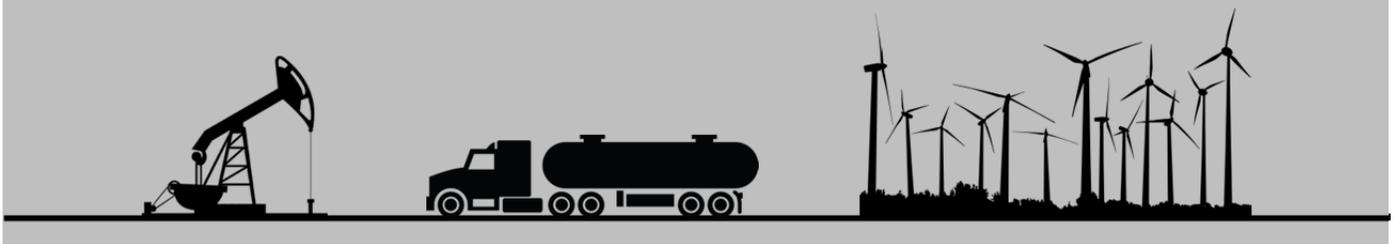


# Pavement Design Catalogue Development for Pavements in Energy Affected Areas of Texas

## Implementation Report IR-15-01



Prepared for Texas Department of Transportation  
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Prepared by  
Texas A&M Transportation Institute

**David E. Newcomb**  
Senior Research Engineer

**Fujie Zhou**  
Research Engineer

**Jon A. Epps**  
Senior Research Fellow

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## **INTRODUCTION**

Texas has undergone a boom in the production of natural gas and crude oil since 2008 due to improvements in the practice of hydraulic fracturing (fracking) of oil and gas bearing rock formations. This development of energy sources in Texas and throughout the U.S. has tremendously impacted the global economy by increasing the world's supply of gas and petroleum which has driven the cost of energy down significantly. While the recent energy development has had a positive economic benefit to the State of Texas, it has had severe impacts on the condition of the state's highway system estimated to be approximately \$2 billion per year.

The process of fracking requires the movement of equipment, materials, and water in order to establish and complete wells, produce oil, and re-frack on a periodic basis. This can translate into 1000 to 2000 loaded trucks per well and with a rate of well completion on the order of 10,000 to 15,000 per year, a total of 10,000,000 to 30,000,000 additional truck trips are being generated annually on state highways. The locations of these wells within Texas are generally in rural areas where the traditional traffic has been largely passenger vehicles with occasional agriculture-related truck traffic. The pavements on these rural roads were vastly under-designed for the amount of traffic they are currently serving. Many of these pavements have suffered severe distress in the form of fatigue cracking, edge cracking and deterioration, and rutting.

## **OBJECTIVE**

The objective of the work presented here was to develop a simplified approach to estimating the required pavement section for roads planned for widening and reconstruction in the form of pavement design catalogs. It is intended for use by TxDOT District Maintenance and Design Engineers to obtain a quick assessment of the pavement structural section for a 10-year design life.

## **METHODOLOGY FOR DEVELOPING PAVEMENT DESIGN CATALOG**

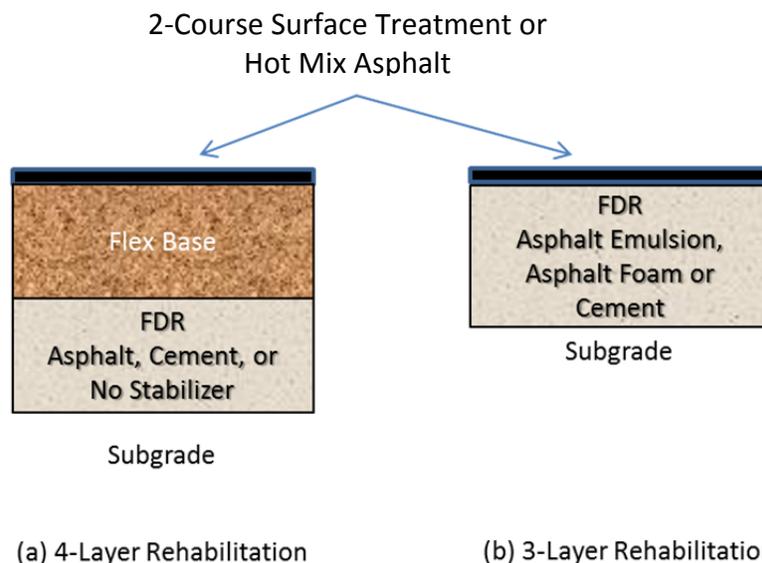
Currently TxDOT designs flexible pavements with the computer program FPS21, and then the Texas Triaxial method is employed to check whether or not the pavement designs have enough structural thickness above the subgrade to avoid shear failure. The Texas Triaxial method is appropriate for those pavements with aggregate base materials (i.e., flex base). Thus, the researchers generated pavement design curves with FPS and, when appropriate, used the Texas Triaxial check for a variety of scenarios which maintenance supervisors and engineers often find on roadways. Analysis of available traffic data in energy affected areas was used to establish traffic loading as a function of the number of gas or oil wells being served. These traffic loadings were then added to the typical non-energy related traffic loadings. The result is a simplified pavement design catalog based on the design curves for various traffic levels in energy affected areas.

Pavement rehabilitation practices associated with the repair of oil and gas development and production activities typically involve some type of pavement strengthening operations either performed by maintenance forces or a maintenance or construction contract. These operations include deep patches, widening of the roadway or rehabilitation of the entire roadway section.

The determination of the structural thickness of the pavement is an important part of selecting a maintenance or rehabilitation alternative for a particular roadway.

Typical rehabilitation sections used by TxDOT in the oil and gas fields employ full depth reclamation (FDR) to pulverize and widen the existing roadway, the placement of a flexible base over the FDR, followed by an asphalt bound surface which is either a surface treatment or hot mix asphalt. Full depth reclamation operations are sometimes performed without the addition of a stabilizer. The use of portland cement at a level of 2 to 3 percent (cement modified) with the FDR operation is common. Districts increasingly are using asphalt emulsions and foamed asphalt as binders in full depth recycling operations. Flexible base is often placed on top of the FDR layer. Some districts have used portland cement as a stabilizer with the new flexible base material. The use of portland cement stabilization as a base course is discouraged if a surface treatment or thin hot mix asphalt layers are to be used as a wearing or surface layer as reflection cracking will occur.

There are two types of structures typically used in the rehabilitation of energy sector roads. One of these is a four-layer pavement structure, a FDR of the existing pavement, followed by a granular base layer plus either a surface treatment or a hot mix asphalt layer. The other is a three-layer pavement where FDR is performed and placed on the subgrade and overlaid with either an asphalt surface mix or a two-course surface treatment or hot mix asphalt. Figure 1 (a) shows a typical 4-layer pavement structure. Generally, the FDR thickness is a minimum of 6 inches, and typically stabilized with portland cement, asphalt emulsion, or foamed asphalt. For surface layers, there are four options: 1) two-course surface treatment, 2) 2 inch asphalt layer, 3) 4 inch asphalt layer, and 4) 6 inch asphalt layer. Figure 1 (b) shows a 3-layer pavement structure. The pavement design process is used to determine the thickness of the flexible pavement layer for the 4-layer option and to determine the thickness of FDR for the 3-layer structure.



**Figure 1. Typical Four-Layer and Three-Layer Pavement Structure for Rehabilitation.**

Two types of wearing or surface courses are typically used on oil and gas development and production impacted roadways; surface treatments or hot mix asphalt. Typically a double surface

treatment is placed on top of the new flexible base material. It is recommended that a minimum of 4 inches of hot mix asphalt be used in the south Texas Districts. It is possible to use 2 inches of asphalt as a surface course when a stabilized FDR is placed directly below as a base course.

**FPS21 Key Inputs**

As mentioned earlier, FPS21 was used to determine the structural sections for the design catalog, after which a check on the Texas Triaxial criteria was performed. After discussing with the technical experts of this project panel, the following key parameters for FPS21 pavement design were selected:

- Length of analysis period: 10 years
- Minimum time to first overlay: 8 years
- Minimum time between overlays: 8 years
- Design confidence level: C-95%
- Initial serviceability index:
  - HMA: 4.5
  - Surface treatment: 4.0
- Final serviceability index: 2.5
- ADT beginning: 4500
- ADT, end 20 year: 7000
- 18 kip ESALS (20 years): 0.1, 0.5, 1, 2, 3, 5, 10, 15, and 20 million
- Pavement material Properties: see Table 1.

**Table 1. Pavement Material Properties for FPS21 Pavement Design**

Layer	Material	Properties		Thickness, in.	Comments
		Resilient Modulus, psi	Triaxial Class		
Surface	Surface Treatment			Less than 1	Single and double surface treatments utilized
	Hot Mix Asphalt	500,000		4 and 6	
Base	Flexible Base	50,000		6 to 12	New flexible base used with FDR subbase
	High* Stabilization	300,000		6 to 11	No flexible base used with these
	Medium* Stabilization	200,000		6 to 13	
	Low* Stabilization	100,000		6 to 15	
Subbase	FDR-salvaged	50,000		6 and 8	No stabilizer
	FDR-PC	150,000			
	FDR-Asphalt	100,000			
Subgrade		7,000	5.8		
		10,000	5.0		
		20,000	3.0		

FDR--Full Depth Recycling

FDR-PC--Full Depth Recycling with portland cement as modifier (2 to 3 percent)

FDR-Asphalt--Full Depth Recycling with asphalt emulsion or foamed asphalt as stabilizer

\*High, Medium and Low levels of Base Stabilization should be based on the amount of material passing the No. 200 sieve, the Plasticity Index of the material, and the amount of asphalt binder (emulsion or foam) used to obtain high, low or medium modulus (stiffness).

### Texas Triaxial Key Inputs

The Texas Triaxial criteria were applied to the designs with flex base layers to ensure an adequate thickness to avoid shear failures in the subgrade. Discussions with the technical experts of this IAC panel led to the following inputs for the Texas Triaxial check of the FPS21 designs:

- Load level factor: Waive use of 1.3 factor for any case
- Texas Triaxial Class (TTL):
  - 7 ksi ----- TTL=5.8
  - 10 ksi ----- TTL=5.0
  - 20 ksi ----- TTL=3.5
- Cohesimeter value (Cm):
  - FDR-PC: Cm=800
  - FDR-Asphalt: Cm=300
  - FDR-salvaged: Cm=100
  - Hot mix asphalt: Cm=550, regardless of HMA thickness
  - Always use the highest Cm value of the materials being incorporated. For example, if the pavement structure has two layers: FDR-PC and hot-mix asphalt, use Cm value corresponding to FDR-PC.

### Fatigue Cracking and Rutting Evaluation

The mechanistic-empirical design approach used in FPS21 evaluates the potential for fatigue cracking and structural rutting. These two distresses are the product of a pavement that is too weak for the traffic, and must be accounted for in the structural design as they are among the most expensive problems to fix. In FPS21, the Asphalt Institute (AI) fatigue and rutting criteria were used as per the equations shown below. The fatigue equation is:

$$N_f = 7.92 \times 10^{-2} (\varepsilon_t)^{-3.291} (E_{AC})^{-0.854}$$

Where:  $N_f$  = Number of loading cycles to failure

$\varepsilon_t$  = Tensile strain at the bottom of the hot mix asphalt pavement layer

$E_{AC}$  = Modulus of the asphalt layer

The rutting equation is:

$$N_f = 1.365 \times 10^{-9} (\varepsilon_v)^{-4.477}$$

Where:  $N_f$  = Number of loading cycles to failure

$\varepsilon_v$  = Vertical compressive strain at the top of the subgrade

If fatigue cracking or rutting failure was likely for a particular structure at a given design traffic loading, it was noted and that structure was not recommended for consideration.

## PAVEMENT DESIGN CURVES FOR 4-LAYER PAVEMENTS

The 4-layer pavement structures were analyzed at the traffic levels presented above through FPS21 and Texas Triaxial check. Additionally, fatigue cracking for all asphalt concrete surfaced pavements and rutting potential for all pavements were analyzed. The subgrade modulus values were selected with typical values for the Eagle Ford Shale representing a soft condition (< 7ksi), the typical values for the Permian Basin representing a stiff condition (> 15 ksi) and the medium subgrade as being bracketed by the stiff and soft subgrades. A total of 24 pavement design curves were developed for the 4-layer cases, and these are described below. These curves show the required thickness of flexible base for a 10-year pavement design for the subgrade modulus, surface type, and the 20-year forecasted traffic.

- Pavement surface layer: Surface treatments
  - FDR with no stabilizer
  - FDR with PC
  - FDR with asphalt
- Pavement surface layer
  - FDR with no stabilizer – 4 inch hot mix asphalt
  - FDR with PC
  - FDR with asphalt
- Pavement surface layer: 6 inch hot mix asphalt
  - FDR with no stabilizer
  - FDR with PC
  - FDR with asphalt

Figure 2 shows the type of design curves developed for the 4-layer pavements. In this case, the curves are for a double surface treatment over flex base over an asphalt stabilized FDR over subgrade. Figure 2(a) illustrates the flex base thickness required for different levels of traffic, FDR subbase thickness, and subgrade stiffness. Figure 2(b) shows the Triaxial Classification check for the same materials and conditions.

## PAVEMENT DESIGN CURVES FOR 3-LAYER PAVEMENTS

The 3-layer pavement structures were analyzed at the traffic levels presented above through FPS21. Additionally, fatigue cracking for all asphalt concrete surfaced pavements and rutting potential for all pavements were analyzed. A total of 36 pavement design curves were developed for the 3-layer cases, and these are described below.

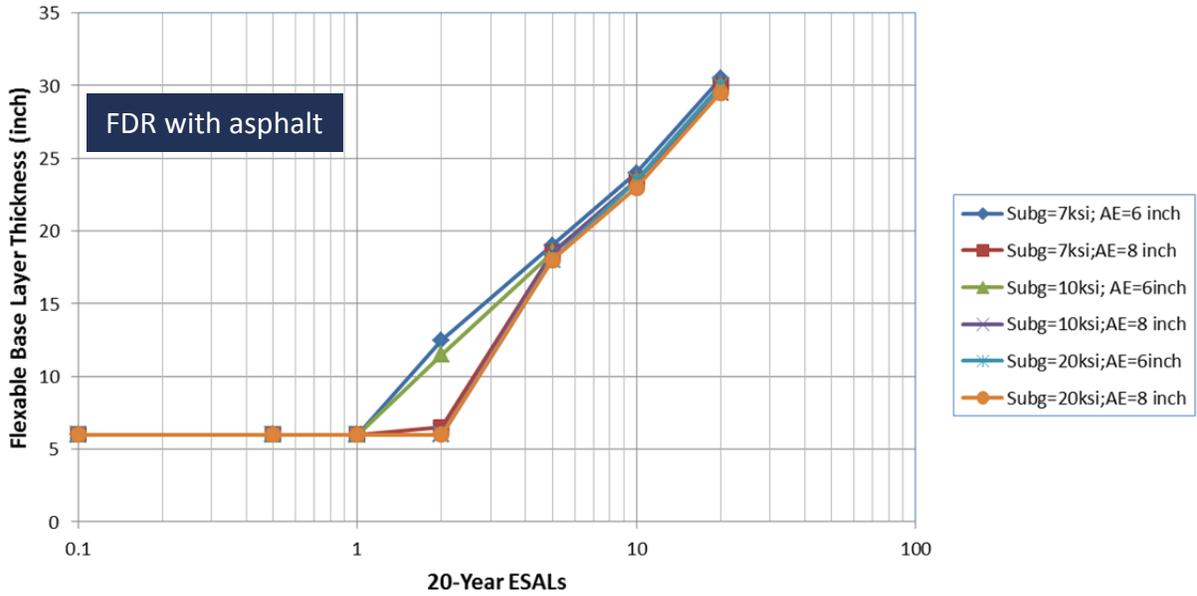
These curves show the required thickness of stabilized base over subgrade for a 10-year pavement design for the subgrade modulus, stabilized base modulus, surface type, and the 20-year forecasted traffic. The subgrade modulus values were selected with typical values for the Eagle Ford Shale representing a soft condition (< 7ksi), the typical values for the Permian Basin representing a stiff condition (> 15 ksi) and the medium subgrade as being bracketed by the stiff and soft subgrades. The stabilized base modulus values are ranked as stiff (300 ksi), medium (200 ksi), and soft (100 ksi). These values are somewhat subjective but the choice should reflect the amount of material passing the No. 200 sieve, the amount of high Plasticity Index (PI) material present, and the degree of stabilization for the FDR base. The amount of minus No. 200

material will be dictated by the quality of the existing base course and the potential for clay soils to be picked up and incorporated into the base during the mixing process.

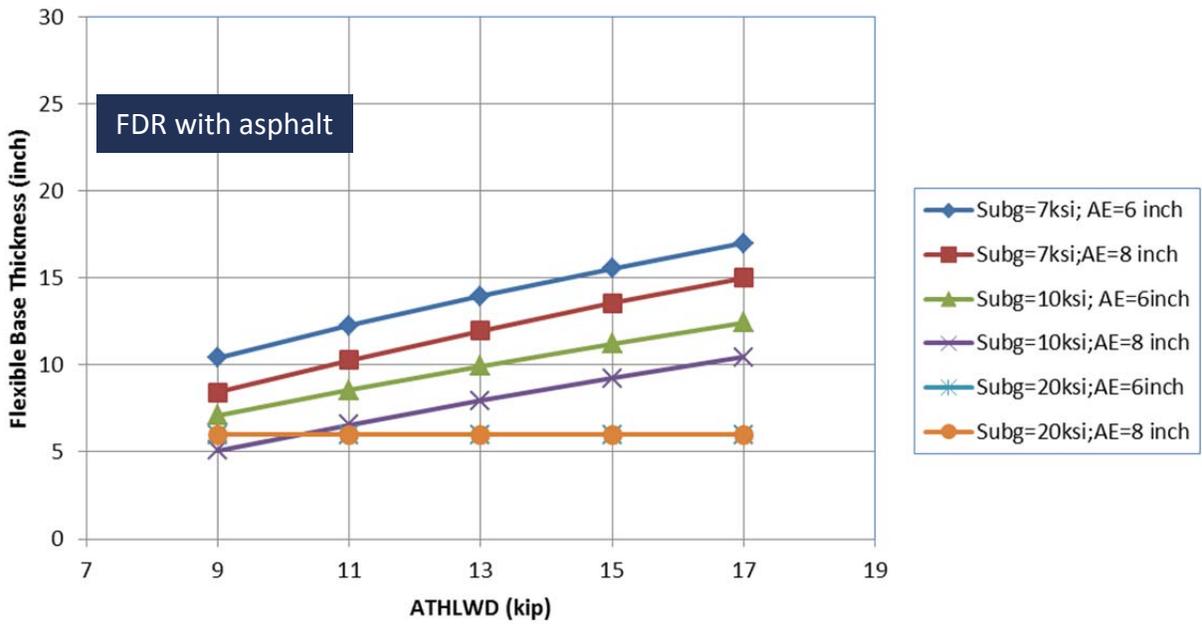
The thickness design curves for each combination of subgrade and base stiffness are as follows:

- Surface Treatment Surface
- 2 Inch AC Surface
- 4 Inch AC Surface
- 6 Inch AC Surface

Figure 3 shows the design curves for a 4-inch asphalt surface over the FDR base and three subgrade modulus values. For these pavements, the Triaxial check was not needed since flex base was not used. These graphs were used to obtain the required depth of FDR base at different levels of traffic.

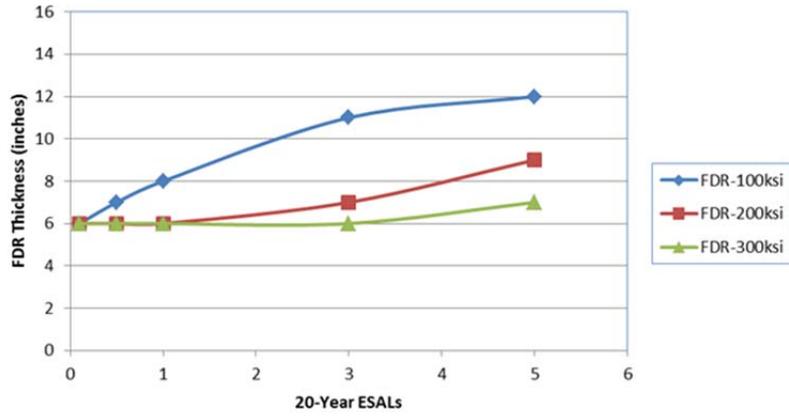


(a) FPS Curves

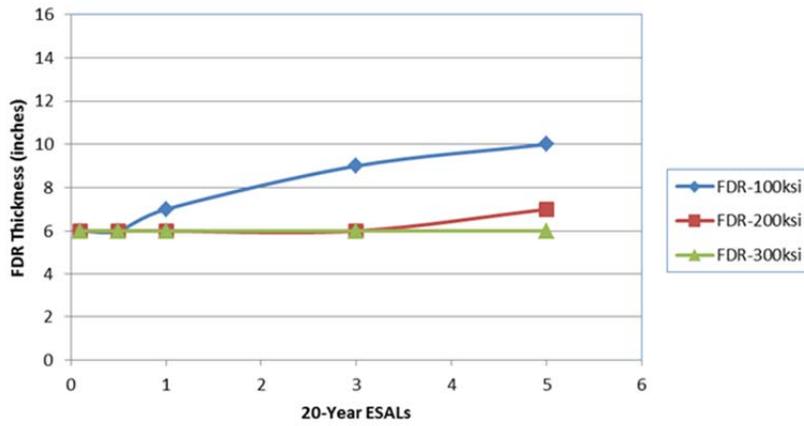


(b) Triaxial Check

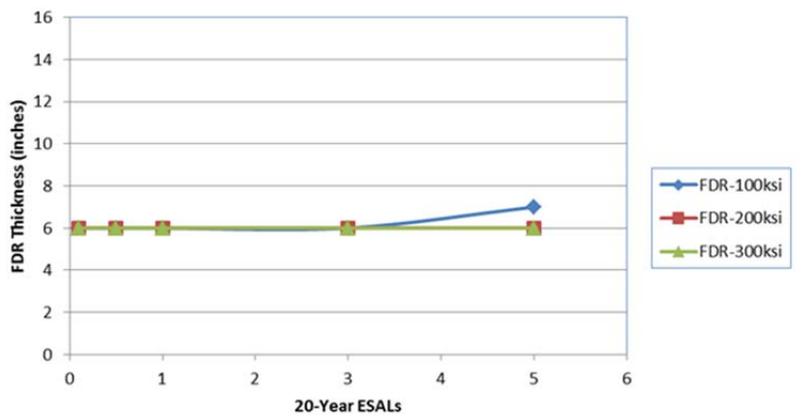
**Figure 2. Pavement Design Curves for FDR with Asphalt Stabilization and Surface Treatments.**



(a) Subgrade Modulus = 7 ksi



(b) Subgrade Modulus = 10 ksi



(c) Subgrade Modulus = 20 ksi

**Figure 3. 3-Layer Design Curves for 4 inch AC Surface.**

## TRAFFIC ANALYSIS

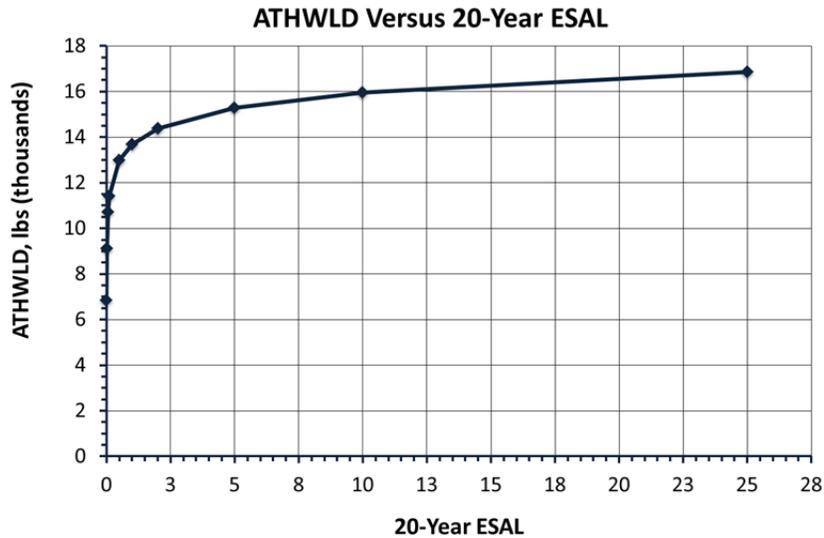
A systematic approach (1) was taken to determine the ESALs in connection with the development and operation of typical horizontal, hydraulically-fracked oil and gas wells in the Eagle Ford Shale, Permian Basin, and Barnett Shale regions of the state. The general process to determine ESALs for individual wells involved the following:

- Determining the number of trucks per well activity phase over a 20-year period. Truck volumes were estimated by relying on information in the literature from around the country as well as information gathered by TxDOT and data available from the FracFocus database (for the amount of water and sand used for fracking operations).
- The axle weight distribution was estimated for the truck types used for each phase of well development. This was accomplished by analyzing weigh-in-motion data which was tied to video logs of the weighed vehicles.
- The axle weight distribution for each truck type used was applied to the number of trucks per well development or operation phase and, with this information, the AASHO road test equations were used to estimate the number of ESALs for each phase.
- The total number of ESALs from the development and operation phases was determined for arriving and departing trucks from an average well in the Eagle Ford Shale, Permian Basin, and Barnett Shale formations. The variation in traffic generated per well in different regions is due to factors such as the amount of horizontal drilling versus vertical drilling, whether the products are primarily gas or oil, and the likely presence of pipelines. From the arriving and departing ESALs the larger value was used for pavement design. This information is found in Table 2.
- The data in Table 2 were used with the number of wells served on a given route to calculate ranges of 20-Year ESALs in each region. Thus, a maintenance supervisor or engineer can use a well count in an area to estimate the traffic level for design purposes.

**Table 2. ESALs per Well during Development and Operation for Different Texas Formations (1).**

	<b>Barnett Shale Region</b>	<b>Eagle Ford Shale Region</b>	<b>Permian Basin Region</b>
Number of trucks	5,413	15,170	10,324
ESALs per well after 20 years (trip to well)	5,804	10,641	6,151
ESALs per well after 20 years (trip from well)	3,823	13,694	10,792

Next, it was necessary to determine the ATHWD for the Triaxial check of the pavement section for the 4-layer cases where flex base is used. This estimate was provided by Figure 4 which shows the relationship between ATWHL and ESAL.



**Figure 4. ATHWLD for 20-Year ESAL Level.**

**PAVEMENT DESIGN CATALOG TABLES**

Once the 20-year ESAL level and the ATHWLD were determined for the number of wells served, the values were entered into graphs like those presented in Figures 2 to determine the flexible base thickness for each pavement structure and traffic level for the 4-layer pavement structures. The project panel of engineers decided upon a minimum flexible base thickness of 6 inches and a maximum of 12 inches for the 4-layer structures. The governing base thickness from FPS21 and the Texas Triaxial Classification check was determined, and the fatigue check was used to preclude premature failure. Also, sections requiring base thicknesses in excess of 12 inches were precluded as they exceeded the recommended maximum.

A similar procedure was used for the 3-layer pavements, except that a Triaxial check was not performed because there was no flexible base material used. In this case, the depth of thickness for the FDR base was determined by using graphs like those in Figure 3.

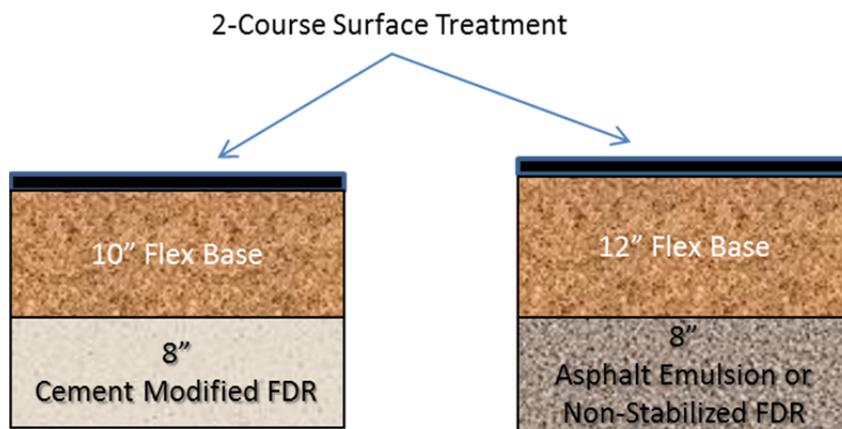
Four-Layer Pavement Catalog (surface, flex base, FDR, and subgrade)

Table 3 shows the final form of the pavement design catalog for 4-layer pavements. To use it, the number of wells serviced by a particular route should be determined. There are three areas identified for the well count: Barnett Shale (BS), Permian Basin (PB), and Eagle Ford (EF). If the expected traffic exceeds the maximum number of wells for a given region or 5 million ESALs, then a more formal approach to pavement design is recommended. Next, the subgrade stiffness should be determined. Soft subgrades are expected in the Eagle Ford Shale area and stiff subgrades are expected in the Permian Basin. The engineer should use the general history of soil behavior in an area to select the subgrade stiffness. The type and thickness of FDR is located on the left column, and these are designated as cement modified (CM), asphalt emulsion (AE), or non-stabilized (NS) at either six inches or eight inches. Next locate the column with the desired surface type, either double-course surface treatment (2CST) or four, or six inch concrete (AC) or

hot mix asphalt. The resulting base thickness will be at the intersection of these. The blank boxes indicate sections that are not recommended for design due to possible premature failure.

As previously stated, the designs in Table 3 for flex base thickness had an additional check against the TxDOT Triaxial Classification to preclude shear failure in the subgrade which explains the sometimes sudden jumps in required thickness of flexible base from one cell to another. In general, it is advisable to avoid the use of seal coat and 4-inch thick asphalt surfaces in high traffic (> 3 million ESAL) pavements as structural rutting and fatigue cracking may occur. However, 2CST may be used with 12 inches of flex base over a stiff subgrade for traffic up to 4 million ESAL. At higher traffic levels hot mix asphalt is the preferred surface material and a minimum thickness of 4 inches is recommended for this heavy traffic. The FPS-21 thickness design procedure should be used to determine the necessary pavement section.

As an example using Table 3 to determine the structural requirements for a pavement, assume a road is located in the Eagle Ford Shale (soft subgrade, modulus < 7 ksi) with approximately 125 wells expected. The existing roadway has an adequate amount of surface and base to allow for a FDR treatment to a depth of 8 inches. With the cement modified (CM) option, the pavement section would be a 2CST over 10 inches of flex base over 8 inches of cement modified subbase. This may be compared with the asphalt emulsion or non-stabilized subbase option where 12 inches of flex base is required for the same surface and same thickness of subbase. These are illustrated in Figure 5. Surface treatments should not be used when predicted 20 year ESALs are at 5.0 million and above.



**Figure 5. Comparison of Pavement Sections Using Table 4 for 2 Million ESAL, Soft Subgrade, and 8 inches of FDR.**

Three-Layer Pavement Catalog (surface, FDR base, and subgrade)

The designs presented in Table 4 are for surfaces placed directly on stabilized FDR bases. The stabilization in this case may be cement modification, asphalt emulsion, or foamed asphalt. The traffic level categories are at the top of the table, and there are three cases of subgrade stiffness as in Table 2. In Table 4, the degree of stabilization is considered to be related to the stiffness. This should be determined by the amount of material passing the No. 200 sieve, the likelihood of

high PI material contaminating the FDR, and the amount of stabilization present. There are three levels of stabilized FDR base stiffness along the left side of the table: high (modulus = 300 ksi), medium (modulus = 200 ksi) and soft (modulus = 300 ksi). Because of the stiffness and thickness of the FDR bases, all the sections presented in Table 4 passed the mechanistic criteria for rutting and fatigue.

An example for using Table 4 is to compare medium stiffness stabilized FDR base thicknesses for a road serving 80 wells in the Permian Basin with a high stiffness subgrade for surface treatment, 2 inches of asphalt mix surface and 4 inches of asphalt mix surface. Reading the chart shows that the surface treatment requires 8 inches of FDR, a 2-inch asphalt surface requires 7 inches, and a 4-inch asphalt surface needs 6 inches as seen in Figure 6.



**Figure 6. Comparison of Pavement Sections Using Table 4 for 80 wells in Permian Basin with Stiff Subgrade and Medium Stiffness FDR.**

## REFERENCES

1. Quiroga, C., Kraus, E., Tsapakis, I., “Traffic Loads for Developing and Operating Individual Wells,” Report No. IR-16-03, Texas A&M Transportation Institute, June, 2016.

**Table 3. Energy Sector Pavement Design Catalog for 4-Layer (Surface, Flex Base, FDR, Subgrade) Pavement. Numbers in table are Flex Base thickness in inches.**

Traffic, ESAL	<0.5 Million			0.5-1.5 Million			1.5-3.0 Million			3.0-4.0 Million			4.0-5.0 Million			>5.0 Million	
EF #Wells	<10			10-90			90-200			200-270			270-340			Use Formalized Design	
PB #Wells	<20			20-110			110-250			250-340			340-440				
BS #Wells	<40			40-210			210-470			470-640			640-810				
<b>Eagle Ford (Subgrade Modulus &lt; 7 ksi)</b>																	
Surface	2CST	4" HMA	6" HMA	2CST	4" HMA	6" HMA	2CST	4" HMA	6" HMA	2CST	4" HMA	6" HMA	2CST	4" HMA	6" HMA		
CM 6"	11	7	6	12	8	6	12	9	7	-	-	7	-	-	7		
CM 8"	9	6	6	10	6	6	10	7	6	-	-	6	-	-	6		
AE/NS 6"	12	8	6	12	9	7	12	10	7	-	-	8	-	-	8		
AE/NS 8"	12	6	6	12	7	6	12	10	7	-	-	8	-	-	8		
<b>Medium Subgrade (Subgrade Modulus &lt; 7 - 15 ksi)</b>																	
CM 6"	7	6	6	10	6	6	12	6	6	-	-	6	-	-	6		
CM 8"	6	6	6	7	6	6	10	6	6	-	-	6	-	-	6		
AE/NS 6"	12	6	6	12	6	6	12	6	6	-	-	6	-	-	6		
AE/NS 8"	12	6	6	12	6	6	12	6	6	-	-	6	-	-	6		
<b>Permian Basin (Subgrade Modulus &gt; 15 ksi)</b>																	
CM 6"	6	6	6	6	6	6	10	6	6	12	-	6	-	-	6		
CM 8"	6	6	6	6	6	6	10	6	6	12	-	6	-	-	6		
AE/NS 6"	6	6	6	9	6	6	12	6	6	12	-	6	-	-	6		
AE/NS 8"	6	6	6	8	6	6	12	6	6	12	-	6	-	-	6		

BS #Wells: Number of wells serviced by road in the Barnett Shale.  
 PB #Wells: Number of wells serviced by road in the Permian Basin.  
 EF #Wells: Number of wells serviced by road in the Eagle Ford Shale.

CM 6" = Cement Modified FDR, 6 inches thick  
 CM 8" = Cement Modified FDR, 8 inches thick  
 AE/NS 6" = Asphalt Emulsion FDR or Non-Stabilized FDR, 6 inches thick  
 AE/NS 8" = Asphalt Emulsion FDR or Non-Stabilized FDR, 8 inches thick

Not Recommended - Premature Failure Expected

**Table 4. Energy Sector Pavement Design Catalog for 3-Layer (Surface, FDR, Subgrade) Pavement. Numbers in table are FDR Base thickness in inches.**

Traffic, ESAL	<0.5 Million				0.5-1.5 Million				1.5-3.0 Million				3.0-4.0 Million				4.0-5.0 Million				>5.0 Million
EF #Wells	<10				10-90				90-200				200-270				270-340				Use Formalized Design
PB #Wells	<20				20-110				110-250				250-340				340-440				
BS #Wells	<40				40-210				210-470				470-640				640-810				
<b>Eagle Ford (Subgrade Modulus &lt; 7 ksi)</b>																					
Surface	2CST	2" HMA	4" HMA	6" HMA	2CST	2" HMA	4" HMA	6" HMA	2CST	2" HMA	4" HMA	6" AC	2CST	2" HMA	4" HMA	6" HMA	2CST	2" HMA	4" HMA	6" HMA	
Stiff Base	8	6	6	6	9	7	6	6	10	8	6	6	-	8	7	6	-	8	7	6	
Med. Base	9	7	6	6	11	9	6	6	11	9	7	6	-	10	8	6	-	11	9	6	
Soft Base	11	9	7	6	14	11	9	7	15	12	10	8	-	14	12	9	-	15	12	9	
<b>Medium Subgrade (Subgrade Modulus &lt; 7 - 15 ksi)</b>																					
Stiff Base	7	6	6	6	8	7	6	6	9	7	6	6	-	8	6	6	-	8	6	6	
Med. Base	8	6	6	6	10	8	6	6	10	8	6	6	-	9	7	6	-	10	7	6	
Soft Base	10	8	6	6	13	10	8	6	13	11	9	6	-	12	10	7	-	13	10	7	
<b>Permian Basin (Subgrade Modulus &gt; 15 ksi)</b>																					
Stiff Base	6	6	6	6	7	6	6	6	7	6	6	6	-	7	6	6	-	7	6	6	
Med. Base	7	6	6	6	8	7	6	6	8	7	6	6	-	8	6	6	-	8	6	6	
Soft Base	8	6	6	6	10	8	6	6	10	8	6	6	-	9	7	6	-	10	7	6	

BS #Wells: Number of wells serviced by road in the Barnett Shale.  
 PB #Wells: Number of wells serviced by road in the Permian Basin.  
 EF #Wells: Number of wells serviced by road in the Eagle Ford Shale.

Stiff:  $E_{FDR} = 300$  ksi  
 Medium:  $E_{FDR} = 200$  ksi  
 Soft:  $E_{FDR} = 100$  ksi

■ Not Recommended - Premature Failure Expected