pavement response, which allows for the direct evaluation of design and comparison between different pavement cross-sections and materials. The sensors and data acquisition used for the project are capable of recording live pavement response in excess of 2,000 samples/sec per sensor. At these high collection rates, the responses show not only the peak response, but also the nature of the response as a truck travels over the pavement. Figure 8 shows an example of the data collected from the asphalt strain gauges and earth pressure cells, in addition to the test vehicle. The steer, tandem and tridem axles are clearly discernible with the tridem axle generating the highest strain and pressure responses.

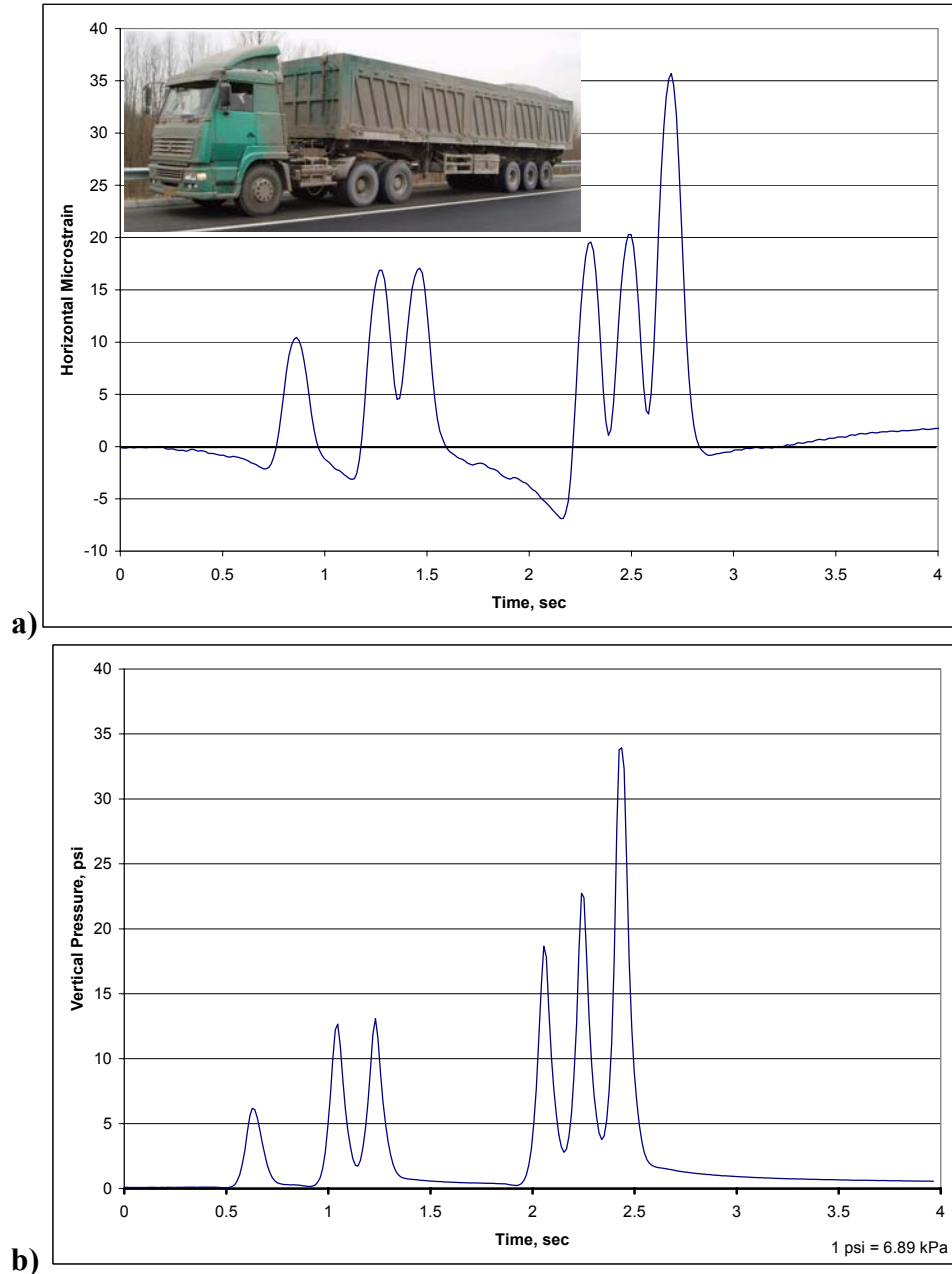


FIGURE 8 Dynamic a) Strain and b) Pressure Response Data.

When collecting dynamic response data, as with all collection efforts, it is important to have a well planned testing scheme with research goals in mind. Otherwise, all the efforts involved with this type of data (i.e., collection, storing, processing and analyzing) can quickly become overwhelming. Also, because the experimental sections are located on a public expressway, the testing plan must also be sensitive to the users by minimizing closures and interruptions. For this experiment, the long-term performance of the sections under live traffic is the main focus as well as evaluating the design methodology. Therefore, the response data collection scheme is split into two main areas of emphasis. One, using control vehicles to allow for comparisons and evaluation of the test sections, and two, collecting response data under live expressway traffic.

The use of control vehicles allows for a more direct comparison among sections as well as providing reliable traffic to evaluate the design and performance of the test sections among one another and over time. Some of the important research goals supported by control vehicle testing are:

1. Compare response among test sections
2. Validate structural design methodology
3. Predict structural performance of the test sections
4. Enhance theoretical models
5. Characterize seasonal and temperature effects on pavement response
6. Evaluate load – response interaction

Through discussion between the U.S. and Chinese team members, the axle weights and configurations shown in Figure 9 were agreed upon considering research needs and practicality. The testing fleet captures a wide range of the existing Chinese truck loads including the more extreme overloads, critical to understanding the past performance and evaluating design of the experimental sections. It was recommended by the U.S. team to sample the dynamic gauges at 2,000 Hz per channel and collect 5 passes of each testing condition. The collection effort is rather cumbersome and time consuming considering lane closures; road-side equipment and staff; and loading, weighing and navigating the trucks. Therefore, the control vehicle testing scheme is planned to be performed monthly from December 2005 to July 2006 and then on a quarterly basis thereafter. This testing scheme should effectively capture seasonal effects, material aging, and deterioration while being practical to researchers and expressway users. Figure 9 shows a conceptual graph representing the expected outcome of the pavement response for the different loads applied at different pavement temperatures.

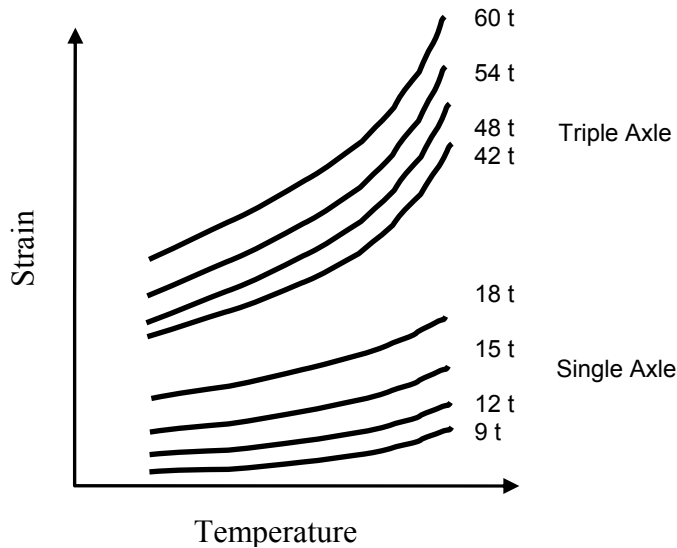


FIGURE 9 Response vs. Temperature and Load (conceptual).

The second major task under the dynamic response umbrella is the collection of live traffic. Obviously, live traffic data, coupled with WIM data, will support a more complete understanding of the loading and induced pavement response for the different sections over the life of the experiment. The two main objectives of the live traffic collection are:

1. Characterize highway traffic and evaluate pavement response
2. Evaluate effect of over-loads

Although the experiment includes WIM and response sensors, a direct relationship between a specific truck load and response is not practical nor necessary. Rather, a relationship between the frequency of traffic loads and response should be investigated. As part of the highway traffic characterization, the lateral positioning sensors will be used to characterize the wheel position and wander of the traffic. Traffic wheel wander is an important measurement in reference to the dynamic response as well as mechanistic-empirical design.

As with the control vehicle testing, live traffic response data will be collected on a quarterly basis. Due to the nature of the data acquisition system and the massive amount of data generated, it is not practical to attempt to collect dynamic response data continually as with other collection systems like the WIM. The amount of data generated is more substantial, and the data processing and analysis is much more time consuming and involved. Further, other studies have found that interstate traffic remains fairly consistent over time (17). Live traffic data will be collected during peak hours, and a short analysis will have to be conducted using WIM data or response data to determine the adequate amount of collection time to establish a reliable dataset. It is also important to make the collection as low-profile and inconspicuous as possible in attempt to keep the influence on traffic patterns to a minimum. Figure 10 illustrates the expected outcome of this portion of the experiment, where distributions of pavement response will be developed to estimate the percentage of loads causing pavement responses above the threshold. This will help formulate a set of recommendations regarding a practical pavement response threshold to use for future designs.

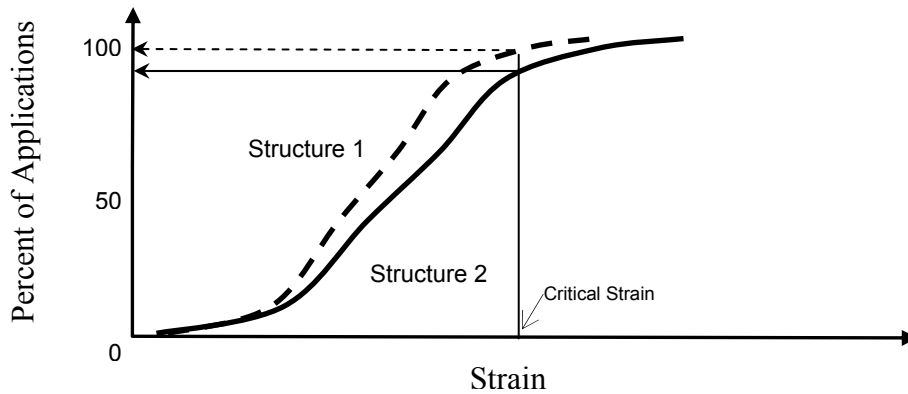


FIGURE 10 Pavement Response Distributions (conceptual).

Along with the quarterly dynamic response data collection, FWD testing of the sections will also be performed on a quarterly basis. These data will be used in backcalculation to determine the in situ material properties and characterize seasonal variation. The material property data will be an essential component in evaluating the design criteria, pavement performance, and pavement response models. The long-term data set can also be used to investigate the effect of pavement deterioration on material properties and the possibility of early damage detection. Finally, the fatigue properties of the lowest asphalt layer in each structure will be evaluated in the laboratory using the beam fatigue test. Knowing fatigue properties and the applied strains, the damage can be estimated as a percentage of the available design life and the remaining life can be predicted.

PROJECT STATUS AND SUMMARY

The Shandong Perpetual Pavement Project was constructed in the summer of 2005 and was opened to traffic in December 2005. Data collection efforts are currently focused upon testing the control vehicle as described above and will be complete by July 2006. This will be followed by testing under live-traffic conditions in addition to quarterly testing with the control vehicle. Laboratories in Shandong Province and in the U.S.A. are performing tests to determine fatigue and stiffness properties. This testing is expected to be completed during the summer of 2006.

While the core objective of this project is to better understand traffic loading conditions and their effect on pavements in China, it is expected that the results will also directly benefit perpetual pavement research and practice in the U.S. Testing under the heavy traffic loads will give U.S. researchers and practitioners a better understanding of flexible pavement performance in extreme traffic conditions. Findings from this research may help guide future decisions toward legal limits and overload permitting in the U.S.

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