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16. Abstract

In recent years, Texas has experienced a boom in energy-related activities, particularly in wind power generation and extraction of oil and natural gas. While energy developments contribute to enhance the state's ability to produce energy reliably, many short-term and long-term impacts on the state's transportation infrastructure are not properly documented. Examples include the impact of frequent truckloads on state highway infrastructure such as pavement structures and shoulders, as well as impacts on roadside infrastructure such as driveways and drainage facilities. There is also a lack of documentation on the impact on TxDOT's ability to manage the state highway right-of-way effectively, e.g., with respect to driveway access and utility crossings.

This report describes the work completed to measure the impact of increased level of energy-related activities on the TxDOT right-of-way and infrastructure, as well as develop recommendations to reduce and manage TxDOT's exposure and risk resulting from those activities. The report addresses a number of topics, including the process to develop a geodatabase of energy developments in the state, field visits, pavement impacts, roadside impacts, operational and safety impacts, and economic impacts. The geodatabase includes non-renewable energy datasets, renewable energy datasets, energy use datasets, and geology-related datasets. The recommendations for implementation were grouped into the following categories: early notification and coordination (five recommendations), road maintenance and repair (four recommendations), roadside management (two recommendations), and funding (five recommendations).

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ENERGY DEVELOPMENTS AND THE TRANSPORTATION INFRASTRUCTURE IN TEXAS: IMPACTS AND STRATEGIES

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DISCLAIMER

The contents of this document reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This document does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Cesar Quiroga, P.E. (Texas Registration #84274).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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LIST OF ACRONYMS, ABBREVIATIONS, AND TERMS

AADT	Average annual daily traffic
AADTT	Average annual daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
ABL	Abilene District at TxDOT
AEI	Alternative Energy Institute
AFA	Advance funding agreement
ALTURA	Alliance of Texans for Uranium Research and Action
CMS	Changeable message sign
CMZ	Congestion management zone
CPS	Central Permitting System
CREZ	Competitive renewable energy zone
CRIS	Crash Record Information System
CSB	Cement-stabilized base
DCIS	Design and Construction Information System
DFO	Distance from origin
EALF	Equivalent axle load factor
EIA	Energy Information Administration
ELLIS	Energy Land Lease Information System
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
ESAL	Equivalent single axle load
FHWA	Federal Highway Administration
FM	Farm-to-Market
FPS	Flexible Pavement Design System
FTW	Fort Worth District at TxDOT
FWD	Falling weight deflectometer
FY	Fiscal year
GIS	Geographic information system
GLO	Texas General Land Office
GPR	Ground penetrating radar
GSD	General Services Division at TxDOT
GVW	Gross vehicle weight
HB	House Bill
HMA	Hot-mix asphalt
IA	Interconnection agreement
IH	Interstate Highway
INL	Idaho National Laboratory
IPP	Initial performance period
IT	Information technology
KML	Keyhole markup language
LBB	Lubbock District at TxDOT
LNG	Liquefied natural gas
LSS	Lime-stabilized subgrade
M-E	Mechanistic-empirical

MMIS	Maintenance Management Information System
MNT	Maintenance Division at TxDOT
Mn/DOT	Minnesota Department of Transportation
MOU	Memorandum of understanding
MPO	Metropolitan planning organization
MRLC	Multi-Resolution Land Characteristics
NATCARB	National Carbon Sequestration Database and Geographic Information System
NBB	National Biodiesel Board
NESC	National Electrical Safety Code
NETL	National Energy Technology Laboratory
NETx	North East Texas
NLCD	National Land Cover Database
NPMS	National Pipeline Mapping System
NRCS	Natural Resources Conservation Service
OS/OW	Oversize/Overweight
OTRA	Overweight Truck Route Analysis
PDF	Portable document format
PHMSA	Pipeline and Hazardous Materials Safety Administration
PMIS	Pavement Management Information System
PNG	Portable network graphics
PS&E	Plans, specifications, and estimates
PSF	Permanent School Fund
PUCT	Public Utility Commission of Texas
RHiNo	Roadway/Highway Inventory Network
RM	Ranch-to-Marker Reference marker
RMA	Regional mobility authority
ROW	Right of Way Division at TxDOT
RRC	Railroad Commission of Texas
RSS	Really Simple Syndication
SECO	State Energy Conservation Office
SH	State Highway
SI	Serviceability index
SMU	Southern Methodist University
SSI	Structural strength index
TCEQ	Texas Commission on Environmental Quality
TMUTCD	Texas Manual on Uniform Traffic Control Devices
TSD	Technology Services Division at TxDOT
TTC	Texas Triaxial Class
TYL	Tyler District at TxDOT
TxDOT	Texas Department of Transportation
TxDPS	Texas Department of Public Safety
TAC	Texas Administrative Code
TTI	Texas Transportation Institute
US	U.S. Highway

USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UAR	Utility Accommodation Rules
UIR	Utility Installation Review
VMT	Vehicle-miles traveled

CHAPTER 1. INTRODUCTION

Energy is a critical pillar of the Texas economy. Following the Texas Comptroller of Public Accounts' 2008 *Energy Report* (*1*), the energy sector employs nearly 375,000 people in Texas who earned more than $35 billion in total wages in 2006. Texas has about one-quarter of oil reserves and one-third of natural gas reserves in the country. The state also has more than a quarter of all U.S. refining capacity. Texas leads the nation in energy consumption (followed by California), accounting for 12 percent of all U.S. energy use and 18 percent of industrial use. Although energy use per capita in Texas has decreased over the years, the total energy consumption in the state has increased by an average of 2.2 percent annually since 1960.

In recent years, there has been a boom in energy-related activities in Texas, particularly in wind power generation and extraction of oil and natural gas (*1*). Texas is now the largest producer of wind power in the country, and continues to grow its wind power generation capabilities rapidly (Figure 1, Figure 2). There are plans for wind power and solar arrays in much of the western half of the state as well as offshore in the Gulf of Mexico.

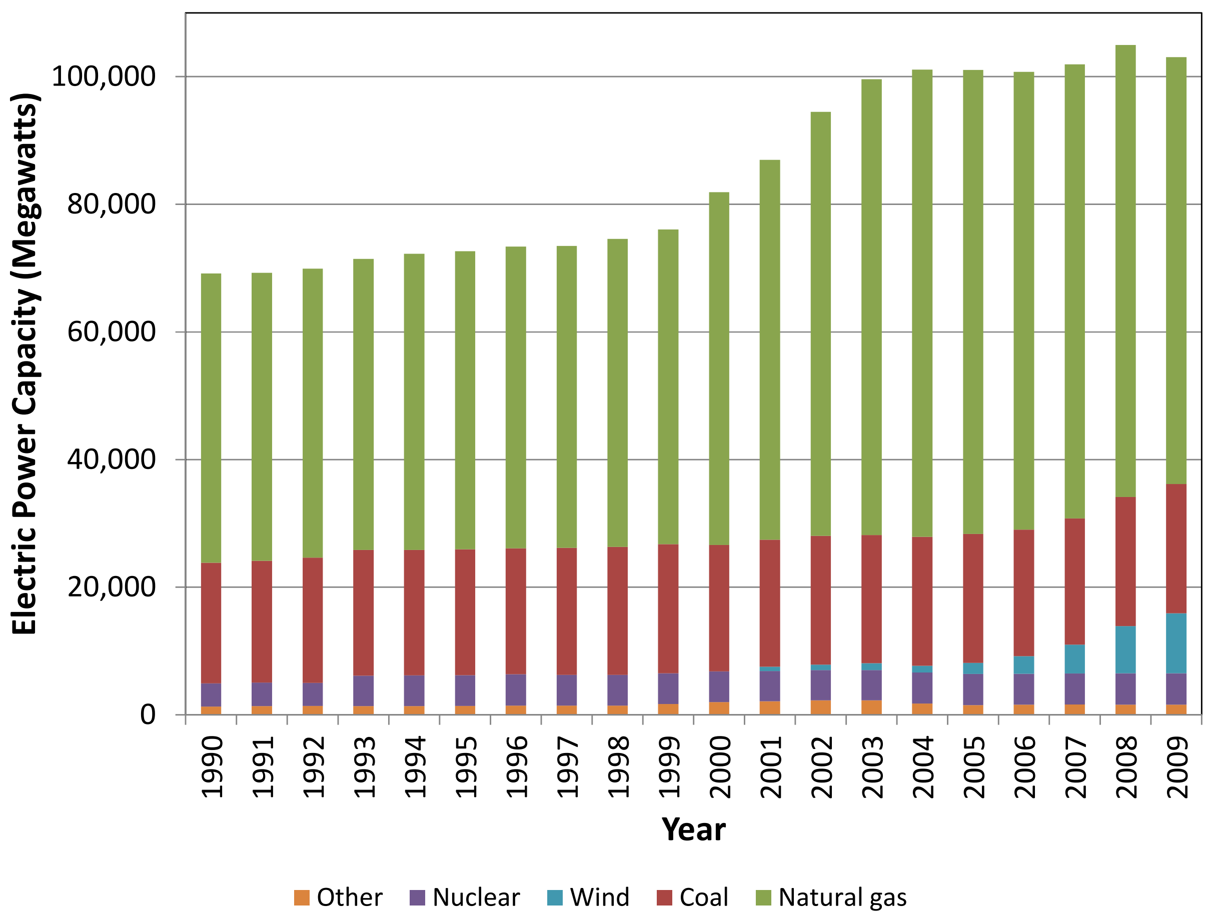
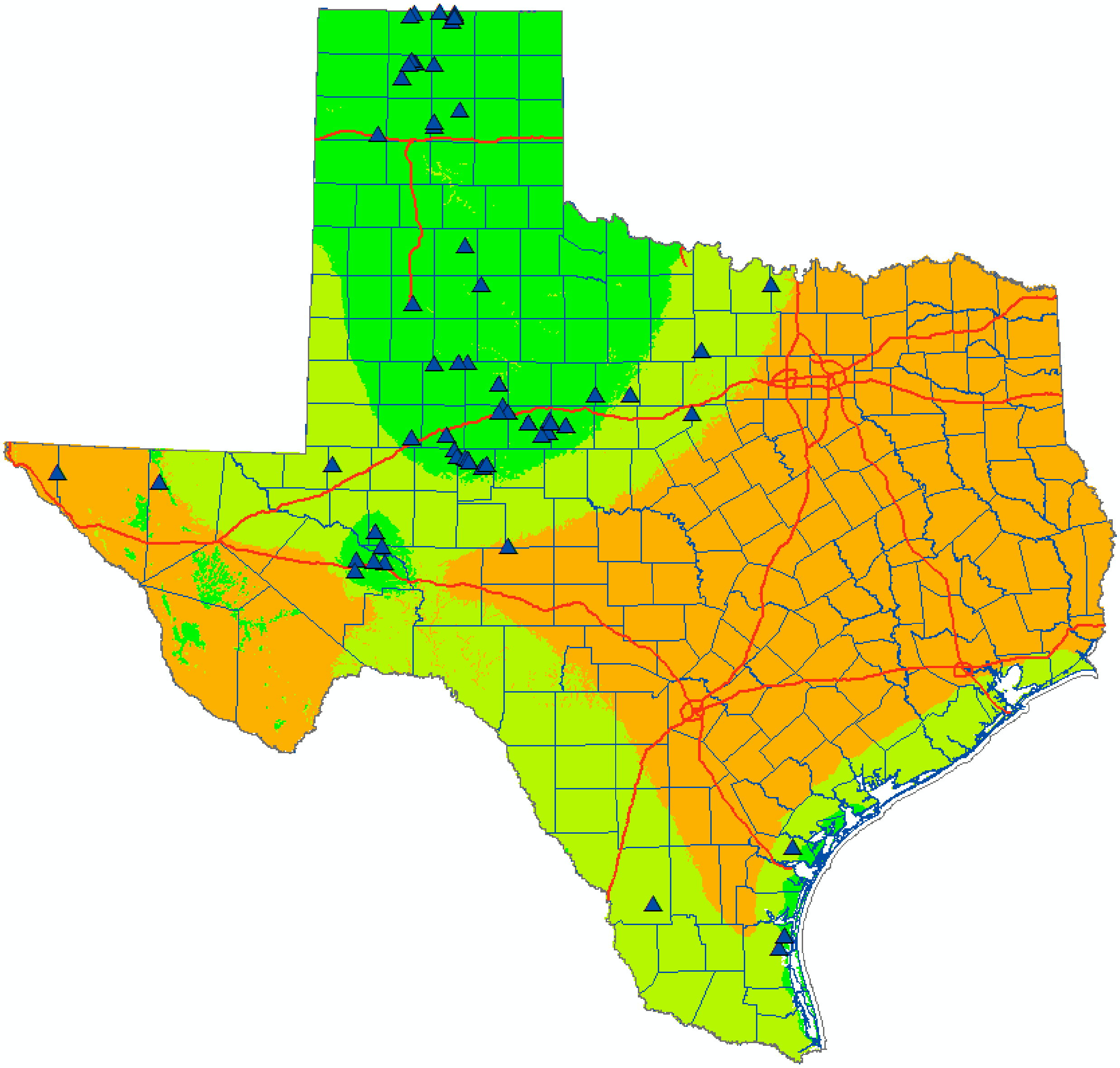


Figure 1. Electric Power Capacity in Texas from 1990 to 2009 (*2*).



Note: Shaded areas represent wind power potential with dark green indicating the highest potential.

Figure 2. Wind Farms in Texas as of 2010.

Wind farms are large operations, each one including tens or hundreds of wind turbines. Wind turbines are massive structures. For example, a typical wind turbine at the Whirlwind wind farm development in Floyd County (Lubbock District) weighs 1,245 tons, is 310 ft in sweep diameter and 422 ft to the top of the blade, and includes the following elements (*3*):

- Site (1.5–2 acres in size), access roads, and other related infrastructure.
- Excavation during construction: 100 ft wide and 8 ft deep.
- Large amounts of caliche used for access roads and backfill.
- Reinforced concrete foundation: 56 ft in diameter and 8.5 ft tall, including 85,300 lb of rebar and 350 cubic yards of concrete.

- Tower (261 ft tall):
  - Base section (133,000 lb): 53 ft tall × 14 ft in diameter (base).
  - Mid section (132,000 lb): 90 ft tall × 13 ft in diameter.
  - Top section (109,000 lb): 118 ft tall × 13 ft in diameter (base).
- Nacelle (193,000 lb): 12 ft × 37 ft.
- Rotor/blade assembly (145,000 lb): 310 ft in diameter.
- Turbine capacity: 2.3 Megawatts.

Figure 3 summarizes the number of oil and gas permits issued in Texas from 1998 to 2009. The number of permits issued per year accelerated in the mid-2000s, thanks to advancements in drilling technology, mainly in connection with horizontal drilling and hydraulic fracturing (or "fracking"), which made it possible to develop tight shale fields in significant quantities profitably. Much of the experience with fracking comes from the Barnett Shale gas play in North Texas (*4*). A common practice is to use "slickwater fracs," which consist of injecting a water-based fracturing fluid that includes a friction reducer, other additives, and sand. Slickwater fracs require enormous amounts of water, and it is common to re-fracture wells several times during the producing life of the well.

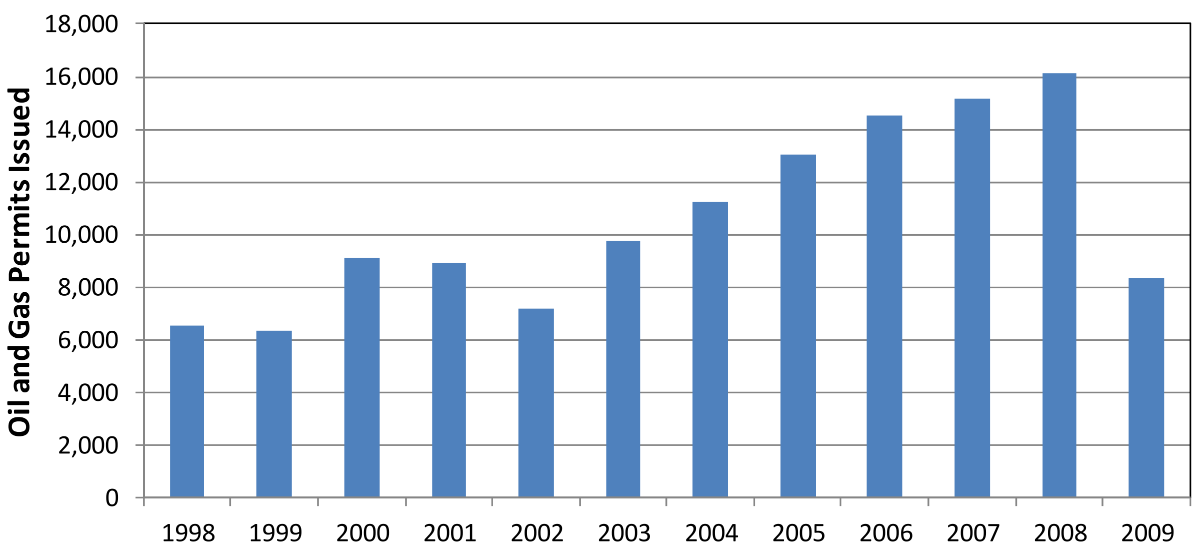


Figure 3. Oil and Gas Permits Issued in Texas from 1998 to 2009.

Figure 4 shows the location of permitted oil and gas wells in the state from 2002 to 2009. Many permitted locations are in areas traditionally associated with oil production in the state (e.g., the Panhandle and West Texas). However, a substantial number of permits are in areas such as the Barnett Shale in North Texas and the Eagle Ford Shale in South Texas, where horizontal drilling and fracking have enabled the development of those areas profitably over the last few years.

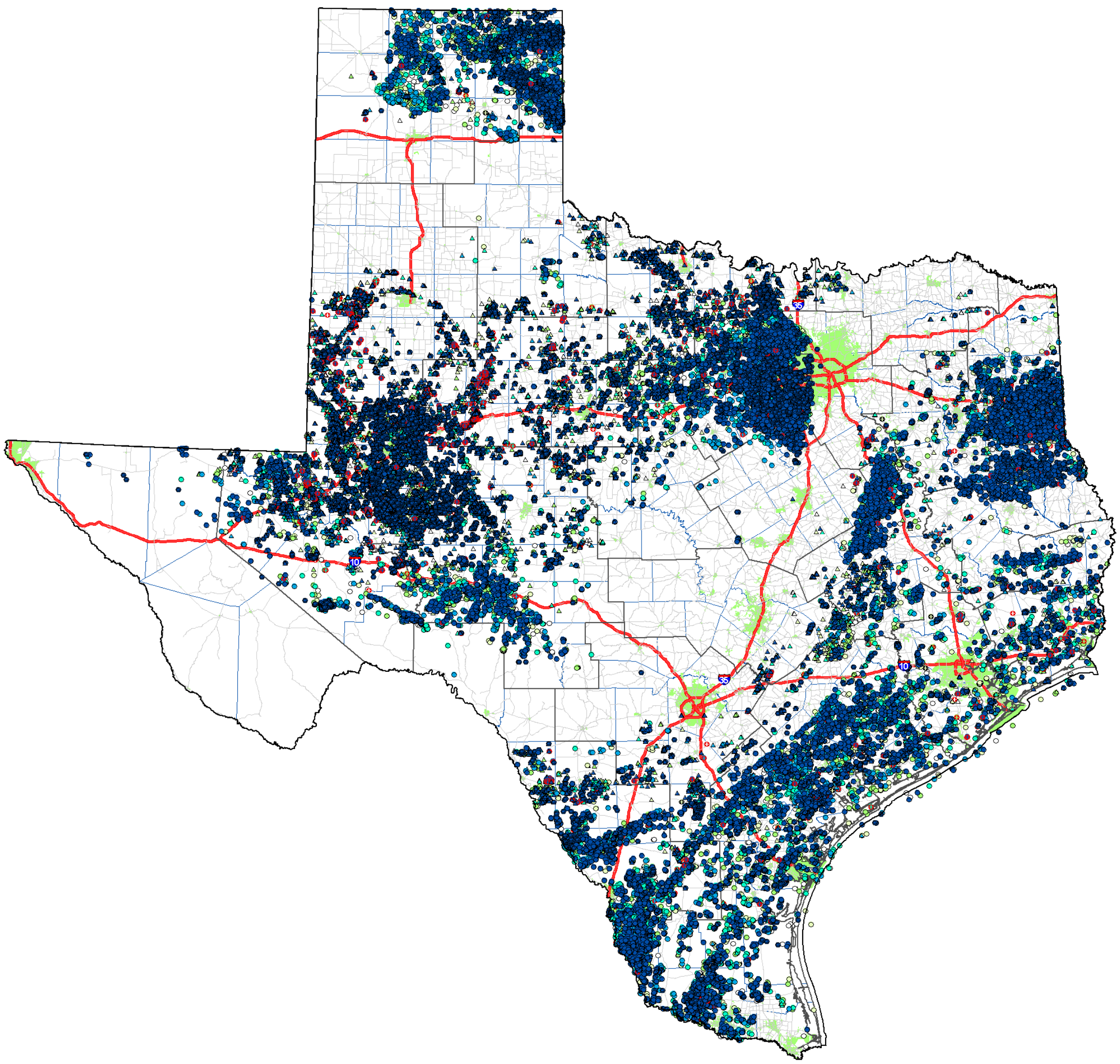


Figure 4. Oil and Gas Permits Issued in Texas from 2002 to 2009.

Developing and managing wells in the context of hydraulic fracturing requires substantial resources. For example, in 2008, TxDOT estimated the following truckloads ranging from 35,000 lb (empty) to 80,000 lb (loaded) in connection with the development of a single gas well in the Barnett Shale area in North Texas (*5*):

- 187 truckloads during pad site preparation, rig mobilization, drilling operations, and rig removal.
- 997 truckloads during hydraulic fracturing operations, assuming 3.7 million gallons (or 88,100 barrels) of water needed for fracking. The amount of water needed could vary substantially depending on location and other factors, with estimates ranging from 2–6 million gallons (*4, 6*).
- 88 truckloads per year for maintenance, most of which involves saltwater loads for gas well injections.
- 997 truckloads every few years for refracking.

Readers should be aware that the number of truckloads to develop gas wells in other areas or situations might vary substantially from these numbers. The reason is that, as documented in the literature, the number of truckloads depends on a variety of factors, including well type and depth, geology, drilling technology, and water need (*7*, *8*, *9*, *10*, *11*).

A typical byproduct of gas well development and operations is saltwater, which needs to be transported and disposed at remote locations. The usual mode of transportation is by truck, although pipelines may be an option if feasible. The maximum amount of saltwater that can be injected into the ground at these facilities is normally regulated by permit, which determines the maximum number of truckloads the facility can accommodate. For example, a facility permitted to inject 25,000 barrels per day could accommodate up to 243 truckloads per day (or 87,360 truckloads per year). In most cases, operators try to minimize costs by routing saltwater to nearby disposal facilities. However, travel distances could increase substantially, e.g., if local ordinances ban the disposal of saltwater within their jurisdiction or if there are routing restrictions (such as load-zoned bridges).

While energy developments contribute to enhance the state's ability to produce energy reliably, many short-term and long-term impacts on the state's transportation infrastructure are not properly documented. Examples include the impact of frequent truckloads on state highway infrastructure such as pavement structures and shoulders, as well as impacts on roadside infrastructure such as driveways and drainage facilities. There is also a lack of documentation on the impact on TxDOT's ability to manage the state highway right-of-way effectively, e.g., with respect to driveway access and utility crossings.

Issues that TxDOT and the Texas Department of Public Safety (TxDPS) identified in the Barnett Shale area include the following (see also Figure 5):

- Night or oversize loads moving short distances without a permit.
- Driving on load-zoned bridges.
- Trucks running over signs.
- Many trucks and trailers registered in Oklahoma.
- Road damage such as rutting, base failures, distress, edge damage, and shoulder damage.
- Inadequate pavement section to withstand loads.
- Bridge hits.
- Traffic safety, increased congestion, and problems at county road intersections.
- Shortage of construction funds to upgrade pavement sections.
- Shortage of maintenance funds to bandage problem areas until it is possible to schedule rehabilitation projects.

In West Texas, TxDOT officials in Lubbock and Abilene have noted a variety of problems in connection with wind farm operations, including the following (*12*, *13*):

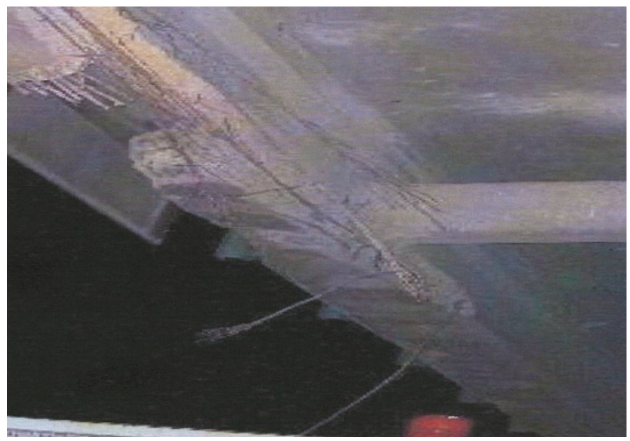
- **Maintenance issues**. Examples include broken edges, severe rutting, pavement failures, edge drop offs, bleeding pavement, and sign issues at intersections. In Lubbock, TxDOT officials noted that haul trucks were responsible for most of the pavement damage. However, the rutting impact due to turbine or crane oversize/overweight (OS/OW) loads was not as significant. (Note: It is important to keep in mind that pavement impact depends not just on the amount of the load but also on the frequency of the load.)

- **Safety issues related to construction haul trucks**. Examples include unsafe work areas due to the operation of the haul trucks and the high speed of loaded and unloaded trucks.

- **Lack of coordination with wind farm developers**. A frequent complaint is that by the time an OS/OW permit application is submitted (or a driveway permit application is submitted), it is already too late for TxDOT to start planning for the development.

(a) Rutting

(b) Bridge hits



(c) Increased congestion

(d) Traffic hazard

Figure 5. Impacts to Transportation Infrastructure in the Barnett Shale Play Area (*5*).

Although TxDOT has begun to document impacts of energy-related activities on transportation infrastructure, a comprehensive document that describes impacts, needs, and strategies is missing. This report describes the work completed to measure the impact of increased level of energy-related activities on the TxDOT right-of-way and infrastructure, as well as develop recommendations to reduce and manage TxDOT's exposure and risk resulting from those activities. The report is organized as follows:

- Chapter 1 is this introductory chapter.
- Chapter 2 discusses the collection and development of relevant datasets.
- Chapter 3 provides a summary of field visits.
- Chapter 4 evaluates pavement impacts.
- Chapter 5 discusses roadside impacts.
- Chapter 6 discusses operational and safety impacts.
- Chapter 7 discusses economic impacts.
- Chapter 8 describes strategies and recommendations for implementation.
- Chapter 9 includes a set of conclusions.
- Appendix A lists remaining pavement life analysis results.
- Appendix B provides a summary of crash data.

At TxDOT's request, this research did not address impacts due to OS/OW loads because this was the subject matter of a separate research project (0-6404). However, as a side note, the number of OS/OW permits in Texas is quite significant. For example, according to the Motor Carrier Division, TxDOT issued over 444,000 OS/OW permits in fiscal year 2004 (FY04). The number of permits increased to 580,000 in FY08 and then decreased to 527,000 in FY09. In FY11, the department issued more than 590,000 OS/OW permits (*14*). While some permits are associated with loads in excess of 200,000 lb of gross weight, many permitted loads are in the 100,000 to 200,000-lb range. For example, in FY09, the 75th percentile for gross weight was 107,000 lb (i.e., 75 percent of permits involved trucks carrying 107,000 lb of gross weight or less). A significant number of OS/OW permits are energy-related, judging from the frequency of keywords such as "generator," "rig," or similar in the permit description information.

The state handles a wide range of OS/OW permit types, depending on factors such as gross vehicle weight (GVW), dimensions, and duration. The Transportation Code (*15*) and the Texas Administrative Code (*16*) establish and regulate maximum legal sizes and weights beyond which a load is considered an "overdimension" load (i.e., overwidth, overheight, overlength, or overweight). Note: The Motor Carrier Division and the OS/OW program responsibilities will move from TxDOT to the Texas Department of Motor Vehicles by January 1, 2012.

TxDOT North East Texas (NETx) district engineers established a NETx Texas Maintenance and Operations Group and charged it with the identification of better ways to permit and route OS/OW loads, hoping to reduce the number of hours used to evaluate routes and minimize damage to the transportation system (*17*). Recommendations from this group included the following areas:

- Strategies to reduce seal coat damage, e.g., by maintaining the five-week minimum timeframe before allowing super heavy loads on a new seal.
- Strategies to improve division-district communications regarding OS/OW routes.
- Strategies to improve route options for OS/OW loads by maintaining preferred corridors to keep these large loads off smaller, less suitable rural loads.

CHAPTER 2. DATA COLLECTION AND DATASET DEVELOPMENT

INTRODUCTION

This chapter documents the process followed to obtain and assemble datasets needed to develop an understanding of energy-sector activities in Texas. The data collection effort included energy and transportation datasets.

ENERGY-RELATED DATASETS

Data Sources

The researchers reviewed current and anticipated energy-related developments that might have an impact on TxDOT facilities and/or business processes. The review also covered additional documentation required to properly characterize energy developments in the state. The data collection effort included four categories of energy-related datasets, as follows:

- Non-renewable energy datasets (Table 1).
- Renewable energy datasets (Table 2).
- Energy use datasets (Table 3).
- Geology-related datasets (Table 4).

Table 1 through Table 4 provide information about the datasets under each category, including a description of the datasets, the corresponding sources, the specific data received from those sources, and the datasets the researchers delivered to TxDOT at the conclusion of the research. This chapter provides a high-level summary of the datasets and highlights issues and other information of interest while gathering and assembling the datasets. Product 0-6498-P1, *Energy Developments and the Transportation Infrastructure in Texas: Geodatabase of Energy Developments in Texas*, includes both a digital copy of the datasets and a detailed description of the process followed to gather and assemble the datasets (*18*). Product 0-6498-P1 also provides information and guidance related to the development of queries to extract data for specific purposes.

Geodatabases

The researchers assembled file geodatabases in Esri™ ArcGIS™ 10.0 format to document the location and basic attribute information associated with energy developments in the state. The organization of the geodatabases followed the four categories described above (i.e., non-renewable energy, renewable energy, energy use, and geology related). Figure 6 shows a view of the geodatabase structure in ArcCatalog™. For illustration purposes, Figure 6 also shows a partial list of feature classes in the oil and gas permit subcategory that show oil and gas drills completed in individual years.

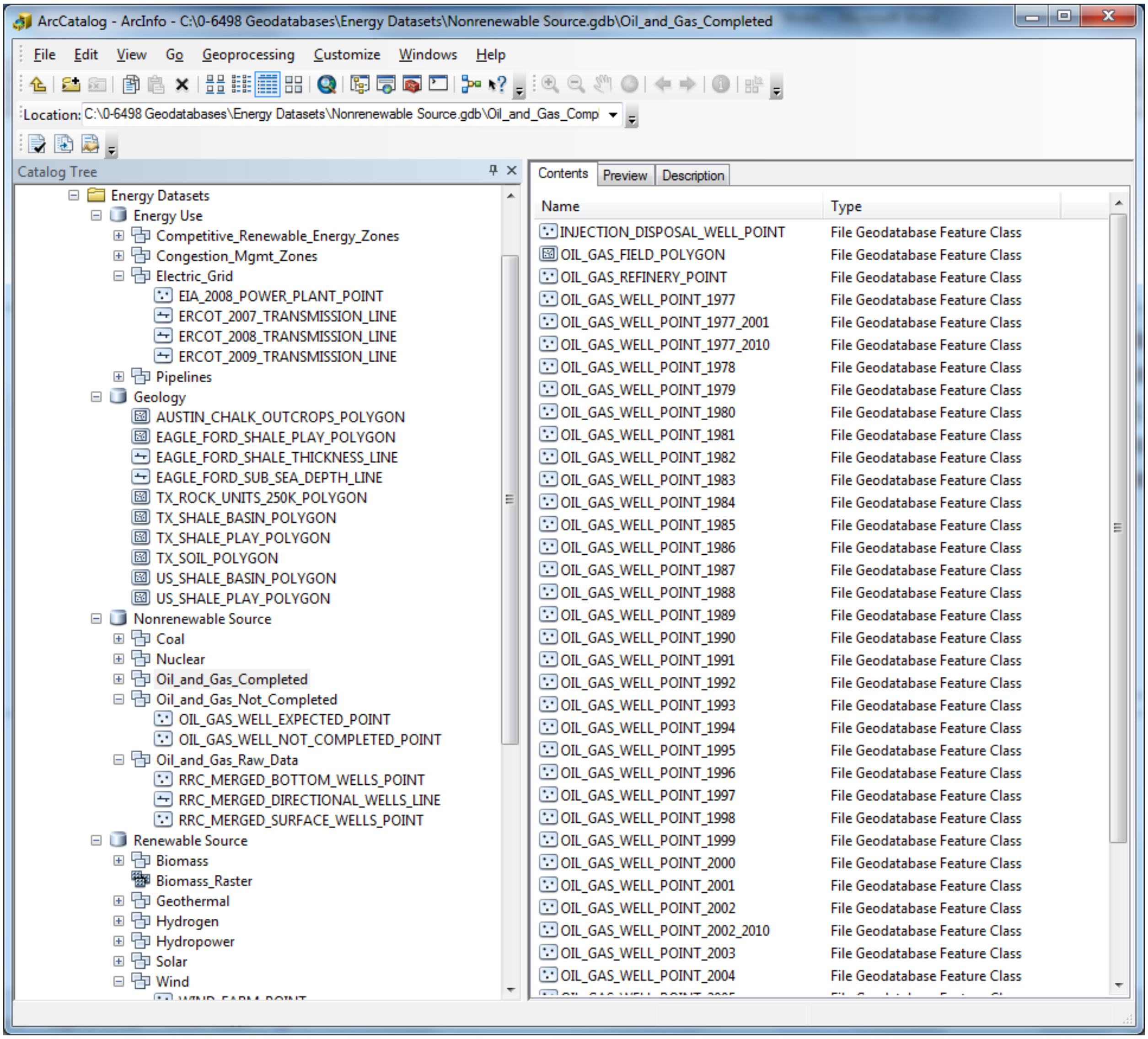


Figure 6. Energy Geodatabases.

The researchers also prepared metadata in ArcGIS 10.0 format to assist with the documentation of the geodatabases. As described in the Product 0-6498-P1 documentation in more detail, the metadata used previous metadata elements that were associated with the data received from the various sources (if available), and enhanced this information to describe the data processing completed as part of the research.

Table 1. Non-Renewable Energy Datasets.

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
Oil and Natural Gas Producing Fields	OIL_GAS_FIELD_POLYGON	The OIL_GAS_FIELD_POLYGON feature class depicts the location and attributes of oil and gas reservoirs in Texas.	National Carbon Sequestration Database and Geographic Information System (NATCARB), National Energy Technology Laboratory (NETL).	NATCARB OilGas (v1103) shapefile.	File geodatabase feature classes, metadata.
Oil and Natural Gas Producing Wells and Drilling Permits by Year	OIL_GAS_WELL_XXXX_POINT, where XXXX is any year from 1977 to 2010	The OIL_GAS_WELL_XXXX_POINT feature class depicts the location and attributes of oil and gas wells in Texas with leases that start between 1977 and 2010.	Railroad Commission of Texas (RRC).	Esri shapefiles providing the location and associated attributes of oil, gas, and disposal wells at the surface, the bottom, and the directional lines connecting the two. Database of well drilling permits and associated attributes from 1977 to May 2011. Manuals and data dictionaries of the drilling permit database and the geospatial well datasets.	File geodatabase feature classes, metadata.
Oil and Natural Gas Refinery Plants	OIL_GAS_REFINERY_POINT	The OIL_GAS_REFINERY_POINT feature class depicts the location and attributes of oil refineries and gas processing plants in Texas as of 2008.	NATCARB, National Energy Technology Laboratory.	NATCARB Sources (v1103) shapefile.	File geodatabase feature class, metadata.
Coal Mines	COAL_MINE_POINT	The COAL_MINE_POINT feature class depicts active coal mines in Texas and their basic information.	RRC, SourceWatch.	Paper map and attributes of Texas-permitted coal mines provided by RRC. Coal mine data, coordinates, and Google Map link provided by SourceWatch.	Populated file geodatabase feature class, metadata.
Power Plants	NUCLEAR_POWER_PLANT_POINT	The NUCLEAR_POWER_PLANT_POINT feature class depicts the location and basic operational attributes of nuclear power plants in Texas.	Texas Comptroller of Public Accounts, Energy Information Administration (EIA), and Wikipedia.	Nuclear power plant locations, names, profiles, and capacities.	File geodatabase feature class, metadata.
Nuclear Waste Storage and Disposal Sites	RADIOACTIVE_WASTE_SITE_POINT	The RADIOACTIVE_WASTE_SITE_POINT feature class identifies the location of radioactive waste sites in Texas.	Texas Commission on Environmental Quality (TCEQ).	Radioactive waste sites shapefile, metadata.	Populated file geodatabase feature class, metadata.
Uranium Mines	URANIUM_MINE_POINT	The URANIUM_MINE_POINT feature class depicts the location and attributes for active, closed, or pending uranium mines listed by TCEQ.	Alliance of Texans for Uranium Research and Action (ALTURA) and TCEQ.	Google Earth map of Texas uranium mines.	Populated file geodatabase feature classes, metadata.

Table 2. Renewable Energy Datasets.

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
Biodiesel Plants	BIODIESEL_PLANT_POINT	The BIODIESEL_PLANT_POINT feature class depicts the location and attributes of biodiesel plants in Texas.	National Biodiesel Board (NBB).	Tabular information including addresses and basic characteristics of current biodiesel plants in Texas.	File geodatabase feature classes, metadata.
EPA Landfill Gas Energy Projects	EPA_LANDFILL_GAS_ENERGY_ PROJECT_POINT	The EPA_GAS_LANDFILL_POINT feature class depicts major operational, under-construction, and candidate landfill gas energy projects in Texas.	Landfill Methane Outreach Program, Environmental Protection Agency (EPA), and TCEQ.	Tabular list of major landfill gas projects in Texas.	File geodatabase feature class, metadata.
Ethanol Refinery Plants	ETHANOL_REFINERY_POINT	The ETHANOL_REFINERY_POINT feature class depicts the location and attributes of ethanol refinery plants in Texas.	State Energy Conservation Office (SECO) and NATCARB, National Energy Technology Laboratory.	NATCARB Sources (v1103) shapefile.	File geodatabase feature class, metadata.
Biomass Areas	BIOMASS_POTENTIAL_POLYGON	The BIOMASS_POTENTIAL_POLYGON feature class depicts the biomass resource potential in Texas.	National Energy Technology Laboratory.	Shapefile and metadata of biomass resource potential.	File geodatabase feature class, metadata.
Tree Canopy Biomass Potential	BIOMASS_TREE_CANOPY_RASTER	The BIOMASS_TREE_CANOPY_RASTER catalog shows the Texas portion of the National Land Cover Database (NLCD) 2001 Percent Tree Canopy layer. The size of each cell is 30 meters (approximately 100 ft) and the value of each cell represents the percentage of area covered by tree canopy.	Multi-Resolution Land Characteristics (MRLC) Consortium, U.S. Geological Survey (USGS).	Raster catalog of the percentage of tree canopy coverage.	File geodatabase raster catalog, metadata.
Geothermal Exploration Wells	GEOTHERMAL_WELL_POINT	The GEOTHERMAL_WELL_POINT feature class contains wells drilled in Texas for geothermal exploration from 1960 to 2008.	Geothermal Laboratory, Southern Methodist University (SMU).	Excel worksheet containing attribute and coordinate values for geothermal exploration wells.	File geodatabase feature class, metadata.
Geothermal Energy Production Regions	GEOTHERMAL_POTENTIAL_ POLYGON	The GEOTHERMAL_POTENTIAL_POLYGON feature class is composed of areas of common geothermal temperature indicating geothermal energy potential.	Geothermal Laboratory, SMU.	Shapefiles of common geothermal temperature in Texas.	File geodatabase feature class, metadata.
Hydrogen Areas	HYDROGEN_POTENTIAL_POLYGON	The HYDROGEN_POTENTIAL_POLYGON feature class contains the potential for producing hydrogen from key renewable resources (onshore wind, solar photovoltaic, and biomass) by county for Texas.	National Renewable Energy Laboratory.	Shapefile of potential hydrogen production resources by county.	File geodatabase feature class, metadata.

Table 2. Renewable Energy Datasets (Continued).

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
Hydroelectric Dams	HYDROELECTRIC_DAM_POINT	The HYDROELECTRIC_DAM_POINT feature class contains the location and attributes of dams with hydroelectric power plants in Texas.	Idaho National Laboratory (INL).	Portable document format (PDF) files of hydroelectric dam locations and related attributes in Texas.	File geodatabase feature class, metadata.
Solar Power Areas	SOLAR_POTENTIAL_POLYGON	The SOLAR_POTENTIAL_POLYGON feature class contains monthly and annual average solar resource potential in Texas.	National Renewable Energy Laboratory.	Surface cell shapefile of solar resource potentials.	File geodatabase feature class, metadata.
Wind Farms	WIND_FARM_POINT	The WIND_FARM_POINT feature class depicts the location and attributes of current wind power farms in Texas.	Alternative Energy Institute (AEI), West Texas A&M University.	A Microsoft® Excel® spreadsheet containing latitude/longitude coordinates of the wind farms and another spreadsheet containing a list of wind farms in Texas with their basic attribute information.	File geodatabase feature class, metadata.
Wind Power Potential	WIND_POWER_POTENTIAL_RASTER	The WIND_POWER_POTENTIAL_RASTER catalog depicts estimated wind power potential at 50 meters (164 ft) above ground level in Texas.	AEI, West Texas A&M University.	Raster catalog of wind power potential in Texas.	File geodatabase raster catalog, metadata.

Table 3. Energy Use Datasets.

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
EIA Electric Power Plants	EIA_EPOWER_PLANT_POINT	The EIA_EPOWER_PLANT_POINT feature class depicts the location of working electric power plants in Texas as of December 31, 2008, according to the Energy Information Administration.	NATCARB, National Energy Technology Laboratory.	2008 Form EIA-860 Annual Electric Generator Report Excel spreadsheets, NATCARB Sources (v1101) file geodatabase feature class.	File geodatabase feature class, metadata.
Electric Reliability Council of Texas (ERCOT) Electric Transmission Grid	ERCOT_2007_TRANSMISSION_LINE, ERCOT_2008_TRANSMISSION_LINE, and ERCOT_2009_TRANSMISSION_LINE	These feature classes depicts the general location of the electric transmission grid in Texas.	ERCOT.	2007–2009 ERCOT electric transmission grid in AutoCAD® format. The 2010 ERCOT transmission grid file in AutoCAD format was not available.	File geodatabase feature classes, metadata.
ERCOT Congestion Management Zones	ERCOT_2007_CSC_ZONE_POLYGON, ERCOT_2008_CSC_ZONE_POLYGON, and ERCOT_2009_CSC_ZONE_POLYGON	These feature classes from 2007 to 2009 depict zones in the ERCOT service area where electricity transmission is managed. Congestion management zone (CMZ) boundaries are defined by identifying and balancing the effects of commercially significant constraints.	PUCT, ERCOT.	2007–2009 ERCOT electric transmission grid in AutoCAD format. The 2010 ERCOT transmission grid file in AutoCAD format was not available.	File geodatabase feature classes, metadata.
Public Utility Commission of Texas (PUCT) Competitive Renewable Energy Zones (CREZs)	ERCOT_2007_CREZ_POLYGON, ERCOT_2008_CREZ_POLYGON, and ERCOT_2009_CREZ_POLYGON	These feature classes depict CREZs in Texas from 2007 to 2009.	PUCT, ERCOT.	2007–2009 ERCOT electric transmission grid in AutoCAD format. The 2010 ERCOT transmission grid file in AutoCAD format was not available.	File geodatabase feature classes, metadata.
National Pipeline Mapping System (NPMS) Pipelines	PHMSA_2004_NPMS_PIPE_LINE	The PHMSA_2004_NPMS_PIPE_LINE feature class depicts the location and attributes of major gas transmission pipelines, hazardous liquid transmission pipelines, and liquefied natural gas (LNG) plants under Pipeline and Hazardous Materials Safety Administration (PHMSA) jurisdiction. The feature class is part of the National Pipeline Mapping System.	PHMSA.	Shapefile of natural gas transmission and hazardous liquid pipelines in Texas, metadata text file, and confidentiality agreement.	Empty file geodatabase feature classes, metadata.

Table 4. Geology-Related Datasets.

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
Austin Chalk Outcrop Rock Unit	AUSTIN_CHALK_OUTCROPS_ POLYGON	The AUSTIN_CHALK_OUTCROPS_POLYGON feature class depicts the boundary of the Austin Chalk rock unit in Texas.	USGS.	Personal geodatabase feature class of rock units in Texas, metadata.	File geodatabase feature class, metadata.
Eagle Ford Shale Play Potential	EAGLE_FORD_SHALE_PLAY_ POLYGON	The EAGLE_FORD_SHALE_PLAY_POLYGON feature class depicts the boundaries of the petroleum window within the Eagle Ford Shale Play, which may produce oil, natural gas, and condensate.	EIA.	EIA shale gas play shapefile and Eagle Ford Shale Play map in PDF format.	File geodatabase feature class, metadata.
Eagle Ford Shale Play Depth	EAGLE_FORD_SUB_SEA_DEPTH_ LINE	The EAGLE_FORD_SUB_SEA_DEPTH_LINE feature class depicts the depth to the top of the shale in the Eagle Ford Shale Play region.	EIA.	Eagle Ford Shale Play map in PDF format.	File geodatabase feature class, metadata.
Eagle Ford Shale Play Thickness	EAGLE_FORD_SUB_THICKNESS_ LINE	The EAGLE_FORD_THICKNESS_DEPTH_LINE feature class depicts the thickness of the shale in the Eagle Ford Shale Play region.	EIA.	Eagle Ford Shale Play map in PDF format.	File geodatabase feature class, metadata.
Texas Rock Units	TX_ROCK_UNITS_250K_POLYGON	The TX_ROCK_UNITS_250K_POLYGON feature class depicts the boundaries at a scale of 1:250,000, of a volume of rock of an identifiable origin and age range in Texas that is defined by distinctive, dominant, easy mapped, and recognizable features that characterize it.	USGS.	Personal geodatabase feature class of rock units in Texas, metadata.	File geodatabase feature class, metadata.
Texas Shale Basins	TX_SHALE_BASIN_POLYGON	The TX_SHALE_BASIN_POLYGON feature class depicts sedimentary basins associated with Texas shale plays.	EIA.	Shapefile of shale basins in the United States, metadata.	File geodatabase feature class, metadata.
Texas Shale Plays	TX_SHALE_PLAY_POLYGON	The TX_SHALE_PLAY_POLYGON feature class depicts the general areas for shale plays in the State of Texas as of May 2011.	EIA.	Shapefile of shale plays in the United States, metadata.	File geodatabase feature class, metadata.
Texas Soils	TX_SOIL_POLYGON	The TX_SOIL_POLYGON feature class depicts the boundaries of soil association units in Texas. An association consists of a set of geographic bodies that are segments of the soil mantle covering the land surface.	Natural Resources Conservation Service (NRCS), U.S. Department of Agriculture (USDA).	Shapefile of general soil association unit boundaries, metadata.	File geodatabase feature class, metadata.
United States Shale Basins	US_SHALE_BASIN_POLYGON	The US_SHALE_BASIN_POLYGON feature class depicts sedimentary basins associated with shale plays in the United States.	EIA.	Shapefile of shale basins in the United States, metadata.	File geodatabase feature class, metadata.

Table 4. Geology-Related Datasets (Continued).

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
United States Shale Plays	US_SHALE_PLAY_POLYGON	The US_SHALE_PLAY_POLYGON feature class depicts general areas of shale plays in the United States.	EIA.	Shapefile of shale plays in the United States, metadata.	File geodatabase feature class, metadata.

Data Processing Comments

Challenges that affected the acquisition and processing of the energy datasets included the following:

- **Lack of data, especially in geographic information system (GIS) format**. In many cases, the data were available only in non-geo-referenced tabular format. In other cases, the data contained limited or no locational information. These limitations made data processing time consuming, especially for large datasets. For example, in the case of power plants, it was necessary to piece together information from several agencies because a comprehensive list of power plants in Texas with location information was not available. To create the electric power plants feature class, the researchers grouped all the generators of each power plant using the EIA dataset. Next, the researchers joined NATCARB carbon dioxide stationary sources, which included coordinate values, with the EIA dataset based on name, location, and owner. Several EIA power plant point features were already included in the NATCARB feature class. In many other cases, the researchers located unmatched electric power locations (i.e., power plants with no coordinates) by using other sources such as Google Maps™, Microsoft Bing® Maps, and Wikipedia. For some plants, it was not possible to obtain coordinate values. In these cases, the attribute data provided approximate location at the city or county level.

- **Inconsistent data formats**. In addition to data in tabular format, there were energy-related datasets in formats such as AutoCAD (DWG), Google Earth, and PDF. Some datasets were geo-referenced (e.g., datasets in keyhole markup language [KML] format). However, PDF and DWG files (even if the original datasets that gave origin to files in those formats were geo-referenced) did not provide coordinate data, which made it necessary to apply a geo-referencing procedure. In some cases, the only option available was to make an educated guess as to the coordinate system or projection associated with the data.

- **GIS data with missing attributes**. Several GIS datasets contained adequate spatial data but limited attribute data. For some datasets, it was possible to add attribute data to the corresponding GIS features manually. For large datasets (e.g., the oil and gas well dataset, which contained a large number of records), it was necessary to apply queries and other procedures to append the needed attribute data to the GIS datasets. Determining and assigning control dates to the oil and gas permit data was particularly challenging because, although the information was available, it was necessary to apply a large number of queries and procedures to process the data. The 0-6498-P1 documentation describes those queries and procedures in detail.

- **Incomplete or missing metadata**. Only a limited number of GIS datasets collected contained complete, standardized metadata, e.g., in the case of the national pipeline dataset. If metadata did not exist, the researchers tried to generate as much metadata content as possible, frequently based on limited documentation that was available with the data or gathered from online sources. Some datasets contained limited metadata, such as limited background information, definitions, and lineage information. In these cases, the availability of at least some metadata enabled the researchers to save valuable time during metadata creation/compilation.

- **Confidential or proprietary data**. Due to security and/or proprietary concerns, a number of datasets the researchers acquired were confidential, involved a nondisclosure agreement, or required a payment fee. In these situations, the researchers documented the existence and process associated with those datasets (including the acquisition process), but did not include a copy of the datasets in Product 0-6498-P1.

TRANSPORTATION INFRASTRUCTURE-RELATED DATASETS

Data Sources

The researchers reviewed transportation-related datasets to help characterize the impact of energy developments on the transportation infrastructure. The data collection effort included the following four categories of transportation-related datasets:

- Oversize/overweight routing and enforcement (Table 5).
- Traffic safety.
- Transportation infrastructure (Table 6).
- Transportation planning (Table 7).

Oversize/Overweight Routing and Enforcement Datasets

Oversize/overweight routing and enforcement datasets used during the research include the following:

- Central Permitting System (CPS) permit frequency per roadway segment.
- CPS sample origin-destination routes.
- Existing and unconstrained top CPS routes.
- Commercial vehicle inspection and violation data.
- Weigh stations (not delivered, since this is a TxDOT dataset).

The CPS datasets were sample datasets that were used during the research for demonstration purposes, primarily for overlaying oversize/overweight permit routes on relevant energy datasets (e.g., showing the location of wind farms or permitted oil and gas wells). The CPS datasets were developed as part of TxDOT research project 0-6404. The entire dataset of oversize/overweight permit routes is one of the deliverables of research project 0-6404.

Table 5. Oversize/Overweight Routing and Enforcement Datasets.

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
CPS Permit Frequency per Roadway Segment	PERMIT_RTE_FREQUENCY_04_09	This dataset depicts total permitted trips traversing a specific roadway segment from 2004 to 2009. This dataset was developed as part of TxDOT research project 0-6404.	TxDOT	CPS exported text files from 2004 to 2009.	File geodatabase feature classes, metadata.
CPS Sample Origin-Destination Routes	HOU_ABL_08_09	This dataset depicts permitted trips between the Houston and Abilene Districts in 2008 and 2009. This dataset was developed as part of TxDOT research project 0-6404.	TxDOT	CPS exported text files from 2004 to 2009.	File geodatabase feature classes, metadata.
Existing and Unconstrained Top CPS Routes	OD_Rte_04, OD_Rte_05, OD_Rte_06, OD_Rte_07, OD_Rte_08, OD_Rte_09, Rte_04_Opti, Rte_05_Opti, Rte_06_Opti, Rte_07_Opti, Rte_08_Opti, and Rte_09_Opti	The datasets depict some of most frequently used permitted routes in Texas from 2004 to 2009. The datasets also show alternate unconstrained routes between the origin and destination of these most frequently used routes. The unconstrained routes are shortest paths with no geometric, structural, or operational restrictions on the roadway network. This dataset was developed as part of TxDOT research project 0-6404.	TxDOT	CPS exported text files from 2004 to 2009.	File geodatabase feature classes, metadata.
Commercial Vehicle Inspection and Violation Data	2007InspDB, 2008InspDB, 2009InspDB	The 2007InspDB, through 2009InspDB contains 2007–2009 TxDPS inspections and associated violations.	TxDPS.	2007–2009 TxDPS inspection data in Access format, description of the database, table specifications, and descriptions and brief attribute descriptions.	2007–2009 Access TxDPS inspection databases.

Table 6. Transportation Infrastructure Datasets – Pavement Management Information System (PMIS).

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
PMIS Data	PMIS_2002_LINE, PMIS_2003_LINE, PMIS_2004_LINE, PMIS_2005_LINE, PMIS_2006_LINE, PMIS_2007_LINE, PMIS_2008_LINE, PMIS_2009_LINE, PMIS_2010_LINE, and PMIS_2011_LINE	These datasets represent 2002–2011 Texas roadway segments (nominally 0.5 miles in length) and associated roadway condition attributes included in PMIS.	TxDOT.	For each year, Access database containing non-spatial data (called PMISZXPDATA) and an Esri personal geodatabase of background base map feature sets (called PMISTARHEGEODB), which included feature classes such as state, district, county, city boundaries, soils, lakes, streams, and routes.	File geodatabase feature classes, metadata.

Table 7. Transportation Planning Datasets – Roadway Inventory.

Dataset	Dataset Name	Description	Source	Data Received	Data Provided to TxDOT
Roadway/Highway Inventory Network (RHiNo) Data	RHINO_2002_LINE, RHINO_2003_LINE, RHINO_2004_LINE, RHINO_2005_LINE, RHINO_2006_LINE, RHINO_2007_LINE, and RHINO_2008_LINE	These feature datasets represent the Texas roadway network and associated roadway attributes contained in RHiNo files from 2002 to 2008.	TxDOT.	RHiNo tables and route centerline shapefiles from 2002 to 2009.	File geodatabase feature class, metadata.

Traffic Safety Datasets

Traffic safety datasets used during the research included Crash Record Information System (CRIS) data. The datasets are standard datasets the researchers obtained from TxDOT and used for analysis purposes.

Transportation Infrastructure Datasets

Transportation infrastructure datasets used during the research included the following:

- Maintenance Management Information System (MMIS) data.
- PMIS data.
- PonTex data.
- Sample driveway permit data.
- Utility installation permit data.

All these datasets are TxDOT-owned datasets. With the exception of the PMIS dataset (which was derived from PMIS and is included in Product 0-6498-P1), the datasets are standard datasets the researchers obtained from TxDOT and used for analysis purposes.

Transportation Planning Datasets

Transportation planning datasets used during the research include the following:

- Control section data.
- Reference marker data.
- RHiNo data.
- Route centerline data.
- Weigh-in-motion data.

All these datasets are TxDOT-owned datasets. With the exception of the RHiNo dataset (which was derived from RHiNo files and is included in Product 0-6498-P1), the datasets are standard datasets the researchers obtained from TxDOT and used for analysis purposes.

Data Processing Comments

Route Centerline Datasets

TxDOT datasets were typically in the form of routes and distances from origin (DFO) or a combination of routes, reference markers, and marker displacements. In order to display these datasets in a GIS environment, it was necessary to map the linearly referenced data to a route centerline dataset.

TxDOT datasets spanned multiple years, which made it necessary to use different route centerline datasets. Unfortunately, while mapping CRIS and RHiNo data to these datasets, it became evident that polylineM measures associated with the 2007 and 2008 route datasets were different compared to those from previous years (Figure 7). In general, polylineM measures for 2007 and 2008 were smaller than those for previous years, which caused features and events to be "located" farther along their routes than when using route centerlines from previous years. The reason is that feature and event measures are not updated every year to match the corresponding route centerline dataset.

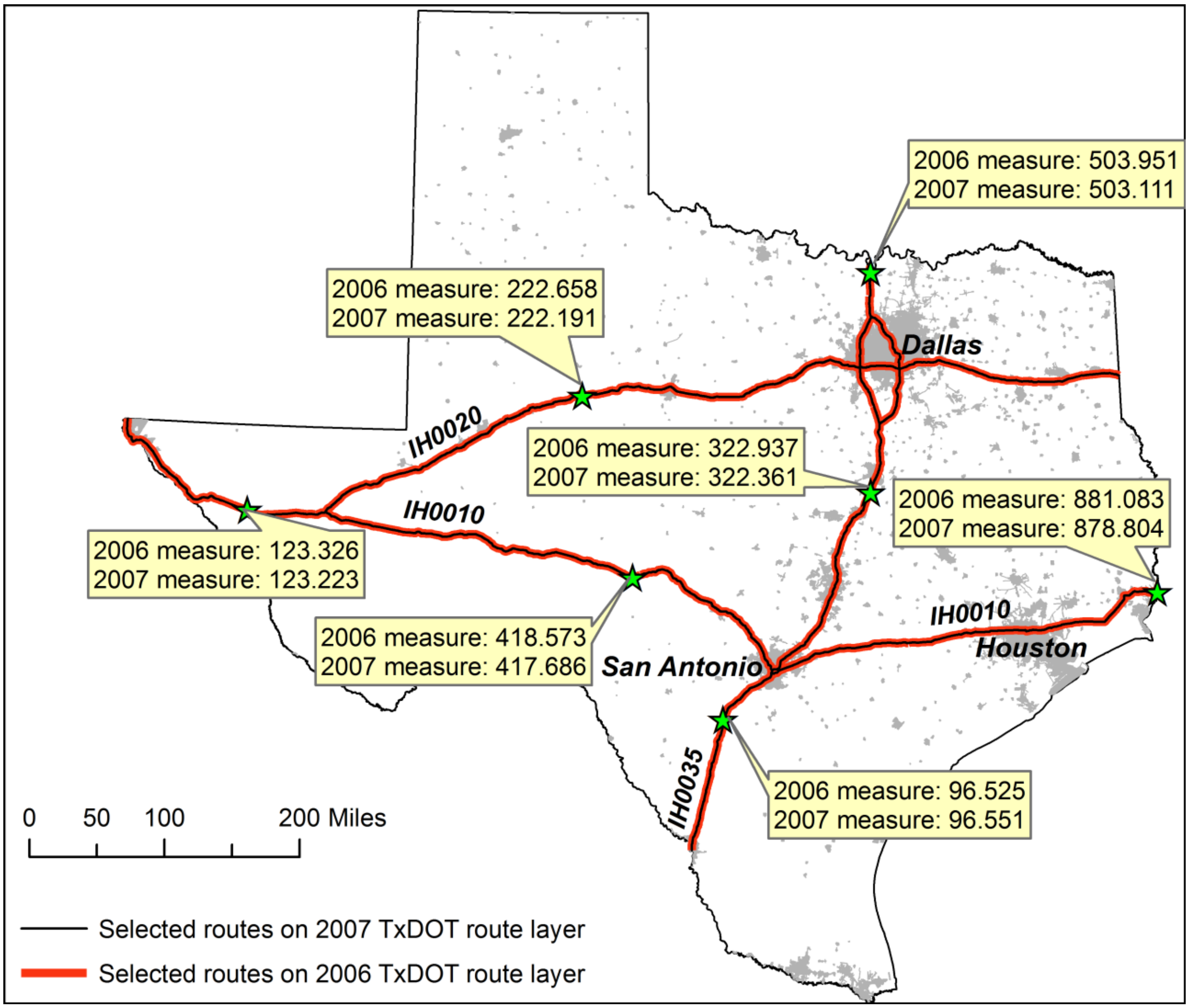


Figure 7. Route Measure Differences between 2006 and 2007 Route Datasets.

In the case of CRIS data, the researchers used DFO data and latitude-longitude coordinate pairs to map crash data. This process worked well as long as the underlying route centerline dataset was 2006 or older (Figure 8a). However, there were noticeable discrepancies between DFO and latitude/longitude data points when the researchers mapped 2007 crash data to the 2007 state transportation network (Figure 8b). A similar problem happened with 2008 data.

(a) 2006 crash data mapped to 2006 route centerline dataset.

(b) 2007 crash data mapped to 2007 route centerline dataset.

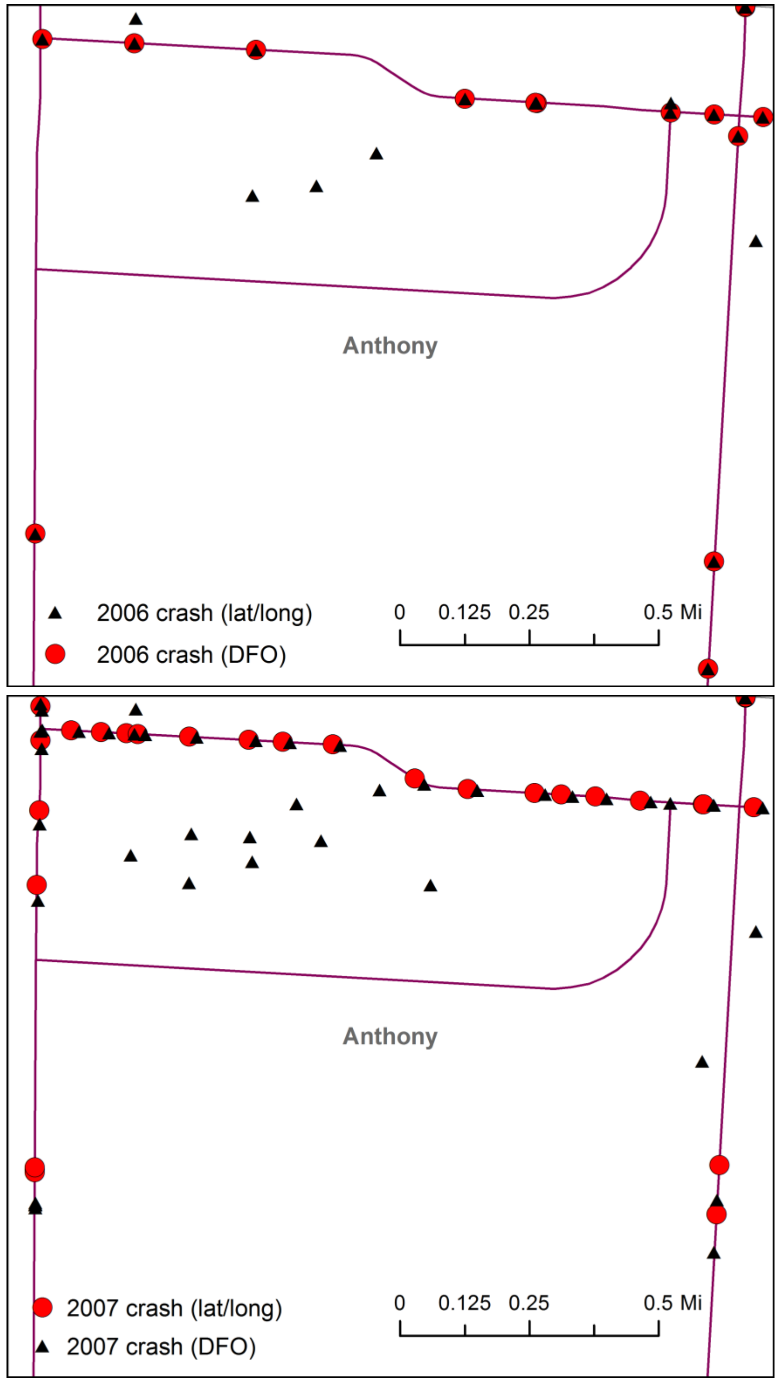


Figure 8. Crash Data Offsets on IH 10, FM 1905, and SH 20 in El Paso District.

In the case of RHiNo data, mapping data to the corresponding route centerline dataset worked as long as the route centerline dataset was 2006 or older (Figure 9). For 2007 and 2008, mapping RHiNo data to the corresponding network version produced RHiNo features that were farther along the route than they should have been.

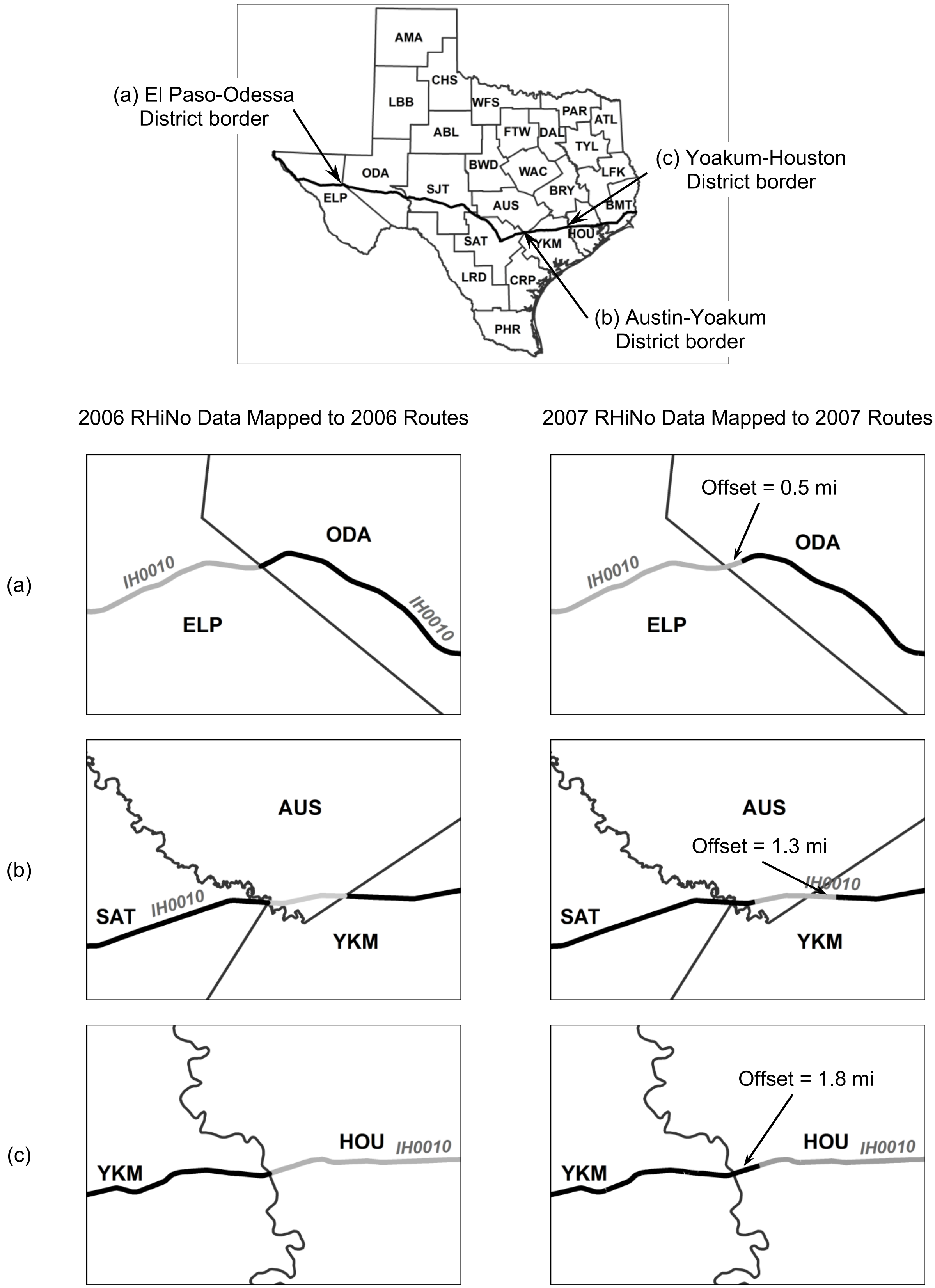


Figure 9. Sample Comparison between Mapped RHiNo Data and Route Centerlines.

PMIS Datasets

The researchers received 2002–2010 PMIS data along with 2002–2009 route centerline datasets that TxDOT uses for mapping purposes within PMIS. A comparison between the route centerline datasets used within PMIS and those described in the previous section revealed that the last year for which the two sets of route centerlines matched was 2006. Further, PMIS centerline datasets for all years matched the 2006 route centerline dataset, with the exception of new segments that were added to the PMIS network each year to reflect new roadway segments that became online (which matched the corresponding segments from the route centerline datasets). Clearly, PMIS centerline datasets are based on the 2006 route centerline datasets, with yearly changes that are obtained from the corresponding route centerline dataset. Because of the need to use a consistent linear reference across all datasets, the researchers decided to map all TxDOT datasets to the latest PMIS route centerline dataset that was available (2009).

PMIS data tables for a year contain pavement scores associated with the same year. However, traffic and maintenance cost data in the tables represent conditions for previous years (two years in the case of traffic data and one year in the case of maintenance cost data). For example, the 2009 PMIS data included 2009 pavement rating scores, 2008 maintenance cost data, and 2007 traffic data.

Crash Datasets

The researchers obtained 2003–2009 crash data from CRIS. The original CRIS data for each year contained a large number of records, including crashes occurred on both on-system and off-system roadways. During the mapping process, the researchers deleted records that did not have valid DFO or street information (Table 8).

Table 8. Number of Crash Records.

Year	Number of Records in Original Datasets	Number of Records in Mapped Data
2003	459,725	221,013
2004	447,037	220,179
2005	463,830	231,737
2006	437,290	221,621
2007	458,289	233,328
2008	439,527	221,337
2009	428,667	217,091

Geodatabases

The researchers assembled file geodatabases in ArcGIS 10.0 format to document the location and basic attribute information associated with transportation datasets. The organization of the geodatabases followed the four categories described above. Figure 10 shows a view of the geodatabase structure in ArcCatalog.

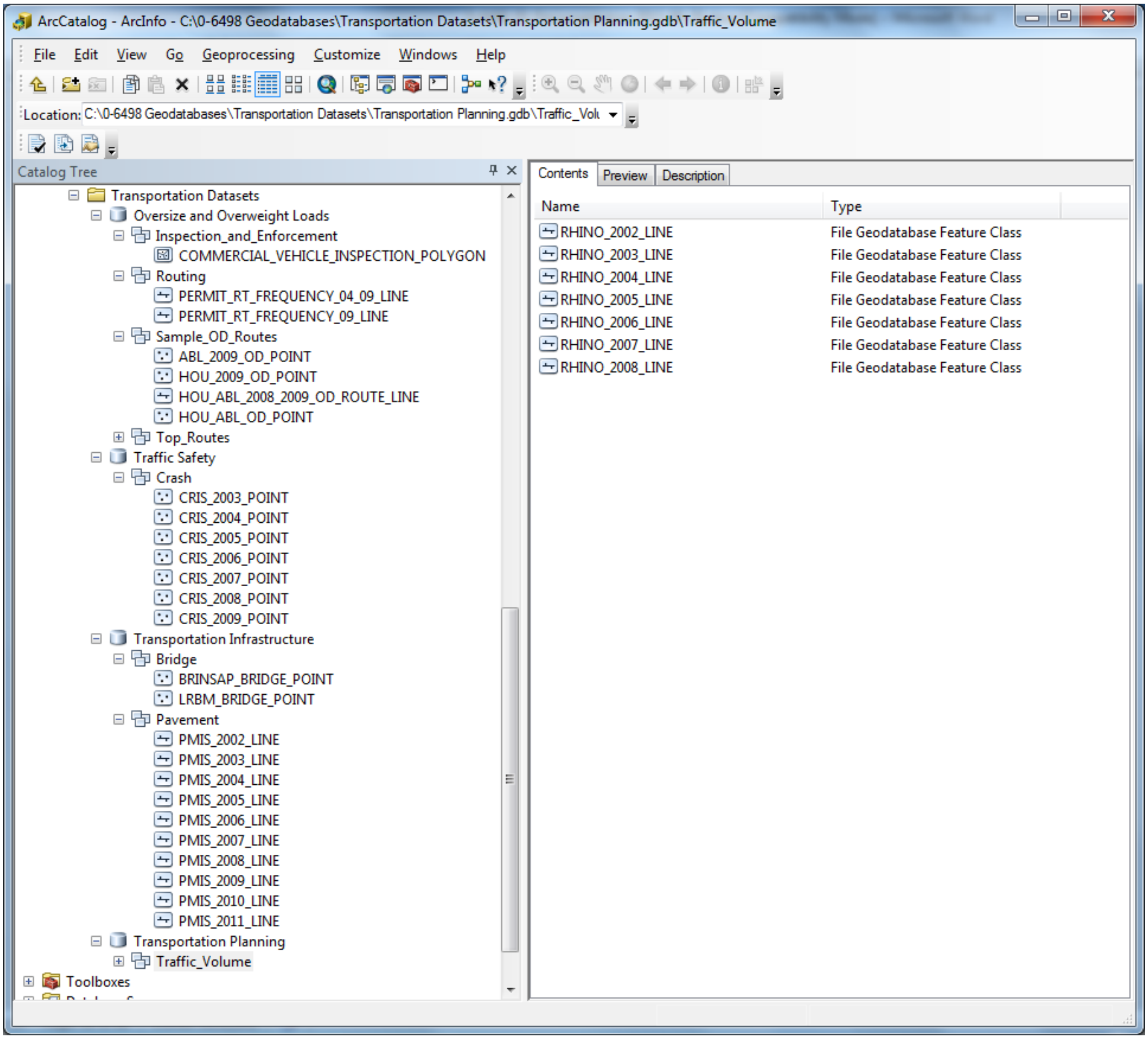


Figure 10. Transportation Geodatabases.

GEODATABASE APPLICATIONS

The researchers used the geodatabases described in the previous sections to generate a wide range of queries, reports, and maps. The potential number of reports and maps that can be generated is nearly endless. Figure 2 and Figure 4 in Chapter 1 are two examples of maps that show the location of energy developments (wind farms and oil and gas wells, respectively). Additional examples included in this section include the following:

- Wind farms, CREZs, and transmission lines in the Lubbock-Abilene region (Figure 11).
- Pipelines and oil and gas wells in South Texas (Figure 12).
- Permitted oil and gas wells in the Fort Worth area (Figure 13).
- Permitted oil and gas wells in South Texas (Figure 14).

- Completed versus non-completed oil and gas wells in the Fort Worth area (Figure 15).
- Completed versus non-completed oil and gas wells in South Texas (Figure 16).

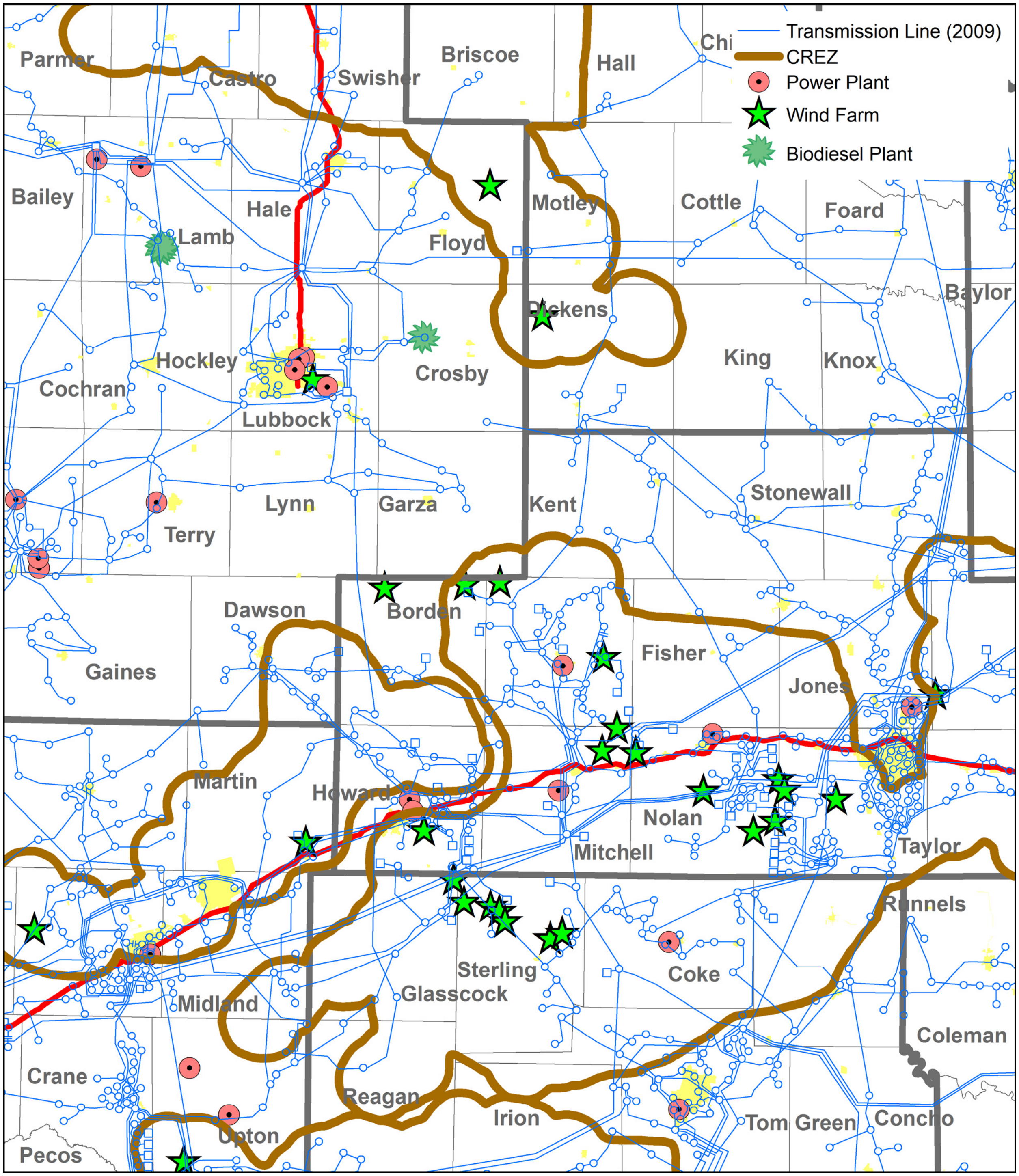


Figure 11. Wind Farms, CREZs, and Transmission Lines in the Lubbock-Abilene Region.

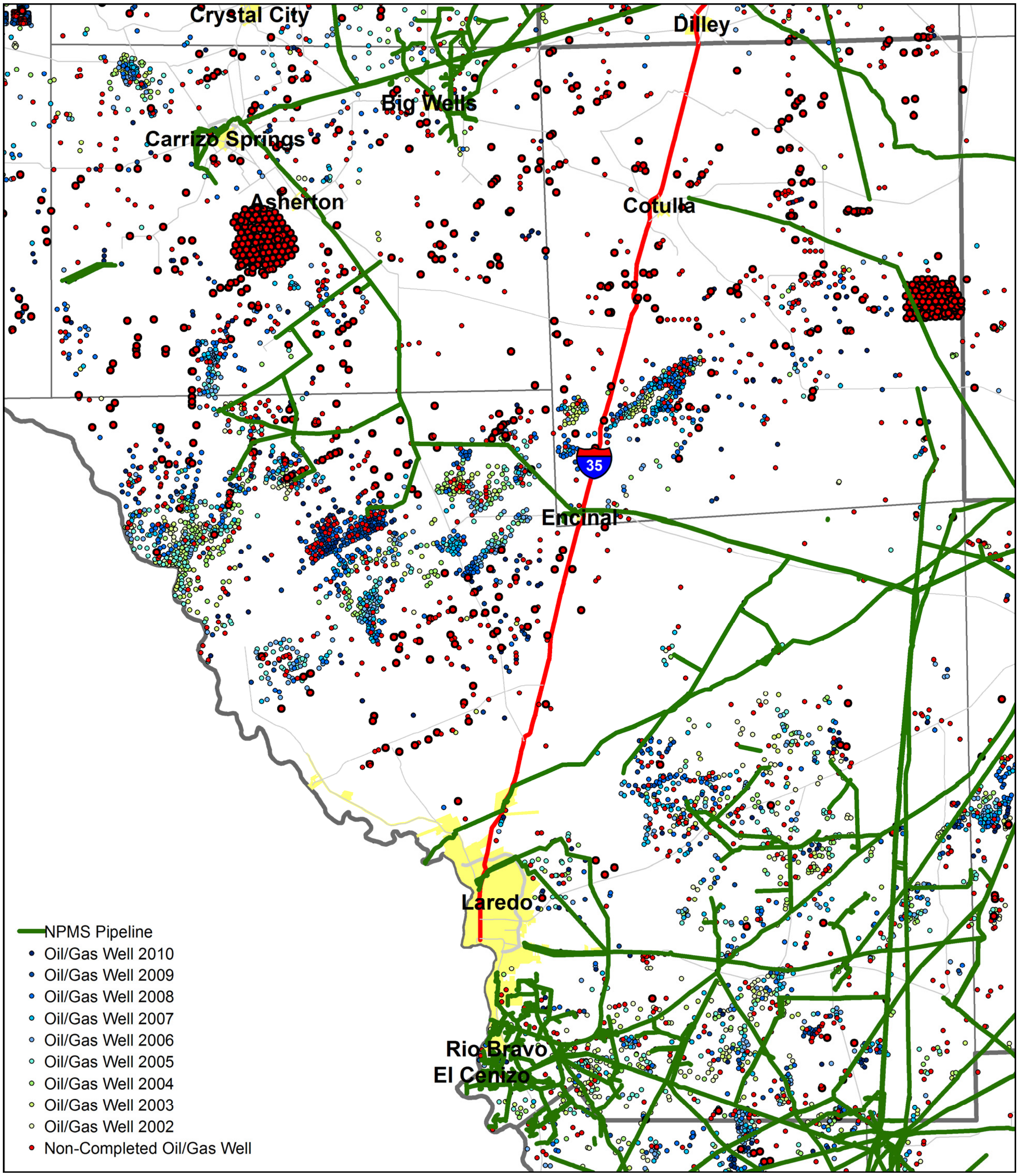
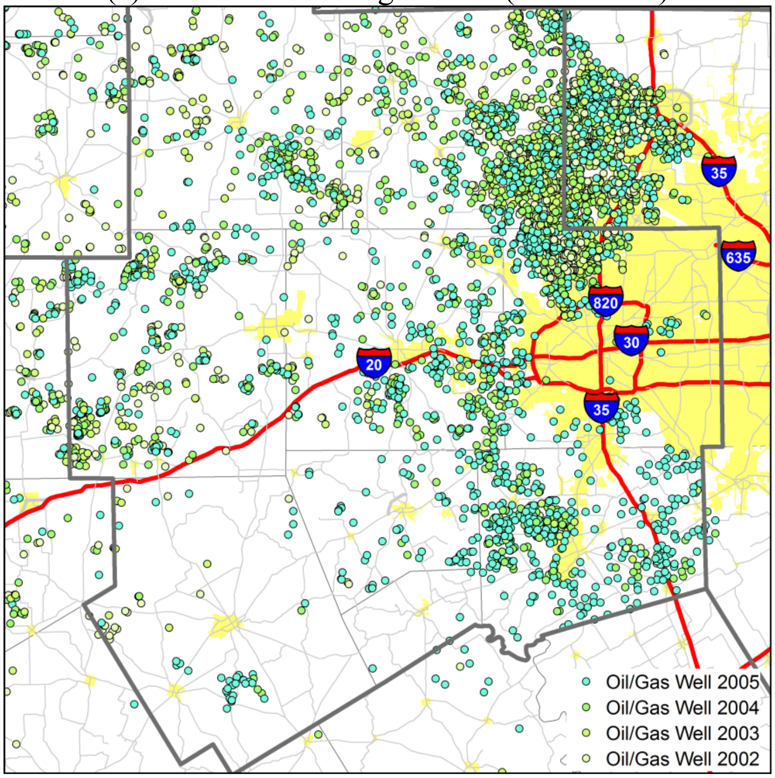


Figure 12. Pipelines and Oil and Gas Wells in South Texas.

(a) Permitted oil and gas wells (2002–2005)



(b) Permitted oil and gas wells (2002–2010)

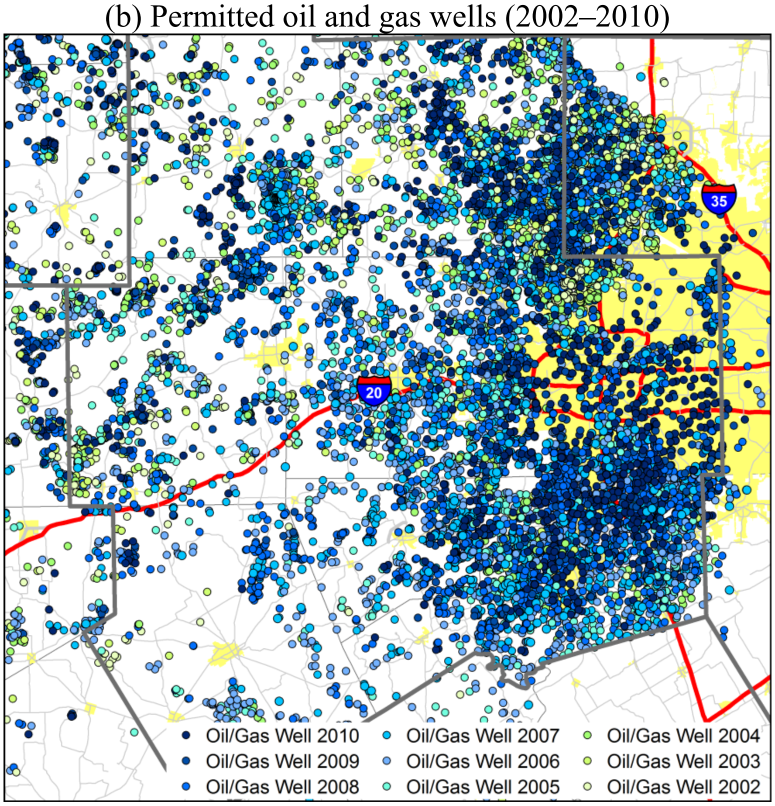
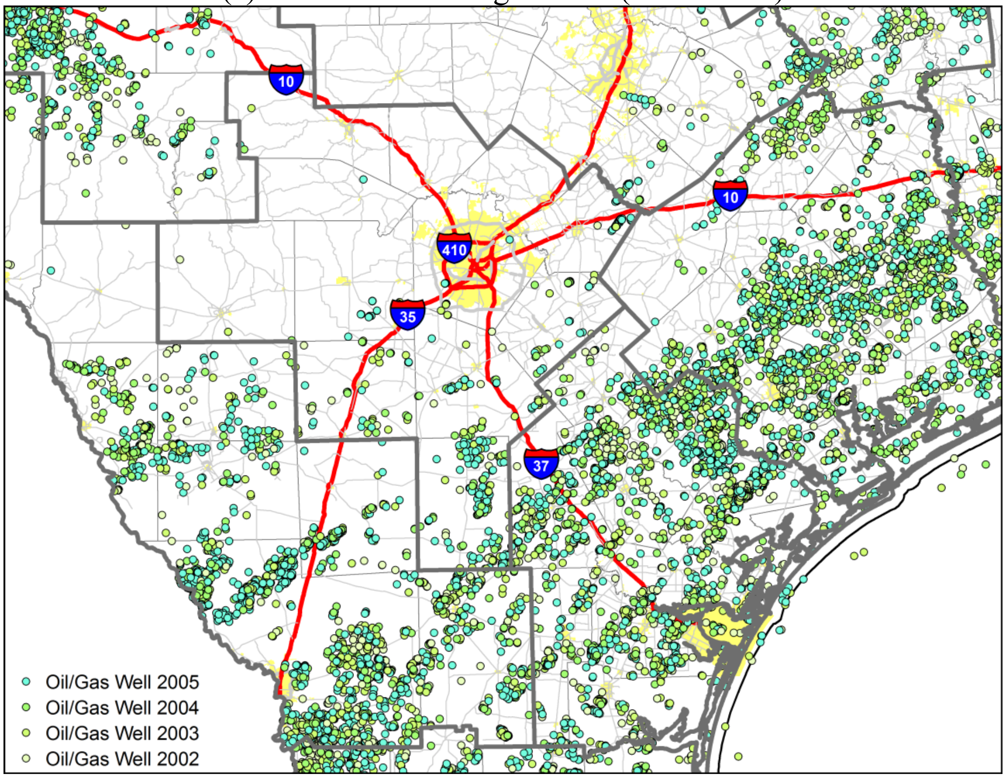


Figure 13. Permitted Oil and Gas Wells in the Fort Worth District Area.

(a) Permitted oil and gas wells (2002–2005)



(b) Permitted oil and gas wells (2002–2010)

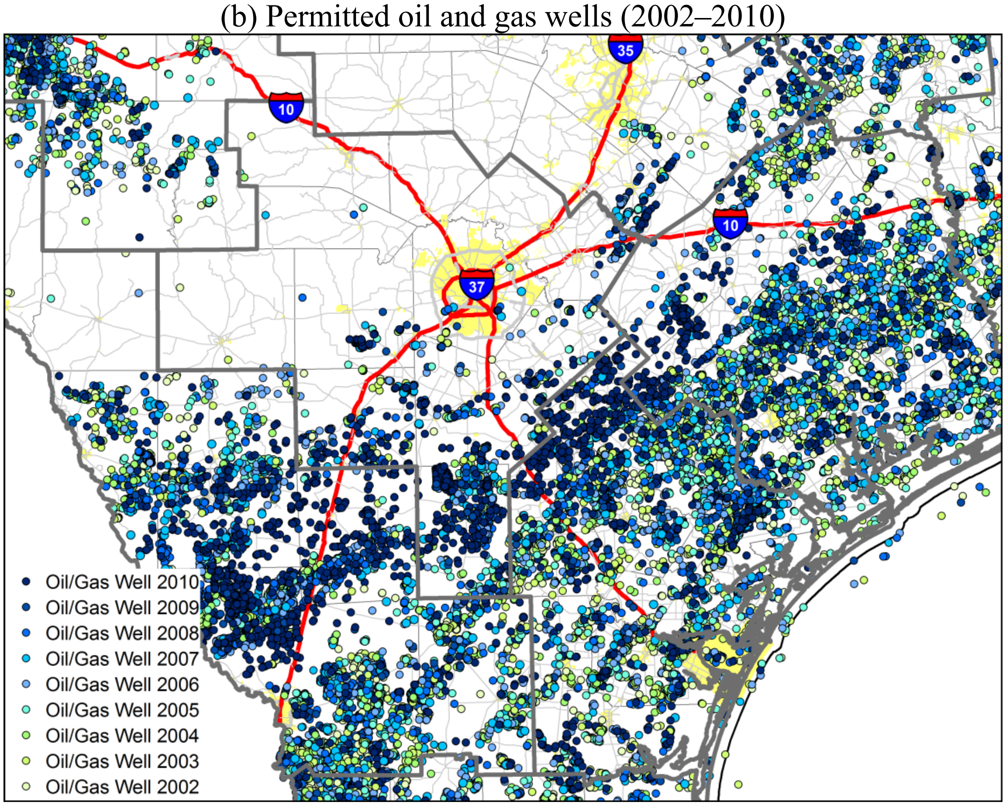
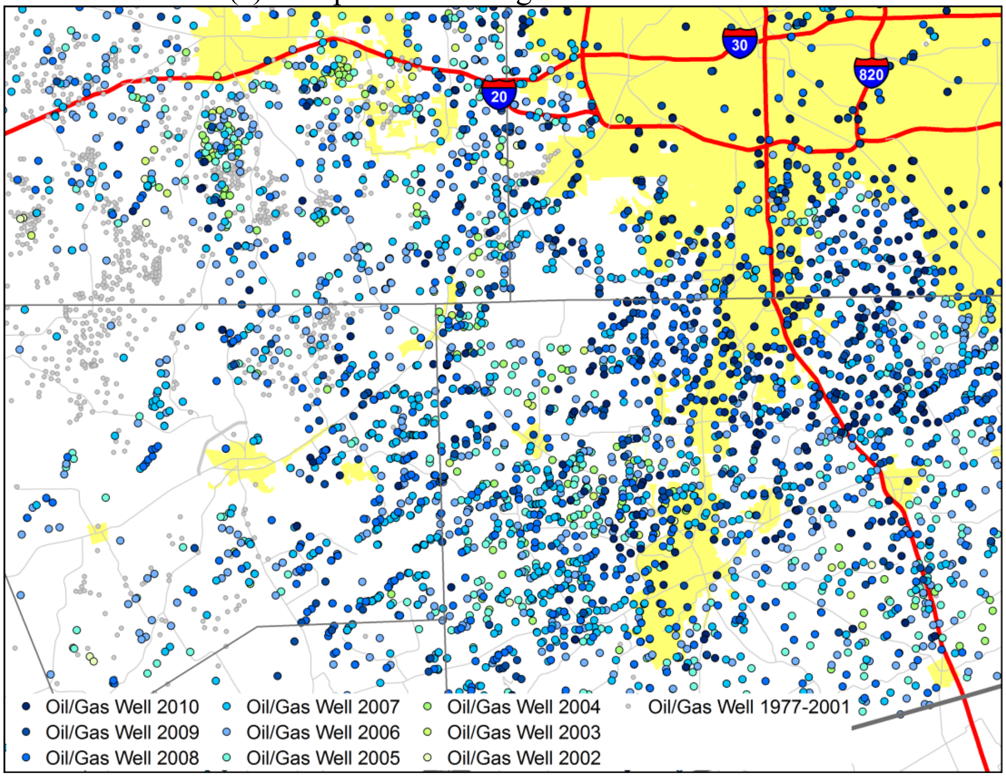


Figure 14. Permitted Oil and Gas Wells in South Texas.

(a) Completed oil and gas wells as of 2010



(b) Non-completed oil and gas wells as of 2010 (dots in red)

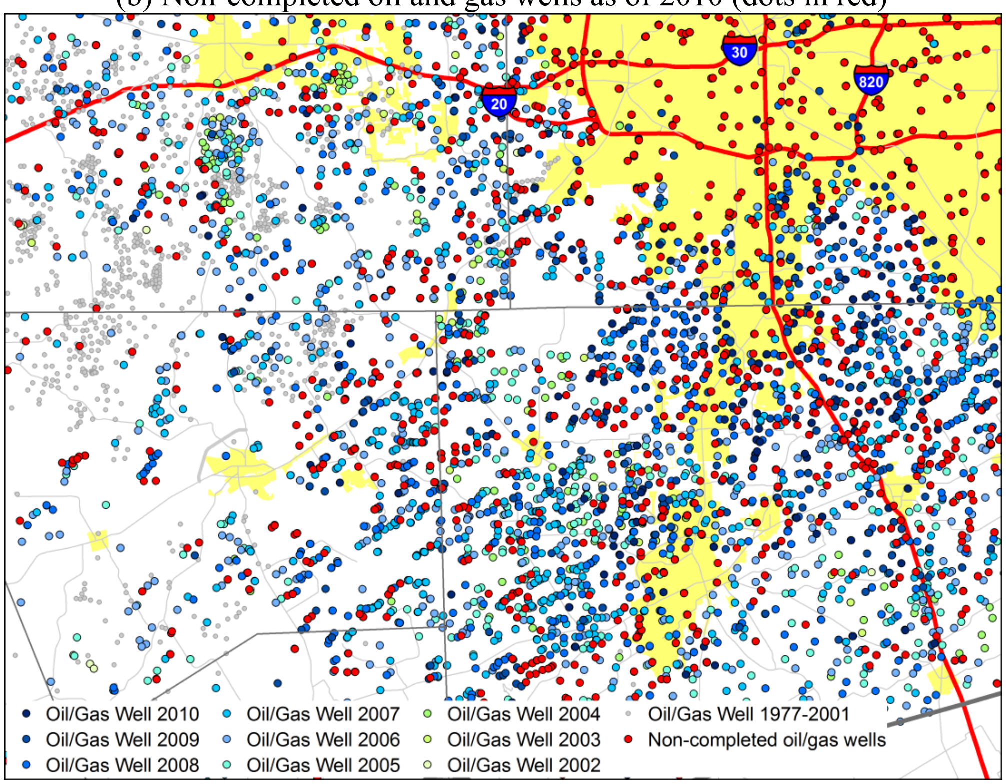
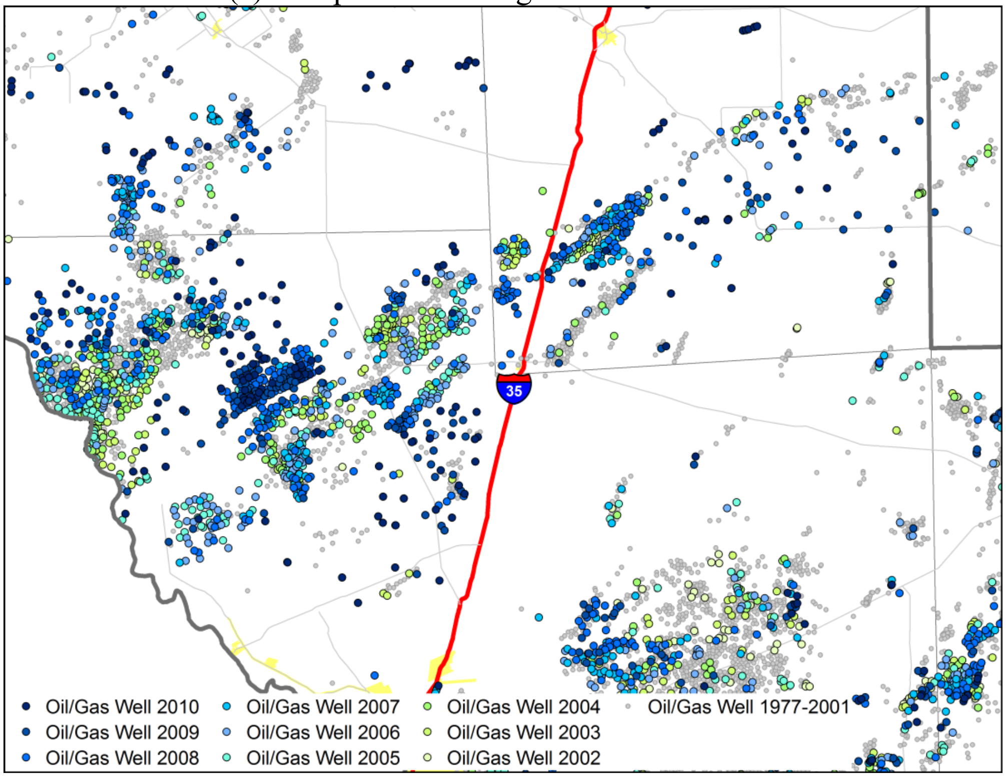


Figure 15. Completed versus Non-Completed Wells as of 2010 (Fort Worth Area).

(a) Completed oil and gas wells as of 2010



(b) Non-completed oil and gas wells as of 2010 (dots in red)

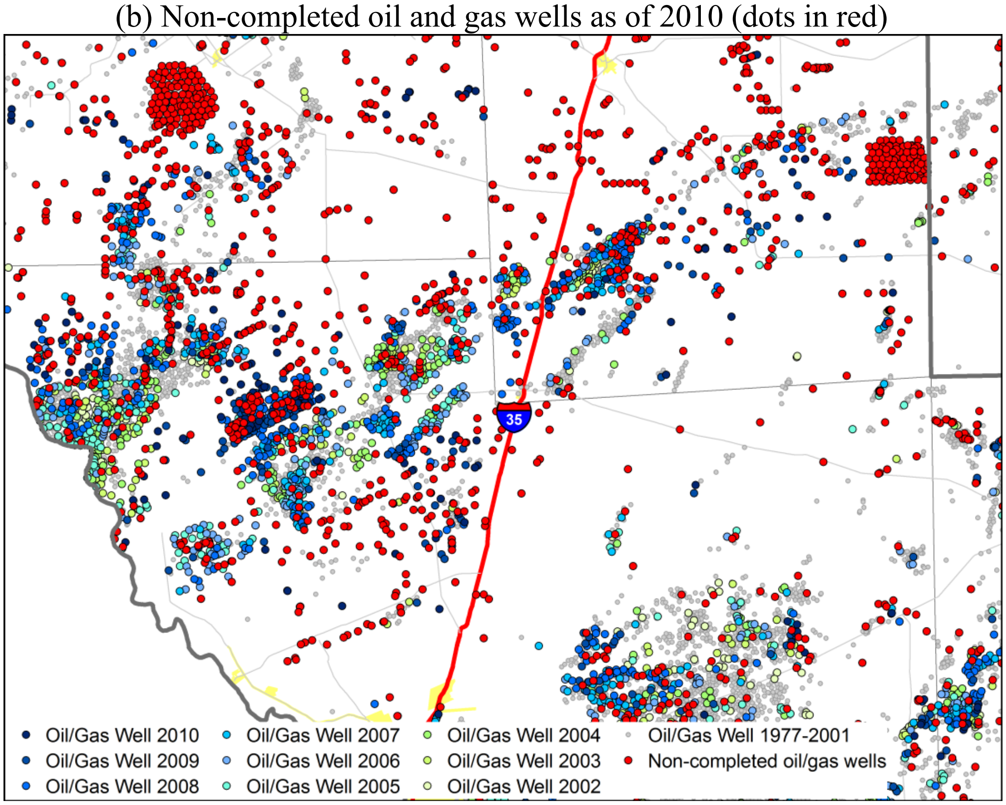


Figure 16. Completed versus Non-Completed Wells as of 2010 (South Texas).

CHAPTER 3. FIELD VISITS

INTRODUCTION

The researchers scheduled field visits to develop a more thorough understanding of potential impacts and issues resulting from energy developments. They visited a sample of corridors and locations at three TxDOT districts in north and northwest Texas: Lubbock, Abilene, and Fort Worth. At each of these districts, the researchers first met with TxDOT officials at the district office and then visited corridors that TxDOT officials identified as being affected significantly by energy developments (Table 9, Figure 17, Figure 18, and Figure 19). In conjunction with the visits, the researchers also collected ground penetrating radar (GPR) and falling weight deflectometer (FWD) data (see Chapter 4). Taking into consideration the increasing level of oil and gas activity in connection with the Eagle Ford Formation in South Texas, the researchers also met with officials from the Laredo, San Antonio, and Yoakum Districts. Given the timing of these visits (toward the end of the research project), it was not possible to schedule individual corridor visits or collect GPR or FWD data.

FIELD OBSERVATIONS

Truck Traffic

Heavy truck traffic was evident on all the corridors used for oil and gas activities. As noted previously, oil and gas developments generate a large number of truckloads both during drilling and during production. By comparison, there was truck traffic on corridors that provide access to wind farms, but only if there was active construction. Construction of wind farms results in a large amount of truck traffic hauling construction materials (e.g., concrete) and wind turbine parts. Ethanol plants require trucks to ship grains, ethanol, and byproducts. Some plants, e.g., the plant located along Farm-to-Market (FM) 2646 in Hockley County (Lubbock District), use railroads to transport ethanol and sometimes byproducts, which reduces the demand for trucks.

Most roadways affected in Lubbock and Abilene were FM roads. By comparison, in Fort Worth, affected roads included a wider range of categories, including FM, State Highway (SH), U.S. Highway (US), and Interstate Highway (IH) frontage roads.

Heavy truck traffic in connection with energy developments does not just happen in the immediate vicinity of the developments. In several cases, TxDOT officials noted a significant amount of truck traffic along highway sections used as shortcuts or that make more sense from a routing perspective. Examples of this situation include SH 16 (Fort Worth District) and the frontage road on IH 35W (Fort Worth). Officials also noted that truck drivers frequently select routes based on other considerations such as wanting to avoid weigh stations, if they observe the presence of law enforcement vehicles or personnel, or if there are road conditions that might make it preferable for drivers to select specific route segments.

Local ordinances play a factor on how energy developments affect the transportation network. For example, in Fort Worth, officials noted that saltwater disposal trucks frequently travel longer distances due to restrictions where saltwater disposal facilities may be placed.

Table 9. Visited Corridors at the Lubbock, Abilene, and Fort Worth Districts.

Highway	Section	County	Activity
Lubbock District			
FM 28	Reference Marker (RM) 180 – RM 202	Floyd, Crosby	Wind farm construction
FM 40	RM 310 – RM 312	Crosby	Oil-related activities
FM 97	RM 324 – RM 344	Floyd	Wind farm construction
FM 179	RM 196 – RM 200	Hale	Gas-related activities
FM 193	RM 336 – RM 338	Crosby	Wind farm construction
FM 378	RM 220 – RM 226	Crosby	Oil-related activities
FM 651	RM 186 – RM 196	Floyd	Wind farm construction
FM 1072	RM 170 – RM 182	Lamb	Wind farm construction
FM 1210	RM 294 – RM 295	Dawson	Wind farm construction
FM 1585	RM 258 – RM 268	Hockley	Oil-related activities (water pumping station)
FM 1760	RM 226 – RM 242	Bailey	Dairy [1]
FM 1842	RM 272 – RM 282	Lamb	Dairy [1]
FM 1958	RM 324 – RM 346	Floyd	Wind farm construction
FM 2479	RM 176 – RM 182	Lamb	Dairy [1]
FM 2646	RM 206 – RM 216	Hockley	Ethanol Plant
Abilene District			
FM 89	FM 126 – US 277	Taylor	Wind farm construction
FM 126	RM 322 – FM 89	Nolan	Wind farm construction
FM 604	IH 20 – SH 351	Shackelford, Callahan	Wind farm construction
FM 1084	RM 268 – US 283	Shackelford	Wind farm construction
FM 1161	US 84 – SH 208	Scurry	Oil/gas-related activities
FM 1899	IH 20 – FM 644	Mitchell	Wind farm construction
Fort Worth District			
FM 52	US 281 – SH 254	Palo Pinto	Oil/gas-related activities
FM 1884	SH 171 – RM 278	Parker	Rock pits
FM 2257	RM 542 – FM 730	Parker	Oil/gas-related activities
FM 2331	SH 171 – US 67	Johnson	Oil/gas-related activities
FM 2738	FM 917 – US 67	Johnson	Oil/gas-related activities
FM 3048	SH 174 – FM 917	Johnson	Oil/gas-related activities
FM 3325	FM 1886 – US 180	Parker	Oil/gas-related activities (compressor plant)
IH 35W Frontage	FM 917 – BI 35V	Johnson	Oil/gas-related activities
IH 35W Frontage	BI 35V – FM 2258	Johnson	Oil/gas-related activities
SH 16	US 180 – SH 108	Palo Pinto	Wind farm construction, oil/gas activities
SH 171	RM 294 – RM 306	Johnson	Distribution center, rock quarries, plant
SH 174	RM 304 – RM 310	Johnson	Oil/gas-related activities

[1] Not energy-related activity. However, district officials highlighted these locations to illustrate the impact resulting from frequent heavy truck traffic on FM roads.

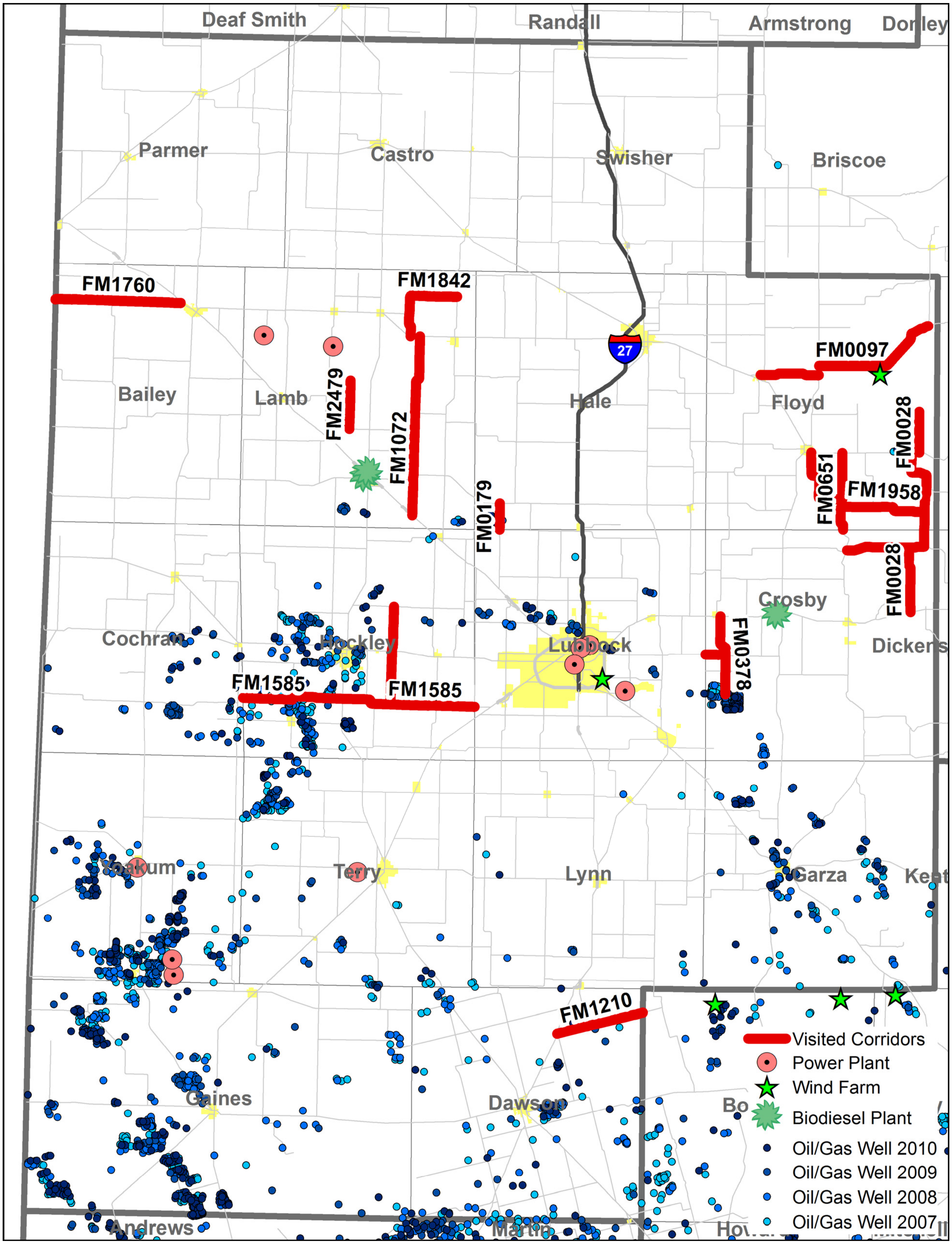


Figure 17. Visited Corridors – Lubbock District.

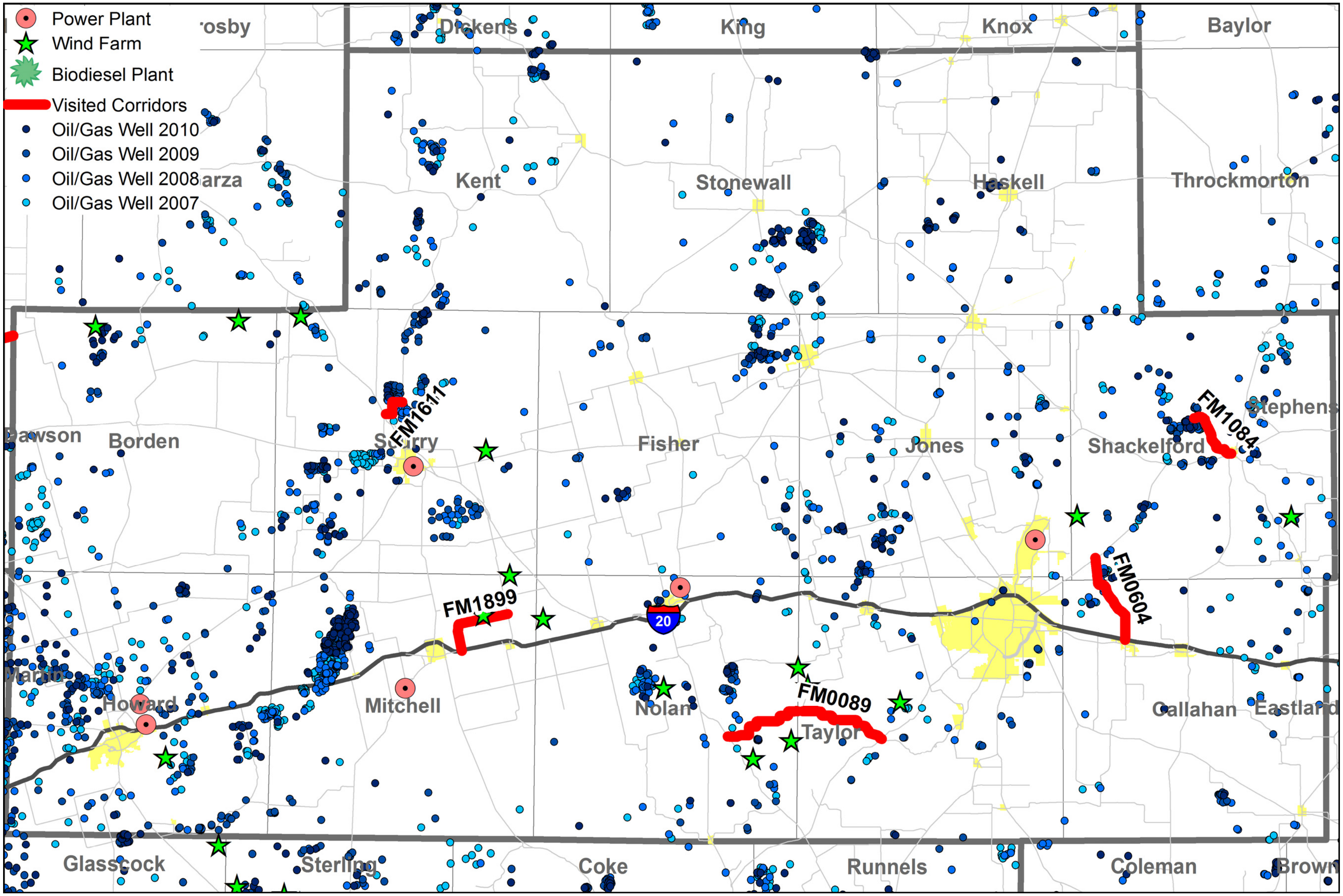


Figure 18. Visited Corridors – Abilene District.

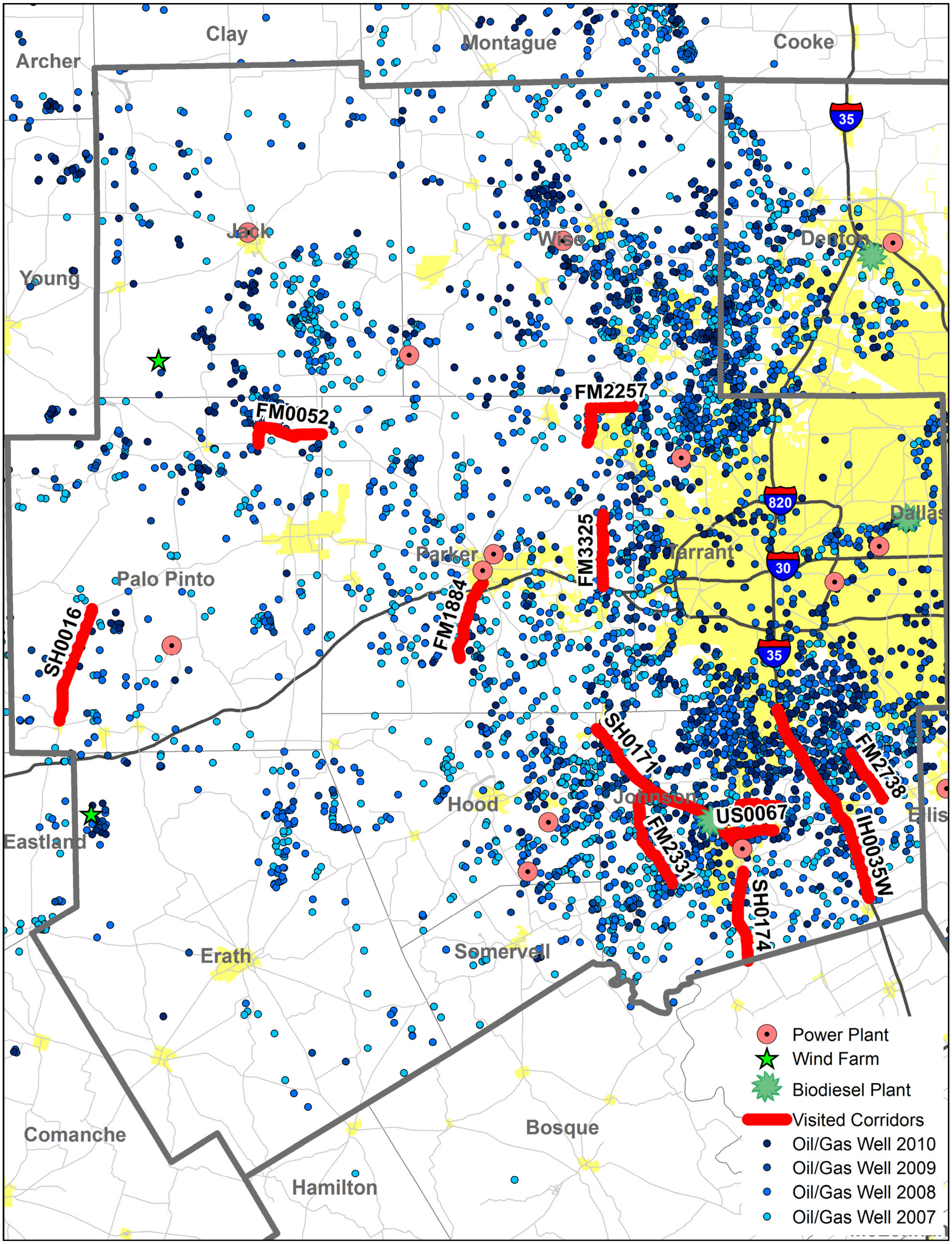


Figure 19. Visited Corridors – Fort Worth District.

Pavement Damage

There was considerable evidence of major damage to pavement structures on all the corridors visited. Examples of common pavement damage were base failure, various types of cracks, bleeding, and worn center and edge lines. Additional damage included pavement ripples and severe localized edge and structural failure at intersections and in close proximity to driveways.

TxDOT officials noted that most pavement damage is due to legal heavy trucks that do not require a permit. Officials also noted that damage is more likely to occur when heavy truck traffic is combined with severe weather conditions. For example, FM 1072 (Lubbock District) sustained significant damage due to wind farm construction trucks driving on icy pavement. Likewise, wind farm construction trucks combined with roadway flooding resulted in damage to a section of FM 28 (Lubbock District).

The impact from permitted OS/OW loads is less of a concern because these loads are less frequent and much more regulated. Nonetheless, overweight permit violations are a concern to districts. Officials indicated that energy-related vehicles sometimes operate in excess of the legal limit without a permit. Violations are more common in areas where there is limited law enforcement, particularly in rural areas. Officials also noted the practice of crossing heavy machinery (e.g., a rig) from one side to the other side of the road, or moving that machinery along short distances along a state road, and the impact of this practice on pavement surfaces if proper protection measures are not used. The issue was particularly troublesome in situations where the machinery was assembled onsite using components that arrived separately by truck (some of which could have been oversized or overweight and required a permit), but then the equipment was not disassembled prior to the crossing or longitudinal movement. This practice is understandable, given the expenses that would be associated with disassembling and subsequently assembling the equipment. The detrimental effect is an increase on the level of risk to TxDOT and damage to the pavement structure, which had not been anticipated and is not being documented.

Roadside Issues

Illegal driveway permits are a concern to districts, although the level of concern varies from district to district. TxDOT inspectors usually identify illegal driveways while driving during the course of routine roadway inspections. In most cases, inspectors attempt to work with the developers to make illegal driveways "legal" by applying for a permit. In some situations, inspectors request developers to reconstruct or relocate the driveways.

Overall, district officials did not express major concerns about utility crossings and longitudinal installations, and indicated the provisions in the Texas Administrative Code (TAC) are adequate to address most situations found in the field. Energy companies, particularly gas companies, prefer dedicated easements on private property, and only resort to the state highway right-of-way when no other alternative locations are possible or viable. The reason is that using the state highway right-of-way involves having to follow stricter regulations and the risk of additional conflicts with other utility installations. Nevertheless, district officials expressed concern about high-voltage transmission lines crossing state highways, particularly during rainy weather, and recommended examining the feasibility of implementing additional safety measures, in particular, those listed in the National Electrical Safety Code (NESC) (*19*).

Safety Issues

The researchers observed a number of safety issues such as mud tracking, illegal turns, and intersections and driveways with poor visibility. In some cases, they noted a combination of issues, e.g., illegal turns even though there was not a sufficient sight distance on either direction. Tire tracks indicating that trucks were driven over safety end treatments were common. In several cases, tire tracks on the pavement clearly indicated illegal left turns, despite signs prohibiting left turns to enter the highway, e.g., from saltwater disposal facilities.

Coordination Issues

Coordination practices between TxDOT, energy developers, and other stakeholders vary wildly. In some cases, there is adequate coordination, but this appears to be the result of individual efforts and goodwill rather than programmatic, systematic coordination efforts. One of the results of the lack of coordination is that TxDOT is not involved early in the energy site development process. In most cases, interaction between energy developers and TxDOT officials start when (a) TxDOT inspectors notice increased traffic or roadside developments (such as driveways), or (b) a developer submits a driveway permit application. Unfortunately, by this point on the energy site development process, driveway and traffic-related planning has concluded and there is little room for modification.

TxDOT officials highlighted that, when approached, some energy developers are forthcoming and willing to provide information that TxDOT needs to cope with the upcoming development. However, other energy developers or contractors are reluctant to cooperate with the department. Several TxDOT officials believe the department's regulatory capabilities to deal with this situation are limited because, in practice, other regulatory agencies need to be involved and may have priority, e.g., in situations dealing with mud tracking and pollution from truck trunks.

Funding Allocation Issues

TxDOT officials highlighted that energy-related activities result in increased roadway maintenance needs. One of the issues that district officials noted is that the current procedures and formulas to allocate maintenance funds among districts do not properly take into account the actual volumes of heavy truck traffic (and the timing of those volumes) used for energy developments, relying instead on highly aggregated measures such as average annual daily traffic (AADT) levels. Energy-related heavy truck traffic is rarely uniform. In fact, it is quite common to see outbursts of intense activity (e.g., during pad construction, drilling, or hydraulic fracturing), which cause most of the damage to pavement structures, followed by periods of inactivity in which relatively little traffic occurs. The probability of capturing truck traffic volumes reliably during regular traffic data collection campaigns is low.

TxDOT officials also pointed out that some energy developers are willing to allocate funds for the maintenance of affected roadways, noting that this type of arrangement is common with local jurisdictions. Some of those developers have also indicated that the time to include roadway maintenance funds in their budgetary process is early while they are still planning the development. Waiting until TxDOT learns about the development (e.g., when driveway permit applications are submitted) would be too late.

District officials highlighted that cost data in systems such MMIS or the Design and Construction Information System (DCIS) are not reliable indicators of the true costs to keep roadways operating properly. Particularly in the case of maintenance expenditures, cost data are a reflection of what districts can afford to spend (based on limited budget allocations), not what they need to spend to maintain the transportation system working effectively.

Similarly, district officials indicated that pavement ratings in PMIS are not necessarily the best indicator of actual pavement conditions on the ground. For example, a pavement rating in PMIS may be based on data collected shortly after a road was fixed, leading to the conclusion that roadway conditions were adequate throughout the year, even though energy-related truck traffic caused substantial pavement damage after the data collection campaign. In addition, certain types of quick maintenance efforts such as seal coating, which frequently result in substantial short-term improvements in pavement rating scores, can actually mask significant structural roadway damage.

Field Visits in Pictures

This section (Figure 20 through Figure 51) provides a visual account of the field visits, which reinforce the observations made previously.

Figure 20. Well Fluid Station (FM 1585, Lubbock District).

Figure 21. Pavement Failure, Surface Ripples (FM 1585, Lubbock District).

Figure 22. Shoulder Damage, Saltwater Disposal Facility (FM 1585, Lubbock District).

Figure 23. Tire Tracks on Unpaved Shoulder (FM 1585, Lubbock District).

Figure 24. Ethanol Plant (FM 2646, Lubbock District).

Figure 25. Edge Failure, Tire Tracks on Unpaved Shoulder (FM 2646, Lubbock District).

Figure 26. Edge Failure, Tire Tracks on Unpaved Shoulder (FM 2646, Lubbock District).

Figure 27. Edge Repairs (FM 89, Abilene District).

Figure 28. Edge Failure (FM 89, Abilene District).

Figure 29. Patching and Flushing (FM 89, Abilene District).

Figure 30. Flushing (FM 89, Abilene District).

Figure 31. Wind Farm (FM 89, Abilene District).

Figure 32. Failures, Alligator Cracks, Flushing (FM 89, Abilene District).

Figure 33. Gas Plant (FM 1611, Abilene District).

Figure 34. Mud Tracking (FM 1611, Abilene District).

Figure 35. Mud Tracking (FM 1611, Abilene District).

Figure 36. Drainage Problems (FM 1611, Abilene District).

Figure 37. Drainage Problems (FM 1611, Abilene District).

Figure 38. Full-Depth Reclamation (FM 52, Fort Worth District).

Figure 39. Failure, Flushing (FM 52, Fort Worth District).

Figure 40. Saltwater Disposal Facility Exit Driveway (FM 2257, Fort Worth District).

Figure 41. Non-Allowed Left Turns from Exit Driveway (FM 2257, Fort Worth District).

Figure 42. County Road next to Saltwater Disposal Facility (FM 2257, Fort Worth District).

Figure 43. Shoulder Patches near County Road Intersection (FM 2257, Fort Worth District).

Figure 44. Alligator Cracking, Base Failure (IH 35W – Frontage, Fort Worth District).

Figure 45. Alligator Cracking, Base Failure (IH 35W – Frontage, Fort Worth District).

Figure 46. Pavement Shoving, Loss of Surface (IH 35W – Frontage, Fort Worth District).

Figure 47. Shoulder Patch (IH 35W – Frontage, Fort Worth District).

Figure 48. Saltwater Disposal Facility (IH 35W – Frontage, Fort Worth District).

Figure 49. Saltwater Disposal Facility (IH 35W – Frontage, Fort Worth District).

Figure 50. Tire Tracks on Unpaved Shoulder (IH 35W – Frontage, Fort Worth District).

Figure 51. Tire Tracks, Safety End Treatment (IH 35W – Frontage, Fort Worth District).

CHAPTER 4. PAVEMENT IMPACTS

INTRODUCTION

This chapter describes the analysis conducted to evaluate the impact of energy developments on pavement structures. It includes a high-level analysis of PMIS data that involves a comparison between the corridors visited in the field and other (control) corridors, as well as a more detailed analysis of pavement characteristics and anticipated pavement remaining life.

DESIGN CRITERIA FOR SECONDARY ROADS

FM roads are typically low-volume highways built with flexible pavement. Following the TxDOT *Pavement Design Guide* (*20*), a low-volume highway is a road with an average daily traffic of less than 3,000 vehicles per day (Note: This criterion used to be 1,000 vehicles per day prior to the 2011 edition of the *Pavement Design Guide*). Information needed to design flexible pavements usually includes the following (*20*):

- **Traffic loads**. Parameters to characterize traffic loads normally include tire loads, axle and tire configurations, typical axle load limits, repetitions of axle loads, traffic distribution (by direction and lane), and traffic projections. Methods to quantify expected loads include equivalent single axle loads (ESALs) and load spectra. The ESAL approach is the most common approach. One ESAL is equivalent to a single axle load of 18,000 lb. A critical factor for the estimation of ESALs is traffic projections. Flexible pavements are normally designed for a 20-year service life and an eight-year minimum initial performance period. Design criteria vary depending on the range of anticipated ESALs (typically, ≤1 million ESALs, 1–5 million ESALs, and >5 million ESALs, according to the *Pavement Design Guide*) (*20*).

  Federal and state laws establish maximum axle and gross vehicle weights in order to limit pavement damage (Table 10).

Table 10. Typical Load Limits (*20*).

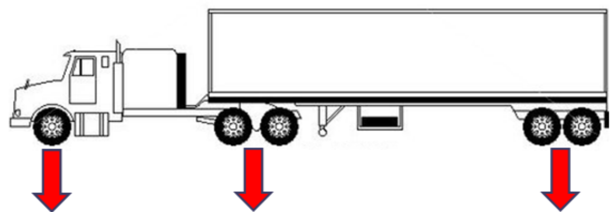
Load Configuration	Limit (pounds)
Single axle	20,000
Tandem axle	34,000
Tridem and quad axles	Bridge formula [1]
Gross vehicle weight	80,000

[1] $W = 500[\,LN/(N-1) + 12N + 36]$

where:

W = load limit for the axle group (pounds).
L = distance between the extreme axles within the group (feet).
N = number of axles in the group.

An equivalent axle load factor (EALF) defines the damage per pass by the axle in question relative to the damage per pass of an ESAL. EALF depends on factors such as type of pavement, thickness or structural capacity, and terminal conditions under which a pavement is considered failed. Following the American Association of State Highway and Transportation Officials (AASHTO) flexible pavement impact model (*21*, *22*), EALF for a five-axle, single trailer truck, loaded to 80,000 lb GVW as indicated in Figure 52, is 2.4 (i.e., the damage is 2.4 times the damage due to an equivalent 18,000-lb single axle load). By comparison, EALF when the same truck is empty (35,000 lb GVW as indicated in Figure 52) is 0.08.



	Steer	Drive	Trailer	Total
Axle group load	P_s	P_d	P_t	
No. of axles/group load	1	2	2	5
Loaded truck: Load per group load (lb)	12,000	34,000	34,000	80,000
Eq. Single Axle Load Factor	**0.19**	**1.1**	**1.1**	**2.4**
Empty truck: Load per group load (lb)	5,000	15,000	15,000	35,000
Eq. Single Axle Load Factor	**0.005**	**0.04**	**0.04**	**0.08**
Total impact per round trip	**0.19**	**1.1**	**1.1**	**2.5**

Figure 52. Sample EALF for a Five-Axle, Single Trailer Truck.

Clearly, the relationship between weight and impact is not linear. For the example shown in Figure 52, while the loaded/empty weight ratio is 2.3, the loaded/empty EALF ratio is 31. As Table 11 shows, loading a truck to 90,000 lb (i.e., overweight by 10,000 lb GVW) would cause the loaded/empty weight ratio to increase to 2.6, but the loaded/empty EALF ratio could potentially increase to 49 (or more depending on the axle load configuration).

Table 11. Relative Pavement Impact.

Total Weight (lb)	EALF	Weight Ratio	EALF Ratio	Weight Ratio	EALF Ratio
		With respect to 35,000 lb		With respect to 80,000 lb	
35,000	0.077	1	1		
80,000	2.4	2.3	31	1	1
90,000	3.8	2.6	49	1.1	1.6
100,000	5.6	2.9	73	1.2	2.4

- **Serviceability index (SI)**. SI is a value that measures the serviceability of a pavement and ranges from 0 (impassable) to 5 (perfectly smooth). The goal for an initial pavement SI is 4 or higher. For highways with moderate to high traffic loads, it is common to use a terminal SI of 2.5 to 3.0. For low-volume highways, TxDOT now allows a terminal SI of 2.0 to 2.5 (previously, it was 2.5), but advises designers to evaluate risks in situations of heavy loads or weak soils, or if the speed limit exceeds 50 mph.

- **Reliability (confidence level)**. TxDOT defines reliability as the probability a pavement will perform as intended under the design conditions (*20*). TxDOT generally uses a reliability of 90–95 percent for rigid pavements and higher volume flexible pavement, but accepts 80 percent for roads with ≤1 million ESALs (while warning that risk levels for the department and need for maintenance are higher).

- **Material characteristics**. This type of information involves the determination of appropriate pavement layer moduli, e.g., the resilient modulus, by using tests such as moisture susceptibility, stress level, strain amplitude, and strain rate.

- **Drainage characteristics**. Examples of factors of interest include general terrain drainage, highway drainage (including ditch depth and capacity), and existing internal pavement drainage features.

- **Existing pavement conditions**.

Table 12 shows typical output pavement design values using TxDOT's Flexible Pavement Design System (FPS)-19W as a function of anticipated ESALs, reliability, and initial and terminal serviceability. Examples of corridors in Texas that correspond to the three ESAL levels according to PMIS records are as follows:

- 0.75 million ESALs: FM 2095 in Milan County (Bryan District).
- 2.5 million ESALs: SH 11 in Hopkins County (Paris District).
- 7.0 million ESALs: US 79 in Panola County (Atlanta District).

Table 12. Typical Output Pavement Design Values Using FPS-19W (*20*).

ESALs ($\times 10^6$)	Reliability	Initial SI	Terminal SI	Surface	Base	Subbase	IPP (years)	Overlay after IPP (inches)
0.75 (low)	80%	4.0	2.0	2CST	6-in flex	6-in LSS	26	-
	90%	4.0	2.5	2CST	6-in flex	8-in LSS	18	2.5
2.5 (medium)	90%	4.5	2.5	2CST	8-in flex	8-in LSS	13	2.5
	95%	4.5	2.5	2CST	11-in flex	8-in LSS	9	2.5
7.0 (high)	90%	4.5	2.5	3-in HMA	10-in CSB	8-in LSS	20	-
	95%	4.5	2.5	3-in HMA	10-in CSB	8-in LSS	11	2.5
	99%	4.8	3.0	3-in HMA	10-in CSB	8-in LSS	8	4.5

Note: 2CST: Two-course surface treatment
HMA: Hot-mix asphalt
CSB: Cement-stabilized base
LSS: Lime-stabilized subgrade
IPP: Initial performance period

Most rural FM roadways are classified as major or minor rural collectors. Most of them are low-volume roads. Table 13 shows typical widths of travel lanes and shoulders recommended for rural collectors based on current TxDOT design standards. As Table 13 shows, roads with average daily traffic lower than 2,000 vehicles per day (typical of most FM roads) are designed with 10-ft or 11-ft lanes and 2-ft to 4-ft shoulders.

Table 13. Lane and Shoulder Width Recommended for Rural Collectors (*23*).

Design Speed (mph)	Minimum Width (feet) for Future Average Daily Traffic of:			
	≤400	400–1500	1500–2000	>2000
	Travel Lane Width			
45 or lower	10	10	11	12
50	10	10	12	12
55	10	10	12	12
60–70	11	11	12	12
	Shoulder Width			
All	2	4	8	8-10

HIGH-LEVEL PMIS DATA ANALYSIS

In order to understand the impact of energy developments on pavement performance, the researchers conducted a high-level comparison between the corridors visited in the field (see previous chapter) and other corridors. These other corridors fell under one of the following categories:

- Sample control corridors of the same functional class as those visited in the field, except the level of energy-related traffic and corresponding impact was generally lower (historically), based on feedback provided by district officials. Table 14, Figure 53, Figure 54, and Figure 55 show the location of the control corridors.

- All state roads of the same functional class in the same district.

- All state roads of the same functional class in the entire state.

Table 14. Control Corridors.

Highway	From	To	From RM	To RM	County
Lubbock District: Rural Major and Minor Collectors					
FM 179	FM 1585	FM 211	RM 228	RM 236	Lubbock/Lynn
FM 212	FM 211	FM 1313	RM 234-0.5	RM 244+1	Lynn
FM 1172	US 60	FM 145	RM 136	RM 158	Parmer
FM 1424	FM 1075	FM 145	RM 138	RM 160	Swisher
FM 3112	US 380	FM 2053	RM 240	RM 252+1	Lynn
Abilene District: Rural Major and Minor Collectors					
FM 600	FM 618	FM 142	RM 254-1.5	RM 262+0.5	Haskell/Jones
FM 1229	FM 670	SH 163	RM 296	RM 304+1	Mitchell
FM 1606	SH 208	FM 644	RM 362-1	RM 370	Scurry
FM 1657	FM 611	US 180	RM 264	RM 270+1	Fisher
Fort Worth District: Rural Major and Minor Collectors					
FM 113	FM 1885	IH 20	RM 260	RM 278	Parker
FM 219	FM 1702	Erath County Line	RM 518	RM 532	Erath
FM 205	FM 51	US 67	RM 528	RM 538	Somervell
SH 220	US 67	Erath County Line	RM 312	RM 324	Erath
FM 1189	Hood County line	US 281	RM 296	RM 306+1.5	Erath
Fort Worth District: Rural Minor Arterials					
US 281	US 67	FM 1824	RM 326	RM 338	Erath
US 281	FM 2803	FM 8	RM 306-0.5	RM 324-0.5	Erath

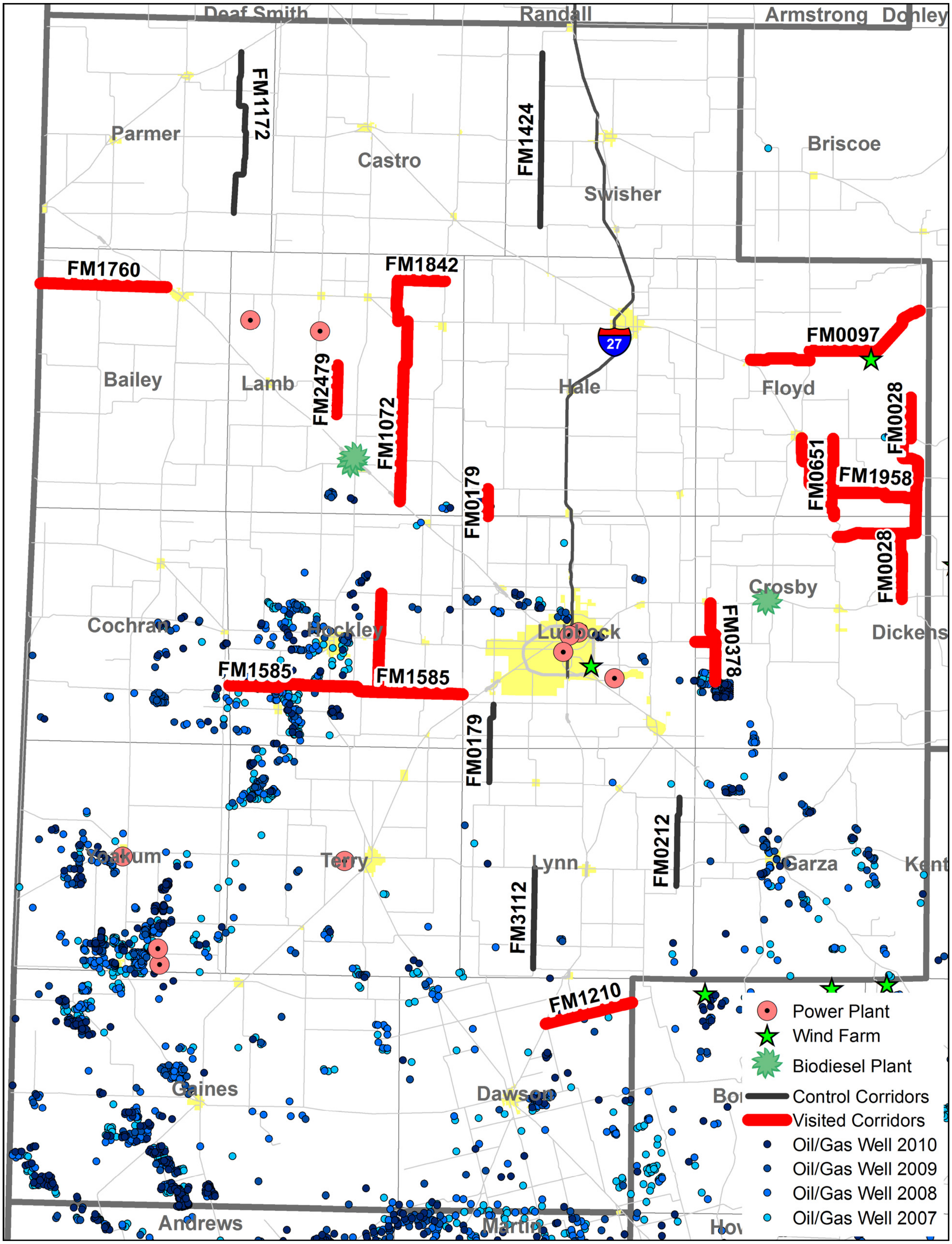


Figure 53. Control Corridors (Lubbock District).

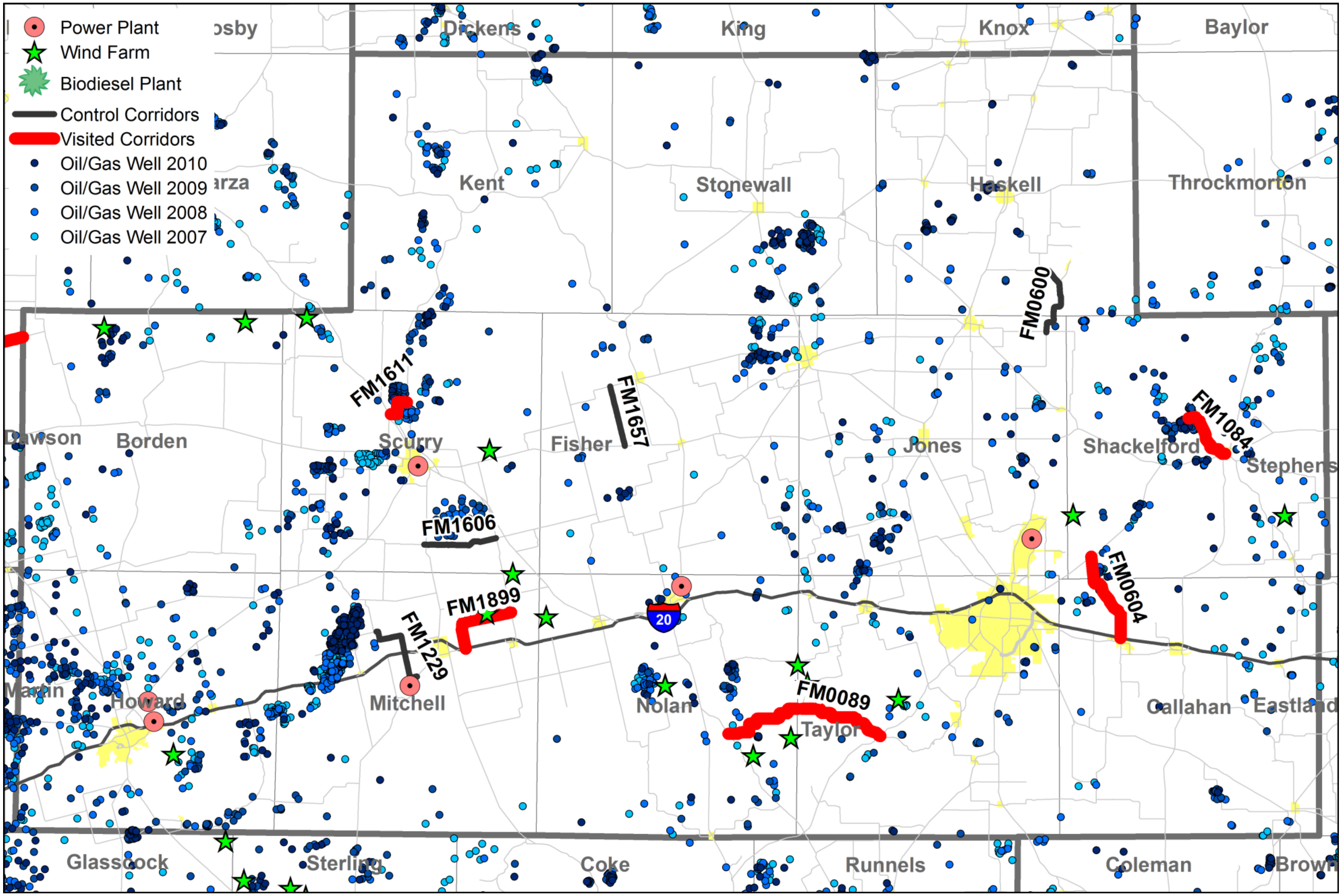


Figure 54. Control Corridors (Abilene District).

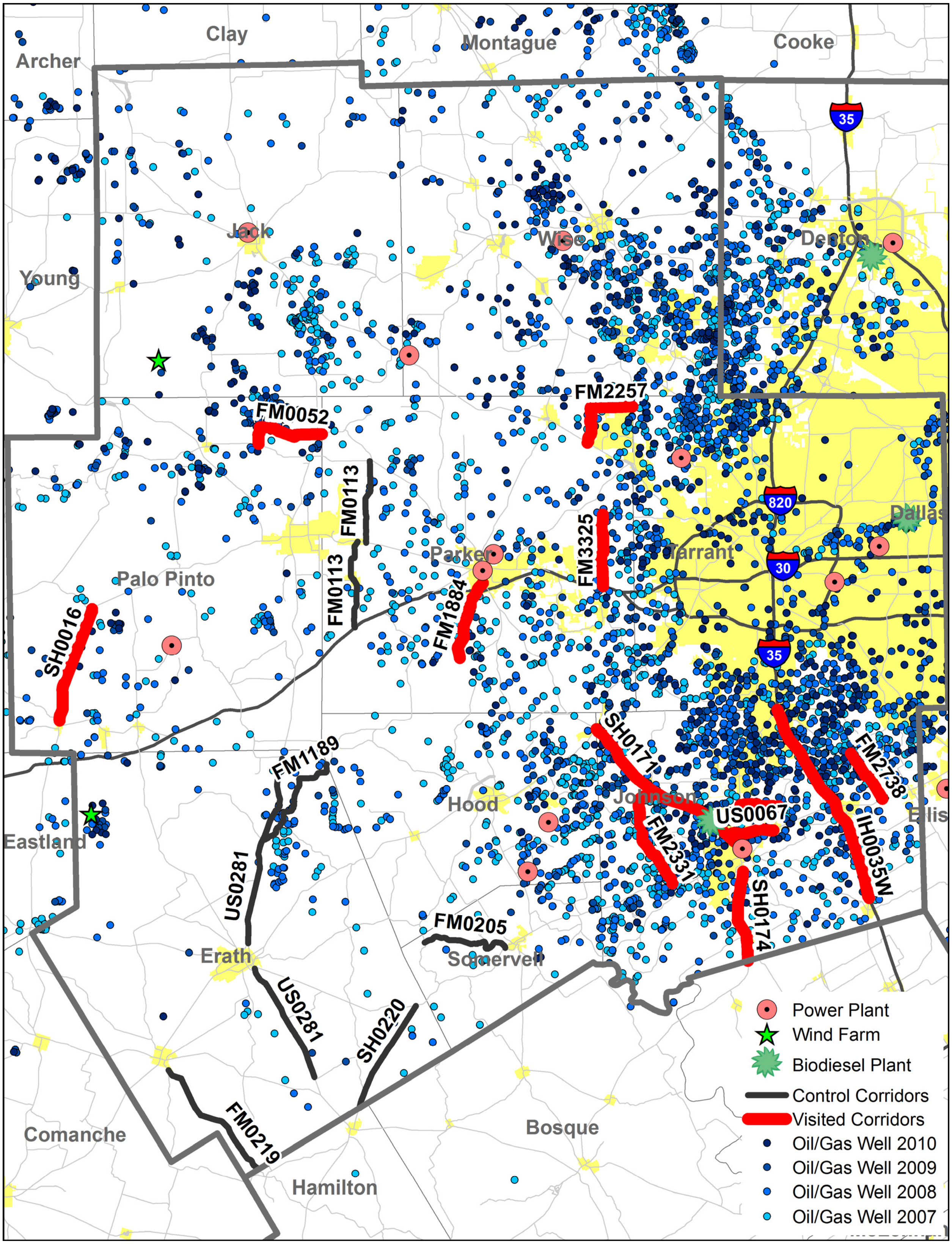


Figure 55. Control Corridors (Fort Worth District).

For the analysis, the researchers used 2002–2010 PMIS data. Of particular interest were traffic data and pavement rating data. For traffic data, the researchers examined traffic data trends, including daily traffic volumes, truck percentages, and truck volumes. The analysis was exploratory and high-level, given the level of uncertainty associated with some of the data items, in particular truck percentages. Readers should note that traffic data in PMIS (e.g., AADT and truck percentages) lag behind pavement rating data by two years. For example, 2010 PMIS records actually contain 2008 traffic data. As a result, while the analysis in this section used 2002–2010 pavement data, the traffic data used were for the 2000–2008 period. For the analysis, the researchers excluded PMIS records with zero or null condition score values.

For each of these data elements, the researchers calculated average values using the following weighted-average formulation:

$$\overline{DE} = \frac{\sum_{i=1}^{n}(DE_i \times N_i \times L_i)}{\sum_{i=1}^{n}(N_i \times L_i)}$$

where:

$\overline{DE}$ = average weighted data element of interest (e.g., daily traffic volume, condition score, or maintenance cost).
DE_i = data element of interest for the i^{th} PMIS data collection segment.
N_i = number of through lanes for the i^{th} PMIS data collection segment.
L_i = length of the i^{th} PMIS data collection segment, typically ½ mile long.

All the corridors in Abilene and Lubbock (either visited or control) were rural major or minor collectors. In Fort Worth, some corridors were of a different functional class, as follows:

- FM 1884. Three segments along this corridor were classified as urban collectors in 2010. For simplicity, the researchers grouped these segments with the rest of the FM 1884 segments.

- FM 3084. Four segments along this corridor were classified as urban collectors in 2010. The researchers grouped these segments with the rest of the FM 3084 segments.

- SH 171. The section of SH 171 visited in the field included one segment that, from 2002–2009, was classified as an urban minor arterial and two segments that were classified as urban minor arterials (other). In 2010, the same section of SH 171 included eight segments classified as urban minor arterials and two segments classified as urban principal arterials (other). Because each PMIS segment is typically ½ mile long, the total number of segments was small compared to the entire length of the section of SH 171 visited, and traffic volumes were roughly comparable for all the segments, the researchers decided to lump all the segments as if they were rural collectors.

- SH 174. This corridor is a rural minor arterial. The researchers analyzed this corridor separately.

PMIS Analysis Results – Lubbock District

For the corridors of interest in the Lubbock District, Table 15 shows basic traffic data and Table 16 shows average condition scores.

Table 15. Traffic Data (Rural Major and Minor Collectors, Lubbock District).

Year	Visited Corridors (148.8 miles)			Control Corridors (79.5 miles)			All District Rural Major and Minor Collectors (3,619 miles)		
	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)
2000	191	23	44	139	25	35	237	23	55
2001	191	23	44	139	25	35	238	23	55
2002	212	19	40	142	17	24	236	21	50
2003	198	19	38	140	32	45	243	20	49
2004	213	18	38	165	16	26	260	18	47
2005	222	20	44	165	26	43	264	24	63
2006	197	21	41	155	26	40	251	25	63
2007	204	19	39	151	22	33	229	22	50
2008	188	19	36	140	20	28	209	21	44
Average	**203**	**20**	**40**	**148**	**23**	**34**	**241**	**22**	**53**

Table 16. Condition Scores (Rural Major and Minor Collectors, Lubbock District).

Year	Average Condition Score			
	Visited Corridors	Control Corridors	District Average	State Average
2002	90	86	89	89
2003	91	93	91	90
2004	95	94	93	91
2005	95	96	94	91
2006	94	92	93	91
2007	91	92	94	91
2008	84	88	93	91
2009	82	86	91	91
2010	79	84	92	92
Average	**89**	**90**	**92**	**91**

Until about 2007, pavement condition scores for the corridors visited in the field were very similar to those for the control corridors and rural collectors in general in the Lubbock District. During the same period, condition scores for rural collectors in the Lubbock District in general were higher than throughout the state. Starting in 2007, pavement condition scores for the corridors visited deteriorated rapidly. In 2010, the average condition score for these corridors reached 79. Pavement condition scores for the control corridors also deteriorated (suggesting these corridors were also affected), although not as aggressively. At the same time, condition scores for rural collectors in general in the Lubbock District remained uniform in the low 90s and substantially the same as rural collectors throughout the state.

PMIS Analysis Results – Abilene District

For the corridors of interest in the Abilene District, Table 17 shows basic traffic data and Table 18 shows average condition scores.

Table 17. Traffic Data (Rural Major and Minor Collectors, Abilene District).

Year	Visited Corridors (48.3 miles)			Control Corridors (35.5 miles)			All District Rural Major and Minor Collectors (2,544 miles)		
	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)
2000	156	18	28	93	20	19	190	17	32
2001	156	18	28	93	20	19	190	17	32
2002	173	18	31	107	31	33	203	24	49
2003	165	24	40	96	23	22	203	21	43
2004	177	15	27	115	14	16	214	19	41
2005	178	22	39	115	21	24	216	23	50
2006	189	21	40	89	23	20	199	24	48
2007	187	20	37	93	15	14	209	19	40
2008	194	15	29	105	21	22	200	19	38
Average	**175**	**19**	**33**	**101**	**21**	**21**	**203**	**20**	**41**

Table 18. Condition Scores (Rural Major and Minor Collectors, Abilene District).

Year	Average Condition Score			
	Visited Corridors	Control Corridors	District Average	State Average
2002	90	98	95	89
2003	90	95	94	90
2004	94	97	94	91
2005	89	90	93	91
2006	86	90	94	91
2007	80	87	94	91
2008	81	97	94	91
2009	66	97	92	91
2010	87	93	92	92
Average	**85**	**94**	**93**	**91**

In general, pavement condition scores for the corridors visited in the field were consistently lower than condition scores for the control corridors, rural collectors in general in the Abilene District, and throughout the state. It was only in 2004 that pavement condition scores for the corridors visited were higher on average than throughout the state. From 2004 to 2009, condition scores for the corridors visited in the field decreased considerably. In 2009, the average condition score for the corridors visited in the field reached 66, while average condition scores for the district and throughout the state remained in the low to mid-90s. The drop in condition scores between 2004 and 2009 coincided relatively well with the wind energy boom in the area.

PMIS Analysis Results – Fort Worth District

Rural Major and Minor Collectors

For the corridors of interest in the Fort Worth District, Table 19 shows basic traffic data and Table 20 shows average condition scores.

Table 19. Traffic Data (Rural Major and Minor Collectors, Fort Worth District).

Year	Visited Corridors (90 miles)			Control Corridors (62.2 miles)			All Similar Roadways in the District (1,689 miles)		
	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)
2000	857	14	120	500	16	80	954	14	134
2001	861	14	121	500	16	80	949	14	133
2002	1,021	13	133	589	17	100	1,034	15	155
2003	1,041	13	135	570	16	91	1,055	14	148
2004	1,038	11	114	574	12	69	1,072	11	118
2005	1,273	13	165	614	12	74	1,147	13	149
2006	1,246	14	174	626	12	75	1,214	13	158
2007	1,705	16	273	662	21	139	1,258	19	239
2008	1,587	18	286	578	21	121	1,091	18	196
Total	**1,180**	**14**	**169**	**579**	**16**	**92**	**1,086**	**15**	**159**

Table 20. Condition Scores (Rural Major and Minor Collectors, Fort Worth District).

Year	Average Condition Score			
	Visited Corridors	Control Corridors	District Average	State Average
2002	89	97	93	89
2003	74	95	93	90
2004	83	97	93	91
2005	87	95	92	91
2006	89	96	93	91
2007	84	94	91	91
2008	85	89	91	91
2009	79	97	90	91
2010	77	98	92	92
Average	**83**	**95**	**92**	**91**

Pavement condition scores for the corridors visited in the field were consistently lower than condition scores for the control corridors, rural collectors in general in the Fort Worth District, and throughout the state. Average condition scores for the corridors visited increased from 2003 to 2006, but then began to deteriorate after 2006. Condition scores for rural collectors in general in the Fort Worth District decreased steadily from 2002 to 2009. In 2009, those condition scores were lower than throughout the state.

Rural Minor Arterials

Table 21 shows basic traffic data, and Table 22 shows average condition scores for the corridors of interest in the Fort Worth District.

Table 21. Traffic Data (Rural Minor Arterials, Fort Worth District).

Year	Corridors Visited (5.9 miles)			Control Corridors (30.5 miles)			All Similar Roadways in the District (192 miles)		
	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)	Average Daily Traffic (veh/ln)	Average Truck Percent	Average Truck Traffic (veh/ln)
2000	3,178	17	540	2,371	14	332	2,055	14	288
2001	3,178	17	540	2,371	14	332	2,055	14	288
2002	3,352	11	369	2,486	13	323	2,248	13	292
2003	3,296	9	297	2,547	13	331	2,170	13	282
2004	2,957	10	296	2,578	12	309	2,236	13	291
2005	3,213	20	643	2,615	11	288	2,256	13	293
2006	4,570	17	777	2,614	11	288	2,347	13	305
2007	3,684	20	737	2,731	17	464	2,372	17	403
2008	4,058	24	974	2,573	14	360	2,254	16	361
Average	**3,498**	**16**	**575**	**2,543**	**13**	**336**	**2,221**	**14**	**311**

Table 22. Condition Score (Rural Minor Arterials, Fort Worth District).

Year	Average Condition Score			
	Visited Corridors	Control Corridors	District Average	State Average
2002	98	92	89	92
2003	97	86	88	92
2004	94	91	87	93
2005	65	86	87	93
2006	63	89	88	93
2007	71	97	89	93
2008	85	95	89	92
2009	95	91	94	92
2010	82	80	89	92
Average	**83**	**90**	**89**	**92**

Through 2004, pavement condition scores for the corridors visited in the field were higher than condition scores for the control corridors, rural minor arterials in general in the Fort Worth District, and throughout the state. From 2004–2009, pavement condition scores for the corridors visited were substantially lower than for the control corridors, rural minor arterials in general in the Fort Worth District, and throughout the state. There was a spike in pavement condition scores for the corridors visited in 2009, but the condition scores deteriorated again substantially in 2010. Except for a short period from 2007–2009, condition scores for rural minor arterials in the Fort Worth District have been lower than throughout the state.

GPR AND FWD DATA ANALYSIS

While a high-level comparison of PMIS data was important to identify general trends, the researchers conducted a more in-depth analysis of pavement characteristics and performance of the various corridors that were visited in the field. The analysis included GPR and FWD data collection, prediction of remaining pavement service life, and a sensitivity analysis.

Data Collection

With district assistance, the researchers collected GPR data to examine pavement layer composition, FWD data to assess existing pavement structural conditions, and project plan sheets to obtain pavement cross-section information. Table 23 shows the corridors and the type of data collected on each corridor. There was no data collection on some corridors due to unavailability of equipment or conflict with other ongoing field tests. Because of time limitations, the researchers decided to move forward with analyzing the available information given the significant amount of useful data collected with which to assess impacts.

GPR Data Analysis

GPR is widely used to determine pavement layer thickness. More specifically, the researchers used GPR to estimate the layer dielectric constant, which is a function of the amplitudes of the reflections from the layer interfaces. The layer thickness can be estimated as follows:

$$h = \frac{C \times \Delta t}{\sqrt{\varepsilon_a}}$$

where:

h = layer thickness.
C = velocity of electromagnetic waves in free space.
Δt = travel time of the electromagnetic wave within the layer according to the radar trace.
ε_a = layer dielectric constant.

The researchers used the PAVECHECK software to process the GPR data collected, determine layer thickness, and identify locations to collect FWD data (*24*). For completeness, the researchers compared layer thicknesses with available plan sheet information. It is worth noting the TTI GPR data collection system had video recording capabilities, which enabled the identification of interesting locations, e.g., those that showed signs of pavement damage or previous maintenance work.

Table 23. GPR, FWD, and Plan Sheet Data Collection.

Highway	Section Limits	Test Lane	GPR	FWD	Plan Sheet
Lubbock District					
FM 28-N	RM 180 – RM 186	K6	●	●	●
FM 28-S	RM 186 – RM 198	K6	●	●	●
FM 28-Crosby	RM 198 – RM 202	K6	●	●	●
FM 40	RM 310 – RM 312	K6	●	●	●
FM 97	RM 324 – RM 344	K1	●	●	●
FM 179	RM 196 – RM 200	K6	●	●	●
FM 193	RM 336 – RM 338	K1	●	●	●
FM 378	RM 220 – RM 226	K1	●		●
FM 651	RM 186 – RM 196	K6	●	●	●
FM 1072	RM 170 – RM 182	K1	●		●
FM 1210	RM 294 – RM 295	K6	●		●
FM 1585	RM 258 – RM 268	K6	●		
FM 1760	RM 226 – RM 242	K1	●		●
FM 1842	RM 272 – RM 282	K6	●		●
FM 1958	RM 324 – RM 346	K1	●	●	●
FM 2479	RM 176 – RM 182	K6	●		●
FM 2646	RM 206 – RM 216	K6	●		●
Abilene District					
FM 89	FM 126 – US 277	K6	●	●	●
FM 126	2 miles east of Nolan – FM 89	K1	●	●	●
FM 604	IH 20 – SH 351	K6	●	●	●
FM 1084	RM 268 – 283	K6	●		●
FM 1611	US 84 – SH 208	K1	●	●	●
FM 1899	IH 20 – FM 644	K1	●	●	●
Fort Worth District					
FM 52	RM 506-0.1 – 512+1.75	K1	●	●	●
FM 1884	RM 270-0.1 – RM 278+0.0	K1		●	
FM 2257	RM 542 – RM 546	K1	●	●	●
FM 2331	RM 292-0.6 – RM 302+0.1	K6	●	●	●
FM 2738	RM 290-1.7 – RM 294+0.2	K1	●	●	●
FM 3048	RM 556-2.1 – RM 558+0.1	K1	●	●	●
FM 3325	RM 264 – RM 270+1.1	K6/K1	●	●	●
IH 35W-1 Frontage	RM 26+0.8 – RM 30+0.6	A1	●	●	●
IH 35W-2 Frontage	RM 17+0.75 – RM 24+0.5	A1	●	●	●
SH 16	RM 296-0.9 – RM 306+1.0	K6	●	●	●
SH 171	RM 294 – RM 306	K1	●	●	●
SH 174	RM 304 – RM 310	K1	●	●	●

Figure 56 through Figure 58 show sample screenshots of the software and the process to analyze GPR data. Figure 56 shows GPR reflections used to estimate layer thickness. Two layer interfaces are visible on the top chart. The upper line (yellow band) corresponds to the bottom of the surface layer and the lower line (red band) corresponds to the bottom of the base. At this location, the radar trace indicated a surface layer thickness of 1.2 inches and a base thickness of 3.9 inches. On average, surface and base thickness on FM 604 was 2.5 and 6.0 inches, respectively. These values compared well against available plan sheet information (Table 24).

Figure 57 shows GPR reflections associated with a section of pavement on FM 52 that underwent full-depth reclamation. In this case, the GPR data showed highly variable reflections, which made it difficult to estimate layer thicknesses. For this corridor, the researchers used surface thickness information provided in existing plan sheets.

The researchers used video data taken during the GPR survey data to identify cracked, patched, or damaged areas, and to determine locations where to conduct (or avoid) FWD tests. For example, in Figure 58, the oval shows a patched area for which the reflections from the bottom of the surface layer were not clearly visible. This location was not appropriate to conduct FWD tests because of the difficulty to back calculate pavement layer moduli reliably. In general, locations with strong reflections were more appropriate for FWD tests because they facilitated the back calculation of pavement layer moduli.

Table 24 compares the estimated average layer thicknesses based on the GPR analysis with the thickness data from the plan sheets. Overall, thicknesses determined based on GPR data look reasonable when compared with plan sheet information.

Note: The red vertical line on the top profile corresponds to the location in the video (bottom left) and the radar trace at this location (bottom right).

Figure 56. GPR Data Analysis on FM 604.

Note: The red vertical line on the top profile corresponds to the location in the video (bottom left) and the radar trace at this location (bottom right).

Figure 57. GPR Data Analysis on FM 52 after Full-Depth Reclamation.

Note: The red vertical line on the top profile corresponds to the location in the video (bottom left) and the radar trace at this location (bottom right). The oval shows a patched area for which the reflections from the bottom of the surface layer were not clear.

Figure 58. Selection of FWD Test Stations Based on GPR Data Analysis on FM 28.

Table 24. Estimated Average Layer Thickness.

Highway	GPR Analysis		Plan Sheets	
	Surface (inches)	Base (inches)	Surface (inches)	Base (inches)
Lubbock District				
FM 97	1.5	6.5	2-course surface treatment (1 – 2")	6.0
FM 28-N	1.5	6.0	2-course surface treatment (1 – 2")	6.0
FM 28-S	2.4	5.0	2-course surface treatment (1 – 2")	6.0
FM 28-Crosby	2.0	7.0	2-course surface treatment (1 – 2")	6.0
FM 651	1.5	7.5	2-course surface treatment (1 – 2")	8.5
FM 1958	1.3	7.0	2-course surface treatment (1 – 2")	9.0
FM 179	2.5	6.0	2-course surface treatment (1 – 2")	6.0
FM 2646	0.9	5.5	2-course surface treatment (1 – 2")	6.0
FM 1585	1.0	5.5	2-course surface treatment (1 – 2")	-
FM 1210	1.5	4.0	2-course surface treatment (1 – 2")	5.0
FM 1072	1.2	6.5	2-course surface treatment (1 – 2")	6.0
FM 2479	1.2	6.0	2-course surface treatment (1 – 2")	6.0
FM 1842	1.5	6.5	2-course surface treatment (1 – 2")	6.0
FM 193	2.0	6.5	2-course surface treatment (1 – 2")	6.0
FM 40	1.2	4.5	2-course surface treatment (1 – 2")	5.5
FM 378	1.4	7.0	2-course surface treatment (1 – 2")	6.0
FM 1760	2.5	7.0	2-course surface treatment (1 – 2")	6.0
Abilene District				
FM 1611	2.5	5.5	2-course surface treatment (1 – 2")	6.0
FM 1899	1.5	6.0	2-course surface treatment (1 – 2")	6.0
FM 126	2.0	5.5	2-course surface treatment (1 – 2")	6.0
FM 89	1.5	5.5	2-course surface treatment (1 – 2")	6.0
FM 604	2.0	6.0	2-course surface treatment (1 – 2")	6.0
FM 1084	2.0	7.0	2-course surface treatment (1 – 2")	6.0
Fort Worth District				
FM 52 [1]			1.5" HMA + 1-course surface treatment	10.0
SH 16	2.5	8.0	2-course surface treatment (1 – 2")	9.0
FM 2257	2.2	6.5	1-course surface treatment (1 – 2")	6.0
FM 3325	5.5	8.0	5" HMAC	8.0
FM 1884	-	-	-	-
SH 171	2.5	10.0	2" HMA + 1-course surface treatment	12.0
FM 2331	4.0	8.5	2" HMA + 1-course surface treatment	8.0
SH 174	1.5	8.5	1" HMA + 1-course surface treatment	8.0
IH 35W-1 Frontage	1.5	10.0	2-course surface treatment (1 – 2")	8.5 – 10
IH 35W-2 Frontage	1.5	10.0	2-course surface treatment (1 – 2")	8.5 – 10
FM 2738	2.0	8.5	1-course surface treatment (1 – 2")	6.0
FM 3048	2.0	7.5	1-course surface treatment (1 – 2")	6.0

[1] Full-depth reclamation project where GPR data showed highly variable reflections below the surface (Figure 57). The variability in the reflections made it difficult to analyze GPR data and estimate layer thicknesses. The surface thickness is based on plan sheet information.

FWD Data Analysis

The falling weight deflectometer is a widely used tool to evaluate structural adequacy and determine pavement layer moduli (Figure 59). The equipment includes a weight that is mounted on a vertical shaft, lifted to a predetermined height, and then dropped to a rubber buffer system resulting in a load pulse. The load is applied to the pavement surface through a circular plate and measured with a load cell. A set of seven geophone sensors then measures the vertical surface deflections due to the load. The first sensor is always mounted at the center of the load plate. Figure 60 shows sample variations of FWD deflections measured from the seventh sensor.

Figure 59. Falling Weight Deflectometer.

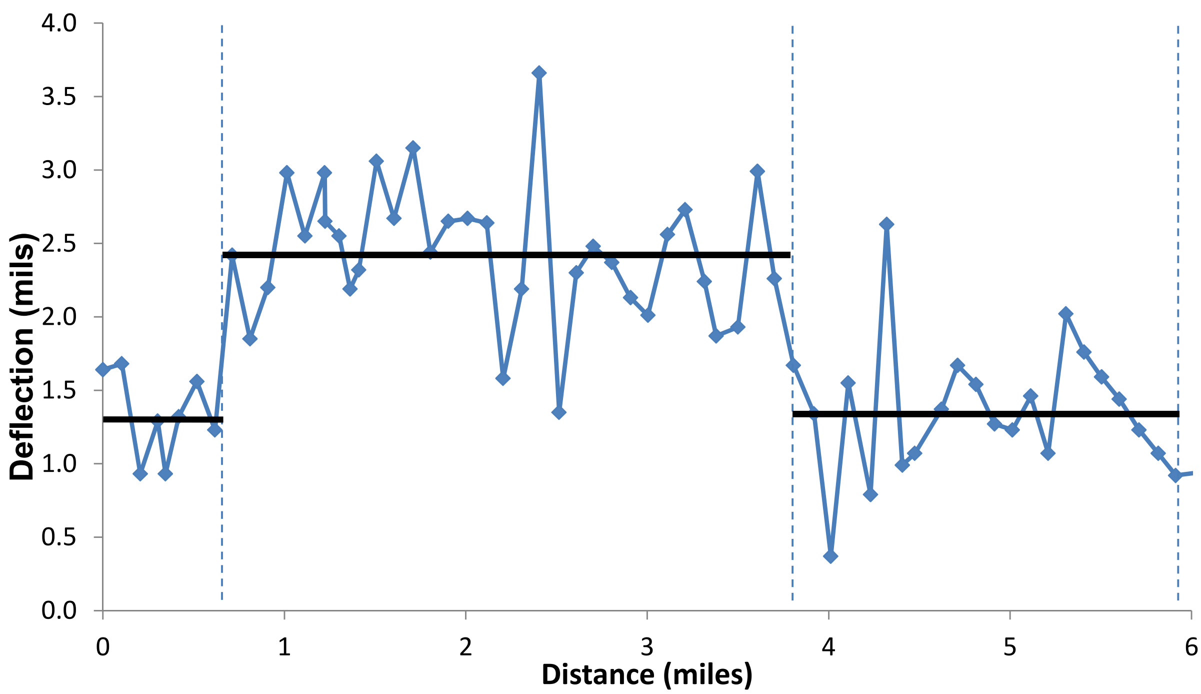


Figure 60. Sample Variation of FWD Deflections (Seventh Sensor).

The researchers used the MODULUS 6 software to analyze deflections to estimate layer moduli (*25*). The process involved assuming a set of pavement moduli in a multilayer elastic system and using an optimization procedure to calculate theoretical deflections by varying layer moduli iteratively until the difference between predicted and measured deflections matched a pre-specified tolerance.

As shown in Figure 60, a wide range in deflections measured in the field resulted in substantial variations in base and subbase moduli. Non-uniformity in deflections and layer moduli could be an indicator of deteriorated areas and/or evidence of past maintenance activities. Table 25 presents the average estimated layer moduli for the various corridors where FWD data were collected. As shown in Table 25, routes in the Fort Worth District generally exhibited higher base and subbase moduli compared to routes tested in the Abilene and Lubbock Districts.

Table 25. Average Estimated Layer Moduli.

Highway	Average modulus (ksi)		
	Surface	Base	Subbase
Lubbock District			
FM 97	324	34	6.8
FM 28-N	355	23	7.3
FM 28-S	315	38	7.9
FM 28-Crosby	312	30	7.5
FM 651	267	25	8.1
FM 1958	403	30	8.0
FM 179	217	21	5.6
FM 193	315	24	4.1
FM 40	217	47	7.3
Abilene District			
FM 1899	446	55	9.4
FM 126	284	60	7.3
FM 89	284	36	15
FM 604	66	28	12
Fort Worth District			
FM 52	432	196	15
SH 16	217	56	13
FM 2257	226	93	19
FM 3325	310	115	14
SH 171	453	87	17
FM 2331	325	32	10
SH 174	200	50	12
IH 35W-1	340	52	15
IH 35W-2	340	45	10
FM 2738	422	117	10
FM 3048	200	70	14

REMAINING PAVEMENT LIFE ANALYSIS

The researchers used MODULUS 6 and the Overweight Truck Route Analysis (OTRA) program to conduct a remaining life analysis using data from the GPR and FWD tests as well as PMIS data, primarily traffic and pavement condition data. Both MODULUS 6 and OTRA enable the prediction of pavement service life based on FWD deflections and limiting strain criteria. The remaining life analysis procedure used in MODULUS was originally developed as part of TxDOT research project 2-18-85-409 in the late 1980s (*26*). OTRA uses a modified version of the load zoning analysis program developed as part of TxDOT research project 0-2123 in the early 2000s (*27*). Both programs have been widely used in a variety of flexible pavement conditions in Texas, including thin-surfaced pavements such as those tested in this research. The researchers considered using a mechanistic-empirical (M-E) methodology to conduct the assessment. However, the computer program to implement the Texas M-E methodology is still under development (*28*). In any case, its use would have required a substantial amount of material characterization tests that were beyond the scope of this research.

Although the primary purpose of the evaluation was to conduct a remaining life analysis, a secondary purpose was to illustrate the use of GPR and FWD tests to identify potentially problematic pavement sections and provide a quantitative basis for making maintenance and rehabilitation decisions on corridors affected by energy developments. Appendix A includes details of the methodology and calculations completed.

Analysis Using MODULUS 6

Figure 61 shows a screenshot of the MODULUS 6 function to estimate remaining life. MODULUS 6 converts performance predictions to an equivalent service life in years based on the projected 20-year 18-kip ESAL applications the user specified. The program adjusts performance predictions to account for existing levels of rutting and cracking along the route. The program output is an assessment of the remaining life at each FWD test station according to the categories shown in Table 26. Figure 62 shows an example output file from the remaining life analysis for the roadway section shown in Figure 61.

The researchers extracted 20-year ESALs and existing rutting and cracking data from PMIS (see Table 27). As mentioned, FY10 PMIS data included FY10 pavement condition data and FY08 traffic condition data. For the remaining life analysis, the researchers assumed FY10 traffic conditions to be the same as in FY08. The researchers also based the remaining life analysis on rutting given the predominantly thin pavements along the tested routes. To predict remaining life, the researchers used the thickness data determined from the GPR analysis (see Table 24).

Figure 63 summarizes the remaining life predictions using MODULUS 6. In Figure 63, the vertical axis represents relative frequency with respect to the total number of ½-mile segments used for the analysis (710). The highest frequency of remaining life predictions (32 percent) fell within the 0–2 year bin (i.e., the pavement on those segments is considered failed). About 19 percent of the pavements tested fell within the 2–5 year bin (i.e., the pavement on those segments is expected to fail in the near future). In other words, at least 50 percent of the segments tested have pavements that have failed or are expected to fail within 5 years.

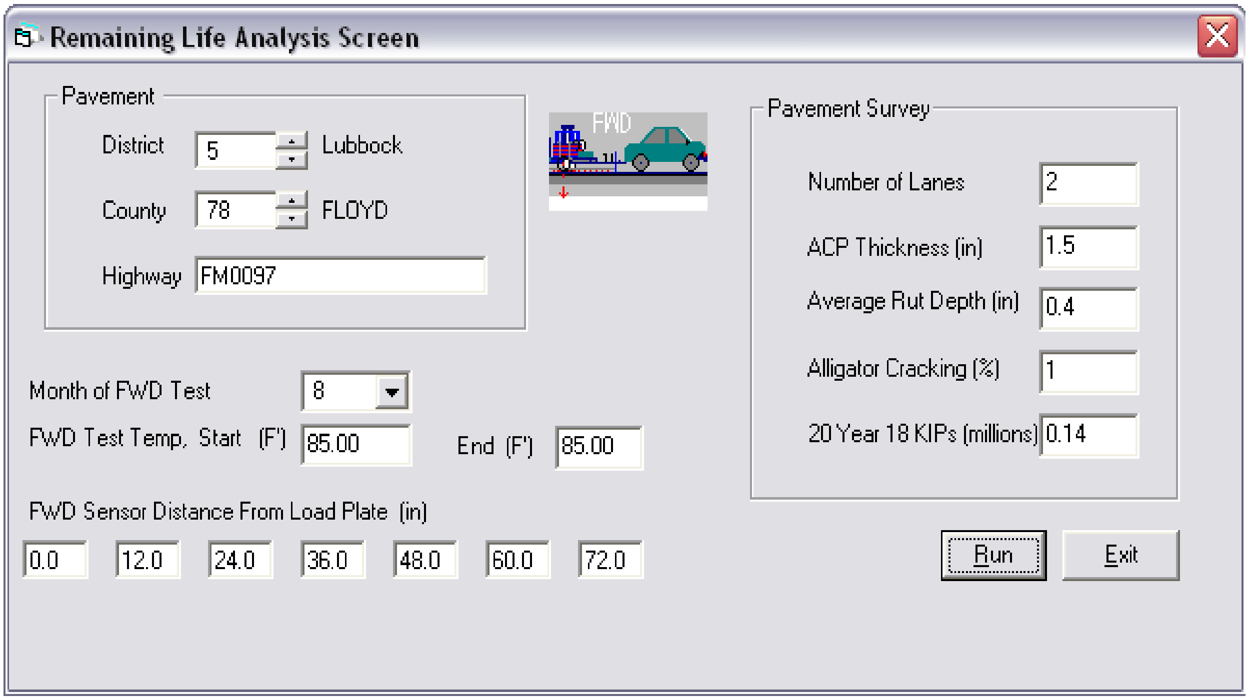


Figure 61. Input Screen for Remaining Life Analysis.

Table 26. Remaining Life Classification Used in MODULUS 6 (*25*).

Class	Remaining Life (years)	Comments
1	0–2	Failed
2	2–5	Failure in the near future
3	5–10	Adequate for now but potential problem in future
4	10+	Structurally sound

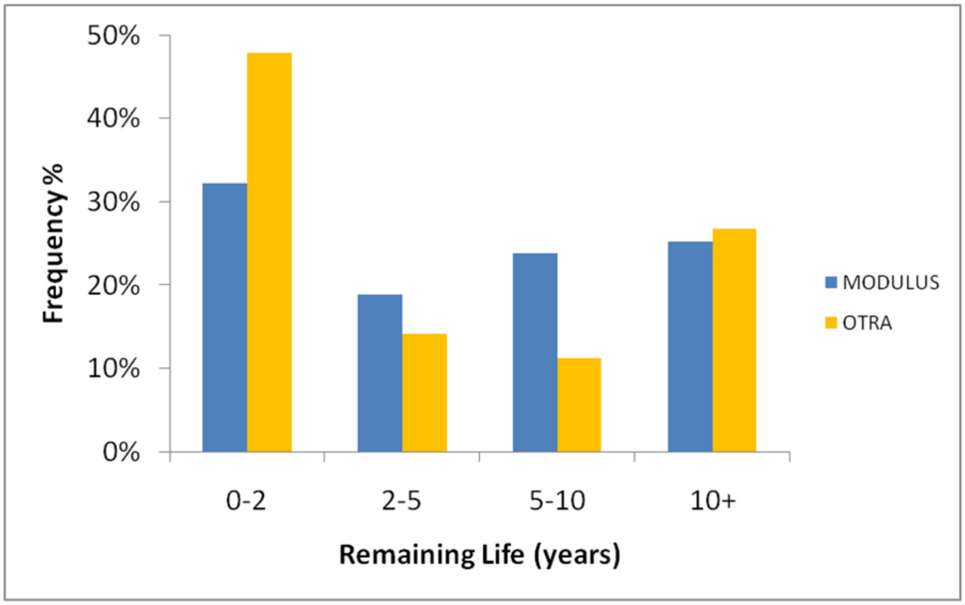
```
                              *****************
                              *  R E L A P S  *
                              *****************

           TTI FLEXIBLE PAVEMENT DEFLECTION BASIN ANALYSIS PROGRAM

--------------------------------------------------------------------------------
  FWD TESTED FILE NAME :  C:\backup\backup\C\OJH\6498\Lubbock\078F0097.FWD
--------------------------------------------------------------------------------
  DISTRICT             :    5--Lubbock           ASPH. THICKNESS  :  1.50
  COUNTY               :   78--FLOYD             MONTH TESTED     :  AUG
  HIGHWAY              :   FM0097                DESIGN LOAD (lbs):  9000
  TEMPERATURE("F) start:   85.0 knd:  85.0       20 year 18 KIP(m):     0.14
  AVERAGE RUT DEPTH(in):    0.4                  LANES            :   2
  ALLIGATOR CRACKING   :    1.0 %                SENSORS: 0 12 24 36 48 60 72
--------------------------------------------------------------------------------
                                               ASPH DESIGN   LAYER     REMAINING
           ** NORMALIZED DEFLECTION (mils) **  TEMP  SCI   STRENGTHS  LIFE (yrs)
   STATION    R1     R2     R3     R4     R7  DEF F  MILS UPR LWR SGR  RUT   CRK
--------------------------------------------------------------------------------
     0.289  66.58  33.74  12.28   6.81   2.84  85.0 32.83  VP  VP  VP  0-2   10+
     1.113  77.12  33.54   8.24   4.08   2.10  85.0 43.57  VP  VP  PR  0-2   10+
     2.001  53.84  21.01   7.10   4.25   2.03  85.0 32.84  VP  PR  PR  0-2   10+
     2.668  58.66  24.14   8.29   4.90   2.05  85.0 34.51  VP  PR  PR  0-2   10+
     4.246  45.02  22.46   8.73   4.72   2.22  85.0 22.56  MD  PR  VP  2-5   10+
     5.105  21.11  12.14   6.74   4.59   2.51  85.0  8.97  VG  GD  VP  10+   10+
     6.324  54.48  24.31   9.14   4.69   2.02  85.0 30.17  VP  PR  PR  0-2   10+
     7.111  86.10  36.45  13.50   7.39   3.29  85.0 49.64  VP  VP  VP  0-2   10+
     8.449  17.75  13.73   8.40   5.86   2.94  85.0  4.02  VG  GD  VP  10+   10+
    10.026  61.22  23.83   7.98   4.54   2.17  85.0 37.39  VP  PR  PR  0-2   10+
    12.008  63.38  24.66   8.87   4.90   2.34  85.0 38.72  VP  PR  VP  0-2   10+
    12.110  58.25  23.87   8.33   4.71   2.16  85.0 34.38  VP  PR  PR  0-2   10+
    13.039  58.77  26.20  10.71   6.07   2.79  85.0 32.57  VP  PR  VP  0-2   10+
    14.217  53.98  26.57  10.98   6.90   3.74  85.0 27.41  PR  PR  VP  0-2   10+
    15.632  69.17  33.32  14.24   8.45   3.90  85.0 35.85  VP  VP  VP  0-2   10+
    16.348  46.06  22.29   8.84   5.23   2.88  85.0 23.77  MD  PR  VP  0-2   10+
    17.281  68.62  35.01  13.01   7.34   3.80  85.0 33.61  VP  VP  VP  0-2   10+
    18.376  50.42  23.01   9.83   5.65   1.69  85.0 27.41  PR  PR  MD  2-5   10+
    19.787  21.89   5.93   2.48   1.82   0.97  85.0 15.96  GD  VG  VG  10+   10+
--------------------------------------------------------------------------------
     MEAN:  54.34  24.54   9.35   5.42   2.55       29.80  PR  PR  PR
  STD DEV:  18.18   7.97   2.73   1.51   0.76       11.13
  COF VAR:  33.46  32.48  29.18  27.93  29.85       37.36
--------------------------------------------------------------------------------
*  0~2:Failed    2~5:Problem    5~10:OK for Now    10+:Good
```

Figure 62. Output Screen of Remaining Life Analysis on FM 97.

Table 27. Traffic and Performance Data Extracted from PMIS.

Highway	AADT	AADTT[1]	ESALs ($\times 10^6$)	Rutting (inches)
Lubbock District				
FM 97	297	44	0.14	0.42
FM 28-N	120	18	0.05	0.44
FM 28-S	127	31	0.09	0.38
FM 28-Crosby	124	21	0.07	0.38
FM 651	160	30	0.14	0.38
FM 1958	152	27	0.08	0.42
FM 179	303	68	0.34	0.38
FM 193	80	16	0.05	0.30
FM 40	500	87	0.39	0.43
Abilene District				
FM 126	295	61	0.27	0.52
FM 604	510	56	0.20	0.40
FM 89	562	94	0.43	0.41
FM 1899	115	18	0.05	0.40
FM 1611	394	53	0.25	0.40
Fort Worth District				
FM 52	266	74	0.29	0.60
FM 2331	3355	150	0.68	0.38
FM 2738	3718	435	1.76	0.47
FM 3048	3200	406	1.79	0.38
FM 3325	5133	1416	8.59	0.60
IH35W-1	1979	63	2.26	0.90
IH35W-2	470	15	0.5	0.50
SH 16	742	233	0.98	0.40
SH 171	9488	2613	15.7	0.40
SH 174	8083	1912	10.9	0.45
FM 2257	2850	920	3.7	0.38

[1] Average annual daily truck traffic



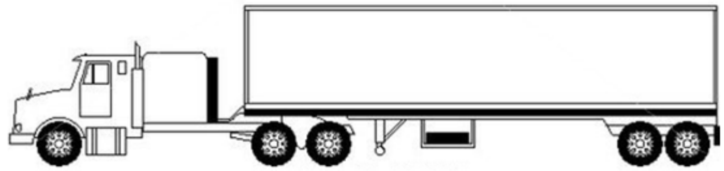
Note: The relative frequency is given with respect to the total number of ½-mile segments used for the analysis (710).

Figure 63. Summary of Remaining Life Analysis Using MODULUS and OTRA.

Analysis Using OTRA

OTRA is used to evaluate the structural adequacy of an existing route to sustain overweight truckloads over a specified design period (*29*). OTRA includes a layered elastic pavement model for predicting the induced response under surface wheel loads given the modulus, thickness, and Poisson's ratio of each pavement layer. The ratio of the expected number of yearly load applications to the allowable number of repetitions prior to failure provides an estimate of the life consumed per year of the design period. Figure 64 illustrates the calculation of service life consumed per truck application. The service life predictions for the route analyzed are then used to compute the probability P_{fail} that the service life is less than the specified design period. Pavement reliability R is then evaluated as $1 - P_{fail}$. The reliability from OTRA is used to determine whether an existing route is structurally adequate to sustain the expected axle load applications over the design period.

Figure 63 summarizes the remaining life predictions using OTRA. As in the case of the MODULUS analysis, the vertical axis represents relative frequency with respect to the total number of ½-mile segments used for the analysis (710). The highest frequency of remaining life predictions (48 percent) fell within the 0–2 year bin (i.e., the pavement on those segments is considered failed). About 14 percent of the pavements tested fell within the 2–5 year bin (i.e., the pavement on those segments is expected to fail in the near future). In other words, according to the analysis using the OTRA program, at least 60 percent of the segments tested have pavements that have failed or are expected to fail within 5 years.



Axle group load	P_s	P_d	P_t
Predicted allowable repetitions to failure	$(N_f)_s$	$(N_f)_d$	$(N_f)_t$
Service life consumed for one axle group application	$\frac{1}{(N_f)_s}$	$\frac{1}{(N_f)_d}$	$\frac{1}{(N_f)_t}$
Service life consumed for one truck application		$\frac{1}{(N_f)_s} + \frac{1}{(N_f)_d} + \frac{1}{(N_f)_t}$	

Figure 64. Concept for the Estimation of Service Life in OTRA.

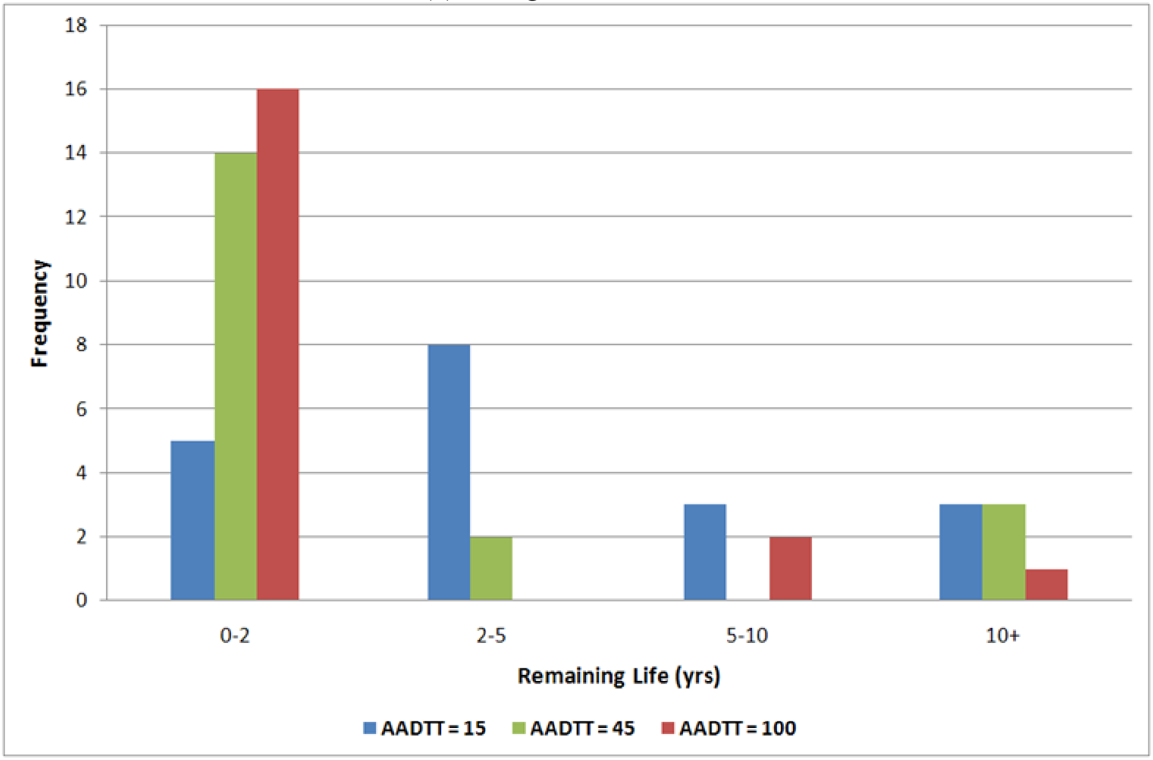
Sensitivity Analysis

Predictions of remaining pavement life are a function of the data that feed the calculations. As mentioned, one of the parameters about which there is considerable uncertainty is traffic volumes. In an effort to understand the sensitivity of the calculations to this parameter, the researchers selected two random corridors, varied the AADTT value for each of these corridors, and ran the MODULUS and OTRA programs for each AADTT value. For FM 97 (Lubbock District), the researchers assumed AADTT levels of 15, 45, and 100 (FY10 AADTT = 44, according to PMIS). For IH 35-1, the researchers assumed AADTT levels of 30, 60, and 120 (FY10 AADTT = 63).

As Figure 65 and Figure 66 show, higher AADTT values generally result in a larger number of segments having shorter remaining pavement lives. Conversely, lower AADTT values generally result in a larger number of segments having longer remaining pavement lives. This result, which is expected, strongly highlights the importance of collecting adequate traffic volume data (particularly heavy truck data) to ascertain both short-term and long-term impacts of heavy truck traffic on pavement structures. In Figure 65(b), the same number of segments was predicted to fail within 2 years for all three AADTT levels used in the analysis (when using OTRA), suggesting the pavement is already too deteriorated to sustain heavy truck traffic.

These results also suggest that software applications such as MODULUS 6 or OTRA could be used to manage corridors more effectively, provided basic information about the pavement structure on those corridors (e.g., by collecting GPR and FWD data) is available. For example, if there is a planned energy development and information can be gathered about the anticipated volume of heavy trucks associated with that development, the methodology described here could be used to measure the impact in terms of anticipated reduction in pavement life.

(a) Using MODULUS 6



(b) Using OTRA

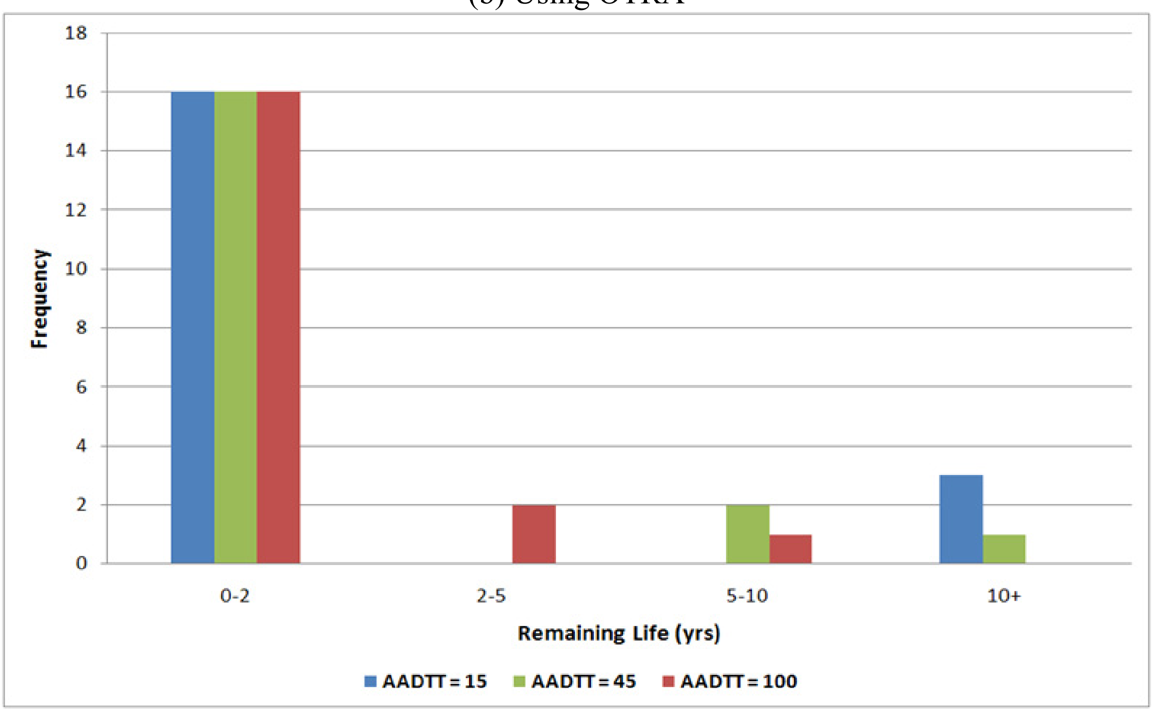
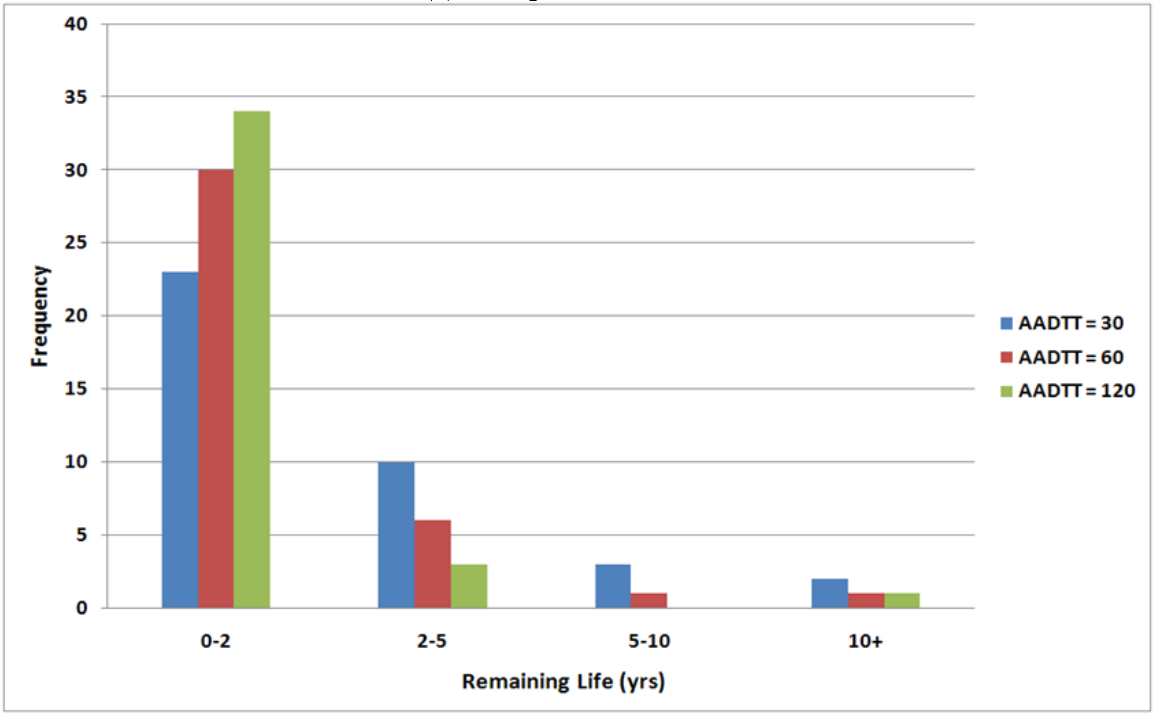


Figure 65. Sensitivity of Predicted Remaining Life to AADTT on FM 97.

(a) Using MODULUS 6



(b) Using OTRA

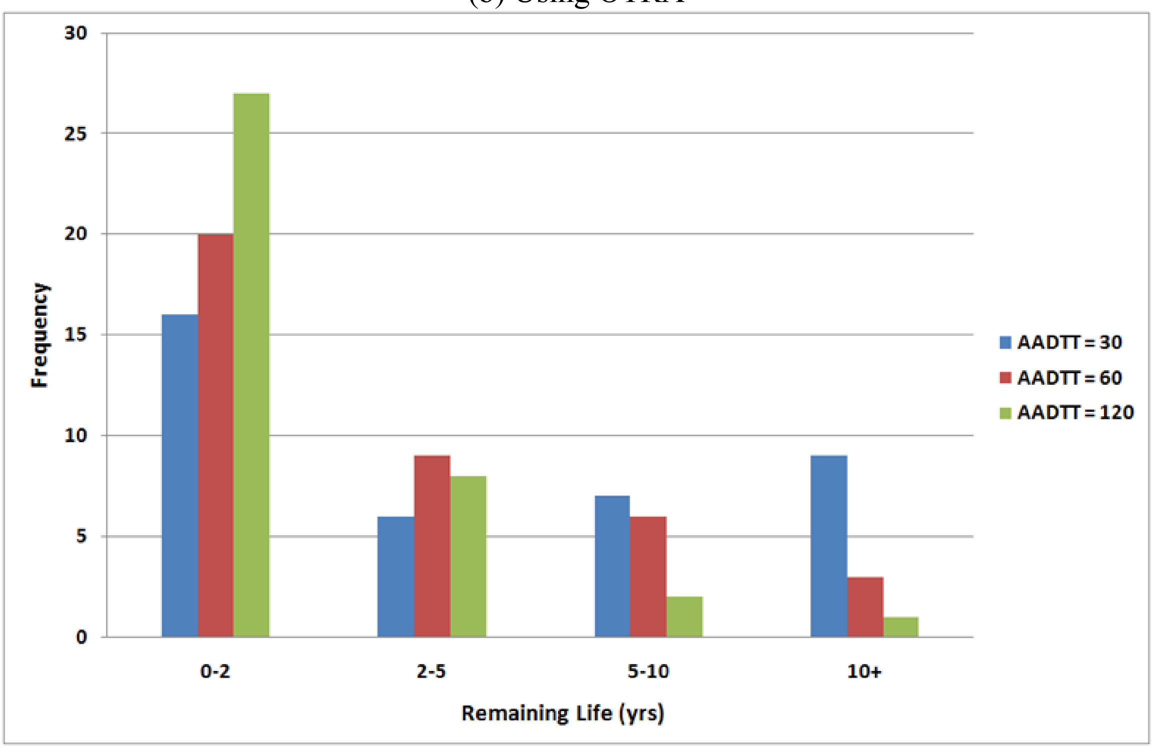


Figure 66. Sensitivity of Predicted Remaining Life to AADTT on IH 35W-2.

APPROXIMATE METHODOLOGY TO ESTIMATE REMAINING PAVEMENT LIFE FOR ENERGY DEVELOPMENTS

Based on the information gathered in the previous sections, the researchers developed a methodology to prepare approximate estimates of remaining pavement life for any section of roadway due to the cumulative impact of heavy truck traffic associated with energy developments. The result of the methodology is a tool that can be used for outreach and coordination activities with the energy industry. As such, it is more appropriate for planning and management purposes rather for detailed pavement analysis or design.

This methodology is based on several assumptions, including, but not limited to, the following:

- The analyst has some information about the roadway in question, more specifically the design ESALs (e.g., 750,000).
- Most of the impact from the energy development is due to heavy truck traffic needed for construction, equipment hauling, maintenance, and other activities associated with the development. For simplicity, the methodology assumes a typical five-axle (18-wheel), single trailer truck (Class 9 in Table 35). As needed, other types of trucks (e.g., carrying super heavy loads) could be added to the analysis.
- The analyst knows the size of the development, e.g., number of wells that will be drilled.
- The analyst knows the number of truckloads needed for each component and phase of the energy development.
- Environmental factors such as ice or flooding are ignored. Likewise, variations in soil or pavement foundation conditions are ignored.
- Each load application contributes to a reduction in pavement life. For simplicity, the reduction is assumed to be linear, i.e., the reduction in pavement life is a function of the cumulative number of load applications. The analysis assumes round trips in which the truck is fully loaded one way and empty the other way.
- The pavement structure is new at the beginning of the analysis. However, if there is information about the number of ESALs that have been applied to the pavement prior to the start of the energy development, the analyst could use that information to reduce the number of "available" ESALs at the beginning of the analysis.

The researchers implemented the methodology using Microsoft Excel. To illustrate its application, consider the development of a gas field that requires hydraulic fracturing and saltwater disposal facilities. As mentioned, the maximum amount of saltwater that can be injected into a saltwater facility is regulated by permit, which determines the maximum number of truckloads the facility can accommodate. For example, a facility permitted to inject 25,000 barrels per day could accommodate up to 243 truckloads per day (or 87,360 truckloads per year, assuming the facility operates 360 days per year). Converting these truckloads to ESALs using the equivalent load factors in Figure 52 results in 214,526 ESALs per year. This would be the number of ESALs applied to the pavement of a road in the immediate vicinity of the saltwater disposal facility.

The final step involves dividing the design ESALs by the total number of ESALs applied to the pavement per year to estimate the pavement life in years, e.g., 3.5 years for the 243 truckloads per day used in the example above, assuming a pavement that was designed for 750,000 ESALs (which is typical for a rural FM road). Table 28 shows truckloads, ESALs for various permitted limits, and the corresponding estimated pavement life for three different design ESALs: 750,000, 2,500,000, and 7,000,000.

Table 28. Pavement Life Reduction in Connection with Saltwater Disposal Facilities.

Saltwater Disposal Facility				Pavement Life (Years) for No. of Design ESALs		
Capacity barrels/day	No. truck loads per day	No. truck loads per year	No. ESALs used per year	750,000	2,500,000	7,000,000
1,000	10	3,494	8,581	87.4	291.3	815.8
3,000	29	10,483	25,743	29.1	97.1	271.9
10,000	97	34,944	85,810	8.7	29.1	81.6
20,000	194	69,888	171,621	4.4	14.6	40.8
25,000	243	87,360	214,526	3.5	11.7	32.6
30,000	291	104,832	257,431	2.9	9.7	27.2
37,000	359	129,293	317,499	2.4	7.9	22.0

Estimating the pavement life of roadway segments around the locations where gas drilling takes place requires knowing the number of wells and the number of truckloads used during the various phases of the development. For illustration purposes, consider the following numbers, which were mentioned previously in connection with the Barnett Shale:

- 187 truckloads during pad site preparation, rig mobilization, drilling operations, and rig removal. Duration: 25 days.
- 997 truckloads during hydraulic fracturing operations, assuming 3.7 million gallons (or 88,100 barrels) of water needed for fracking. Duration: 14 days.
- 88 truckloads per year for maintenance, most of which involves saltwater loads for gas well injections.
- 997 truckloads every 5–10 years for refracking.

Table 29 shows the impact on pavement life in connection with these activities, assuming an energy development that includes 100 gas well locations. The table shows truckloads per well for each activity (e.g., drilling or annual maintenance), cumulative truckloads for all 100 wells, the corresponding number of ESALs that are applied to the pavement, and the remaining ESALs. For example, after drilling and fracking, a pavement that was designed for 750,000 ESALs (which is typical for a rural FM road) would have 459,250 ESALs left. After the first year of gas well maintenance activities, the pavement would have 437,640 ESALs left. At this rate, assuming refracking every five years, the pavement would reach the end of its life sometime before the end of Year 10.

For comparison purposes, Table 30 shows the impact on pavement life, assuming the energy development has 200 gas well locations. In this case, a pavement that was designed for 750,000 ESALs would only have 168,500 ESALs left after drilling and fracking, and would reach the end of its life sometime before the end of Year 4. Although extreme, this example shows how the methodology can be used to estimate pavement life for a variety of scenarios and conditions.

The methodology can also be used to conduct a variety of sensitivity analyses and "what if" scenarios. For example, assume there is uncertainty regarding the number of truckloads needed for annual maintenance. Table 29 assumes 88 truckloads per well and per year for this activity. However, if the number is 150 instead of 88, the methodology can be used to estimate the impact. In this case, the analysis indicates the 750,000-ESAL pavement would reach the end of its life sometime before the end of Year 6, i.e., four years earlier than originally estimated.

Interestingly, the methodology suggests the impact on pavement life due to annual truckloads needed for maintenance could be more important than the impact due to re-fracking frequency. For the example in Table 29, refracking once at the end of Year 10 instead of twice (i.e., at the end of Year 5 and then at the end of Year 10) would still cause the pavement to reach the end of its life sometime in Year 10. The difference is that this stage would be reached in the middle of the refracking operations in Year 10.

Table 29. Sample Pavement Life Analysis for a Gas Development (100 Wells).

		Design ESALS		
Type of Facility	**Gas well locations**			
Number of wells served by road	**100**	**750,000**	**2,500,000**	**7,000,000**

Year	Truck loads	Truckloads			ESALs	Remaining ESALs		
		Delta	Cumul/well	Cumulative				
0	Drilling	187	187	18,700	45,921	704,079	2,454,079	6,954,079
0	Fracking	997	1,184	118,400	290,750	459,250	2,209,250	6,709,250
1	Annual maintenance	88	1,272	127,200	312,360	437,640	2,187,640	6,687,640
2	Annual maintenance	88	1,360	136,000	333,969	416,031	2,166,031	6,666,031
3	Annual maintenance	88	1,448	144,800	355,579	394,421	2,144,421	6,644,421
4	Annual maintenance	88	1,536	153,600	377,189	372,811	2,122,811	6,622,811
5	Annual maintenance	88	1,624	162,400	398,799	351,201	2,101,201	6,601,201
5	Refracking (every 5 years)	997	2,621	262,100	643,628	106,372	1,856,372	6,356,372
6	Annual maintenance	88	2,709	270,900	665,238	84,762	1,834,762	6,334,762
7	Annual maintenance	88	2,797	279,700	686,847	63,153	1,813,153	6,313,153
8	Annual maintenance	88	2,885	288,500	708,457	41,543	1,791,543	6,291,543
9	Annual maintenance	88	2,973	297,300	730,067	19,933	1,769,933	6,269,933
10	Annual maintenance	88	3,061	306,100	751,677	(1,677)	1,748,323	6,248,323
10	Refracking (every 5 years)	997	4,058	405,800	996,506	(246,506)	1,503,494	6,003,494
11	Annual maintenance	88	4,146	414,600	1,018,116	(268,116)	1,481,884	5,981,884
12	Annual maintenance	88	4,234	423,400	1,039,725	(289,725)	1,460,275	5,960,275
13	Annual maintenance	88	4,322	432,200	1,061,335	(311,335)	1,438,665	5,938,665
14	Annual maintenance	88	4,410	441,000	1,082,945	(332,945)	1,417,055	5,917,055
15	Annual maintenance	88	4,498	449,800	1,104,555	(354,555)	1,395,445	5,895,445
15	Refracking (every 5 years)	997	5,495	549,500	1,349,384	(599,384)	1,150,616	5,650,616
16	Annual maintenance	88	5,583	558,300	1,370,994	(620,994)	1,129,006	5,629,006
17	Annual maintenance	88	5,671	567,100	1,392,603	(642,603)	1,107,397	5,607,397
18	Annual maintenance	88	5,759	575,900	1,414,213	(664,213)	1,085,787	5,585,787
19	Annual maintenance	88	5,847	584,700	1,435,823	(685,823)	1,064,177	5,564,177
20	Annual maintenance	88	5,935	593,500	1,457,433	(707,433)	1,042,567	5,542,567
20	Refracking (every 5 years)	997	6,932	693,200	1,702,262	(952,262)	797,738	5,297,738

Table 30. Sample Pavement Life Analysis for a Gas Development (200 Wells).

Type of Facility	Gas well locations	Design ESALS		
Number of wells served by road	200	750,000	2,500,000	7,000,000

Year	Truck loads	Truckloads			ESALs	Remaining ESALs		
		Delta	Cumul/well	Cumulative				
0	Drilling	187	187	37,400	91,842	658,158	2,408,158	6,908,158
0	Fracking	997	1,184	236,800	581,500	168,500	1,918,500	6,418,500
1	Annual maintenance	88	1,272	254,400	624,719	125,281	1,875,281	6,375,281
2	Annual maintenance	88	1,360	272,000	667,939	82,061	1,832,061	6,332,061
3	Annual maintenance	88	1,448	289,600	711,158	38,842	1,788,842	6,288,842
4	Annual maintenance	88	1,536	307,200	754,378	(4,378)	1,745,622	6,245,622
5	Annual maintenance	88	1,624	324,800	797,598	(47,598)	1,702,402	6,202,402
5	Refracking (every 5 years)	997	2,621	524,200	1,287,256	(537,256)	1,212,744	5,712,744
6	Annual maintenance	88	2,709	541,800	1,330,475	(580,475)	1,169,525	5,669,525
7	Annual maintenance	88	2,797	559,400	1,373,695	(623,695)	1,126,305	5,626,305
8	Annual maintenance	88	2,885	577,000	1,416,914	(666,914)	1,083,086	5,583,086
9	Annual maintenance	88	2,973	594,600	1,460,134	(710,134)	1,039,866	5,539,866
10	Annual maintenance	88	3,061	612,200	1,503,353	(753,353)	996,647	5,496,647
10	Refracking (every 5 years)	997	4,058	811,600	1,993,012	(1,243,012)	506,988	5,006,988
11	Annual maintenance	88	4,146	829,200	2,036,231	(1,286,231)	463,769	4,963,769
12	Annual maintenance	88	4,234	846,800	2,079,451	(1,329,451)	420,549	4,920,549
13	Annual maintenance	88	4,322	864,400	2,122,670	(1,372,670)	377,330	4,877,330
14	Annual maintenance	88	4,410	882,000	2,165,890	(1,415,890)	334,110	4,834,110
15	Annual maintenance	88	4,498	899,600	2,209,109	(1,459,109)	290,891	4,790,891
15	Refracking (every 5 years)	997	5,495	1,099,000	2,698,768	(1,948,768)	(198,768)	4,301,232
16	Annual maintenance	88	5,583	1,116,600	2,741,987	(1,991,987)	(241,987)	4,258,013
17	Annual maintenance	88	5,671	1,134,200	2,785,207	(2,035,207)	(285,207)	4,214,793
18	Annual maintenance	88	5,759	1,151,800	2,828,426	(2,078,426)	(328,426)	4,171,574
19	Annual maintenance	88	5,847	1,169,400	2,871,646	(2,121,646)	(371,646)	4,128,354
20	Annual maintenance	88	5,935	1,187,000	2,914,865	(2,164,865)	(414,865)	4,085,135
20	Refracking (every 5 years)	997	6,932	1,386,400	3,404,524	(2,654,524)	(904,524)	3,595,476

Table 31. Sample Pavement Life Analysis for a Gas Development (Impact of Annual Maintenance Truckloads).

Type of Facility	Gas well locations
Number of wells served by road	100

Design ESALS		
750,000	2,500,000	7,000,000

Year	Truck loads	Truckloads			ESALs	Remaining ESALs		
		Delta	Cumul/well	Cumulative				
0	Drilling	187	187	18,700	45,921	704,079	2,454,079	6,954,079
0	Fracking	997	1,184	118,400	290,750	459,250	2,209,250	6,709,250
1	Annual maintenance	150	1,334	133,400	327,585	422,415	2,172,415	6,672,415
2	Annual maintenance	150	1,484	148,400	364,420	385,580	2,135,580	6,635,580
3	Annual maintenance	150	1,634	163,400	401,254	348,746	2,098,746	6,598,746
4	Annual maintenance	150	1,784	178,400	438,089	311,911	2,061,911	6,561,911
5	Annual maintenance	150	1,934	193,400	474,924	275,076	2,025,076	6,525,076
5	Refracking (every 5 years)	997	2,931	293,100	719,753	30,247	1,780,247	6,280,247
6	Annual maintenance	150	3,081	308,100	756,588	(6,588)	1,743,412	6,243,412
7	Annual maintenance	150	3,231	323,100	793,423	(43,423)	1,706,577	6,206,577
8	Annual maintenance	150	3,381	338,100	830,258	(80,258)	1,669,742	6,169,742
9	Annual maintenance	150	3,531	353,100	867,093	(117,093)	1,632,907	6,132,907
10	Annual maintenance	150	3,681	368,100	903,928	(153,928)	1,596,072	6,096,072
10	Refracking (every 5 years)	997	4,678	467,800	1,148,757	(398,757)	1,351,243	5,851,243
11	Annual maintenance	150	4,828	482,800	1,185,591	(435,591)	1,314,409	5,814,409
12	Annual maintenance	150	4,978	497,800	1,222,426	(472,426)	1,277,574	5,777,574
13	Annual maintenance	150	5,128	512,800	1,259,261	(509,261)	1,240,739	5,740,739
14	Annual maintenance	150	5,278	527,800	1,296,096	(546,096)	1,203,904	5,703,904
15	Annual maintenance	150	5,428	542,800	1,332,931	(582,931)	1,167,069	5,667,069
15	Refracking (every 5 years)	997	6,425	642,500	1,577,760	(827,760)	922,240	5,422,240
16	Annual maintenance	150	6,575	657,500	1,614,595	(864,595)	885,405	5,385,405
17	Annual maintenance	150	6,725	672,500	1,651,430	(901,430)	848,570	5,348,570
18	Annual maintenance	150	6,875	687,500	1,688,265	(938,265)	811,735	5,311,735
19	Annual maintenance	150	7,025	702,500	1,725,099	(975,099)	774,901	5,274,901
20	Annual maintenance	150	7,175	717,500	1,761,934	(1,011,934)	738,066	5,238,066
20	Refracking (every 5 years)	997	8,172	817,200	2,006,763	(1,256,763)	493,237	4,993,237

CHAPTER 5. ROADSIDE IMPACTS

INTRODUCTION

This chapter summarizes the work completed to evaluate the impact of energy developments on the state highway right-of-way, more specifically in the following areas:

- Accommodation of energy-related facilities on the state right-of-way.
- Access to the state right-of-way from adjacent areas undergoing energy-related activities.
- Management of mineral rights within the state right-of-way.

The state right-of-way is a huge, valuable asset that involves the application of a wide range of business processes. Understanding the impact of increased energy activities on that asset and the corresponding business processes is necessary in order to develop appropriate implementation recommendations.

ACCOMMODATION OF ENERGY FACILITIES ON THE STATE RIGHT-OF-WAY

The researchers examined a sample of utility permit applications, obtained information from TxDOT districts, and reviewed the utility accommodation rules (UARs) in the Texas Administrative Code (*30*) to determine trends and potential impacts on TxDOT business practices. For utility permitting sample documentation, the researchers used sample records and data from the Utility Installation Review (UIR) system. For consistency with other analyses completed during the research, the focus was on utility permit applications in Abilene, Lubbock, and Fort Worth Districts. In addition, the researchers looked at trends at districts affected by recent energy developments (primarily oil and gas) in connection with the Eagle Ford Shale formation in southeast Texas (i.e., Corpus Christi, Laredo, San Antonio, and Yoakum).

Anecdotal information from district officials indicates that one of the results of energy-related activities is an increase in the number of utility permits in those areas. For example, districts have reported an increase in the number of oil and gas pipeline crossing permit applications in areas of active oil or gas production. District officials also indicated a secondary increase in other types of utility installations, e.g., data communication and electric lines to provide temporary or permanent support to energy-related activities.

Although the UIR system provides a great deal of information in connection with individual permit applications (including location, permit application documentation, special approval provisions, and communications), the system has only been in place since 2005, which limits the usability of the data for this research. Through the end of 2008, the system was operational in five districts (San Antonio, since 09/2005; Pharr, since 06/2006; Bryan, since 05/2007; Fort Worth, since 06/2007; and Houston, since 09/2007). In 2009 and 2010, TxDOT provided training to the rest of the districts. All districts are now receiving utility permit applications online. For illustration purposes, Table 32 shows the earliest dates of utility permit records in UIR for the districts studied in this research.

Table 32. Month and Year District Started Processing Utility Permits Using UIR.

District	In UIR Since	Energy Development Relationship
San Antonio	09/2005	Eagle Ford Shale
Fort Worth	06/2007	Barnet Shale
Lubbock	04/2010	Oil, gas, and wind
Yoakum	04/2010	Eagle Ford Shale
Abilene	05/2010	Oil, gas, and wind
Laredo	05/2010	Eagle Ford Shale
Corpus Christi	06/2010	Eagle Ford Shale

For illustration purposes, Table 33 shows the number of oil and gas permit applications logged in UIR for individual counties at selected districts in which TxDOT officials indicated recent energy-related activities. Note the following:

- At the Fort Worth District, the number of gas-related utility permits is quite significant, particularly in Johnson and Tarrant Counties. Permit activity decreased in 2009, but increased again in 2010, particularly in Tarrant County.

- At the San Antonio District, there was significant gas-related utility permitting activity in Atascosa County in 2007 and 2008. There was a drastic decrease at that county in 2009, but it increased again in 2010. Gas and, to some degree, oil permits have been issued at Frio, McMullen, and Wilson Counties. Overall, the number of gas permits in these counties is lower than in the Fort Worth area. However, it is likely the number of permits in San Antonio District counties will increase since production activity at the Eagle Ford Shale is in its early stages.

- Yoakum, Laredo, and Corpus Christi have all experienced a significant number of gas-related, at to some degree, oil-related utility permits. As in San Antonio, it is likely the number of oil and gas utility permits at those districts will increase as the production activity at the Eagle Ford Shale continues to increase.

An area of interest to TxDOT was any potential impact from the use of gathering lines in connection with gas developments longitudinally along the state right-of-way. According to the Texas Administrative Code (*30*), a gathering line is "a line that delivers a raw utility product from various sites to a central distribution or feed line for the purposes of refining, collecting, or storing the product." The TAC also defines a high-pressure line as a line that is expected to operate at over 60 lb per square inch (psi) and a low-pressure line as a line that is expected to operate at 60 psi or lower.

A search of UIR records revealed eight permit applications through the end of 2010 for which the utility installation type was "gas" and the description included the term "gathering line." All records involved state highway crossings but not longitudinal installations within the state right-of-way. In several cases, the crossing connected gas lines that ran outside and parallel to the state right-of-way on private easements. Most crossing permits were for high-pressure gas lines (typical operating pressure between 650 and 1,100 psi).

Table 33. Oil and Gas Utility Permits for Selected Counties in UIR.

District	Utility	County	2007 [1]	2008	2009	2010 [1]
Fort Worth	Gas	Jack	3	6	0	13
		Johnson	46	60	18	15
		Palo Pinto	1	13	4	5
		Parker	13	27	7	7
		Tarrant	32	75	34	73
		Wise	4	24	13	18
		Total	**99**	**205**	**76**	**131**
Fort Worth	Oil	Jack	1	0	0	2
		Johnson	1	0	1	0
		Palo Pinto	0	1	0	0
		Parker	0	0	0	0
		Tarrant	0	2	1	0
		Wise	0	0	0	2
		Total	**2**	**3**	**2**	**4**
San Antonio	Gas	Atascosa	16	5	3	7
		Frio	2	1	6	2
		McMullen	0	0	3	3
		Wilson	2	0	4	3
		Total	**20**	**6**	**16**	**15**
San Antonio	Oil	Atascosa	9	1	0	5
		Frio	1	0	0	0
		McMullen	0	0	0	2
		Wilson	0	0	0	0
		Total	**10**	**1**	**0**	**7**
Yoakum	Gas	De Witt	n/a	n/a	n/a	17
		Fayette	n/a	n/a	n/a	6
		Gonzales	n/a	n/a	n/a	2
		Lavaca	n/a	n/a	n/a	6
		Total	**0**	**0**	**0**	**31**
Yoakum	Oil	De Witt	n/a	n/a	n/a	6
		Fayette	n/a	n/a	n/a	0
		Gonzales	n/a	n/a	n/a	0
		Lavaca	n/a	n/a	n/a	0
		Total	**0**	**0**	**0**	**6**
Laredo	Gas	Dimmit	n/a	n/a	n/a	8
		La Salle	n/a	n/a	n/a	4
		Maverick	n/a	n/a	n/a	1
		Webb	n/a	n/a	n/a	3
		Total	**0**	**0**	**0**	**16**
Laredo	Oil	Dimmit	n/a	n/a	n/a	6
		La Salle	n/a	n/a	n/a	1
		Maverick	n/a	n/a	n/a	0
		Webb	n/a	n/a	n/a	1
		Total	**0**	**0**	**0**	**8**
Corpus Christi	Gas	Karnes	n/a	n/a	n/a	28
		Live Oak	n/a	n/a	n/a	10
		Total	**0**	**0**	**0**	**38**
Corpus Christi	Oil	Karnes	n/a	n/a	n/a	10
		Live Oak	n/a	n/a	n/a	7
		Total	**0**	**0**	**0**	**17**

Notes:

1 Starting dates varied: Fort Worth (06/2007); Yoakum (04/2010); Laredo (05/2010); Corpus Christi (06/2010).

For completeness, the researchers also ran a query to select any permit application for which the utility installation description included combinations of terms such as “gas,” “oil,” “petroleum,” “along,” and “longitudinal.” In this case, 197 records were retrieved through the end of 2010. Most permit applications were for low-pressure lines or for crossings that required a short segment along a state highway right-of-way. Only a handful of applications were for high-pressure longitudinal installations.

During the 81st session (regular) in 2009, the Texas Legislature passed House Bill (HB) 2572, which specifically enabled the installation of gas pipelines along public roads, including state highways (Figure 67), provided that pipelines comply with all applicable safety rules and regulations and that pipeline operators restore the right-of-way to its original condition after installation or maintenance activities. HB 2572 was the result of lobbying from a major gas energy developer to allow gas pipelines to run longitudinally within Interstate highway right-of-way or within controlled access areas in situations where access to a private easement (the preferred option for gas operators) is not otherwise possible or feasible.

There was not a law or regulation specifically prohibiting high-pressure gas lines along state highways prior to HB 2572. However, in 2004, TxDOT established an internal procedure requiring all high-pressure gas line proposals to be routed to the Maintenance Division (if submitted as part of a utility permit application) or the Right of Way Division (if submitted as part of a utility joint use agreement) for review and approval. The rationale for the internal procedure was safety concerns for TxDOT maintenance personnel, the roadway environment, and the public. As a result, access of high-pressure gas lines to the state right-of-way was often denied on safety grounds.

The legislature did not anticipate a significant fiscal impact to the state from the passage of House Bill 2572. However, the Railroad Commission was concerned that passage of the bill might make it much more difficult to verify compliance with pipeline safety regulations. In addition, TxDOT was concerned that passage of the bill could increase the number of lines on the state right-of-way and utility adjustment costs on interstate highways and toll roads, which, in turn, would result in increased administrative and inspection costs to the agency.

In December 2009, after the bill was passed, TxDOT revised Rule 21.36 (which had been in place since March 2005) (see Figure 68 and Figure 69) to require the submission of documentation certifying the applicant has been authorized to install, operate, and maintain facilities “over, under, across, on, or along state highways,” and the facilities are subject to public safety regulations.

In March 2010, the Fort Worth District issued a permit for the installation of an 8-inch high-pressure gas line (715 psi) within the state right-of-way of IH 30, which included approximately 1,000 ft of gas line on a longitudinal strip within the right-of-way on the north side of IH 30. The installation specifications called for open trench excavation in this area subject to conditions such as no equipment within 30 ft from the edge of pavement and no access to the utility facility from the highway (access would need to be secured from abutting property). Provisions also included a minimum cover depth of 6 ft and a concrete cap (6 inches × 3 times the pipe diameter, minimum reinforcement of wire mesh) located 1 ft below the natural ground grade and 4 ft above the pipe.

SECTION 1. Section 121.2025(a), Utilities Code, is amended to read as follows:

(a) Except as otherwise provided by this section or Section 182.025, Tax Code, a municipality may not assess a charge for the placement, construction, maintenance, repair, replacement, operation, use, relocation, or removal of a gas pipeline facility on, along, under, or across a public road, highway, street, alley, stream, canal, or other public way.

SECTION 2. Section 181.005, Utilities Code, is amended to read as follows:

Sec. 181.005. AUTHORITY TO LAY AND MAINTAIN LINES.

(a) A gas corporation has the right to lay and maintain lines over, along, under, and across a public road, a railroad, railroad right-of-way, an interurban railroad, a street railroad, a canal or stream, or a municipal street or alley only if:

(1) the pipeline complies with:
(A) all safety regulations adopted by the Railroad Commission of Texas and all federal regulations relating to pipeline facilities and pipelines; and
(B) all rules adopted by the Texas Department of Transportation or the Railroad Commission of Texas and all federal regulations regarding the accommodation of utility facilities on a right-of-way, including regulations relating to the horizontal or vertical placement of the pipeline; and
(2) the owner or operator of the pipeline ensures that the public right-of-way and any associated facility are promptly restored to their former condition of usefulness after the installation or maintenance of the pipeline.

(b) The right granted by Subsection (a) relating to the use of a municipal street or alley is subject to the payment of charges in accordance with Section 121.2025 of this code and Sections 182.025 and 182.026, Tax Code.

(c) In determining the route of a pipeline within a municipality, a gas corporation shall consider using existing easements and public rights-of-way, including streets, roads, highways, and utility rights-of-way. In deciding whether to use a public easement or right-of-way, the gas corporation shall consider whether:

(1) the use is economically practicable;
(2) adequate space exists; and
(3) the use will violate, or cause the violation of any pipeline safety regulations.

(d) The Texas Department of Transportation may require the owner or operator of a pipeline to relocate the pipeline:

(1) at the expense of the owner or operator of the pipeline, if the pipeline is located on a right-of-way of the state highway system;
(2) at the expense of this state, if the pipeline is located on property in which the owner or operator of the pipeline has a private interest; or
(3) in accordance with Section 203.092, Transportation Code, at the expense of this state, if the pipeline is owned or operated by a gas utility as defined by Section 181.021 of this code or a common carrier as defined by Chapter 111, Natural Resources Code.

(e) Rules adopted by the Texas Department of Transportation regarding horizontal and vertical placement of pipelines must be reasonable and, for rights-of-way of the state highway system, must provide an appeals process through the Texas Department of Transportation.

SECTION 3. This Act takes effect immediately if it receives a vote of two-thirds of all the members elected to each house, as provided by Section 39, Article III, Texas Constitution. If this Act does not receive the vote necessary for immediate effect, this Act takes effect September 1, 2009.

Figure 67. HB 2572 – 81st Texas Legislature (Regular).

(a) Under state law, certain utilities have a right to operate, construct, and maintain their lines over, under, across, on, or along highways, subject to highway purposes. This includes utilities authorized by law to transport or distribute natural gas, water, electric power, telephone, cable television, or salt water and those that are authorized to construct and operate common carrier petroleum and petroleum product lines.

(b) Private lines may cross, but are not permitted longitudinally on highway rights of way. This includes privately-owned lines from gas or oil wells, lines owned by oil companies within refinery and oil storage complexes or by firms engaged in businesses other than those described in subsection (a) of this section, private purpose lines of an entity described in subsection (a) of this section, and service lines owned by individuals.

Figure 68. Utility Accommodation Rule 21.36 (03/17/2005–12/09/2009).

(a) Under state law, public utilities have a right to operate, construct, and maintain their facilities over, under, across, on, or along highways, subject to highway purposes. This includes entities authorized by law to transport or distribute natural gas, water, electric power, telephone, cable television, or salt water and those that are authorized to construct and operate common carrier petroleum and petroleum product lines.

(b) A private utility may place a utility facility over, under, or across a highway, subject to highway purposes, but it is not permitted to place a utility facility longitudinally on a highway right of way.

(c) If an entity requests the installation of a new utility facility or the adjustment or relocation of an existing utility facility longitudinally within a highway right of way and the entity's legal authority to install, adjust, or relocate its facility longitudinally within the highway right of way is not readily evident, the department may require that the entity provide:

(1) a written certification that it is an entity authorized by state law to operate, construct, and maintain its utility facilities over, under, across, on, or along state highways; and
(2) documentation that substantiates that the entity filed its status with the applicable state regulatory commission or agency and its facilities are subject to public safety regulation.

Figure 69. Utility Accommodation Rule 21.36 (12/10/2009–Present).

Overall observations related to energy-related utility installations within the state right-of-way include the following:

- The state will likely continue to experience an increase in utility permits in connection with energy developments. TxDOT already has an effective tool (the web-based UIR system) to track and manage the review of utility permit applications. Challenges for TxDOT will be related to the department's ability to monitor and inspect the construction and maintenance of utility facilities effectively.

- The utility accommodation rules in the Texas Administrative Code appear to be adequate to help TxDOT manage the increased influx of utility installations in connection with energy developments. An area to monitor in the future is the possibility of additional high-pressure gas lines along state roads since it is too early to assess the impact of HB 2572 on TxDOT operations.

ACCESS TO THE RIGHT-OF-WAY FROM ADJACENT AREAS

As part of the analysis, the researchers reviewed TxDOT's access management policy and requirements and examined sample driveways on selected corridors affected by energy developments.

The TxDOT *Access Management Manual* includes requirements for driveway spacing, design, and other considerations for a wide range of applications, including residential and commercial applications, as well urban and rural environments (*31*). The *Access Management Manual* includes references to a number of other publications, including the TxDOT *Roadway Design Manual* (*23*) and TxDOT's bridge standards for safety end treatments (*32*), as well as federal and state accessibility guidelines.

Figure 70 shows the basic design elements associated with a driveway. Not shown in the figure are drainage and surface cover elements. Table 34 shows the current design requirements for two-way commercial driveways, as described in the TxDOT *Road Design Manual* (*23*). This manual clarifies that the requirements in Table 34 are for two-way commercial driveways that would be expected to accommodate only "P" and "SU" design vehicles. Further, the manual indicates that designs for larger vehicles are considered on a case-by-case basis, but does not provide guidance as to what values to use or references that access permit applicants could use to prepare drawings and permit applications.

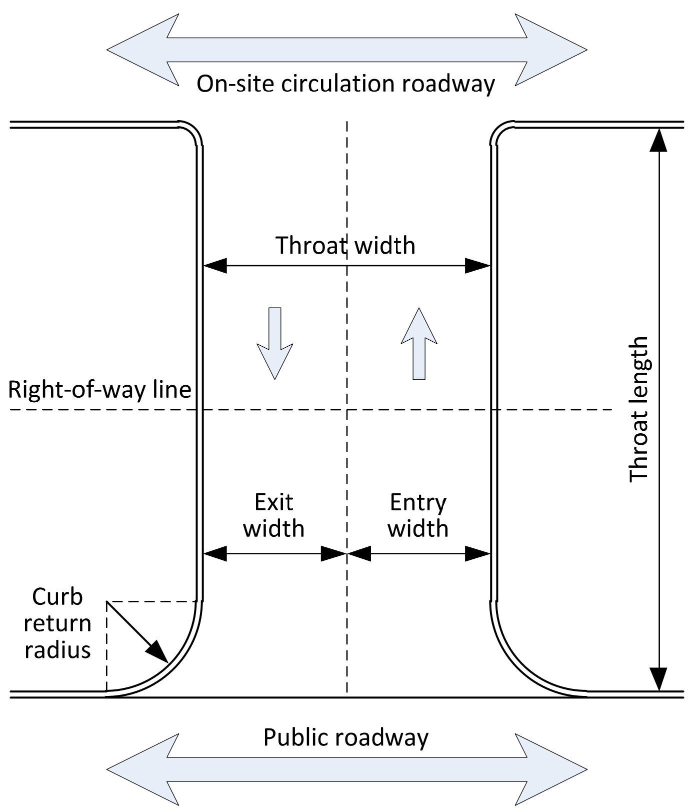


Figure 70. Driveway Design Elements (*23*).

Table 34. Design Requirements for Two-Way Commercial Driveways (*23*).

Condition	U.S. Customary Units		Metric Units	
	Curb Return Radius (ft)	**Throat Width (ft)**	**Curb Return Radius (m)**	**Throat Width (m)**
One entry lane and one exit lane, fewer than 4 large vehicles per hour	25	28	7.5	8.4
One entry lane and one exit lane, 4 or more SU vehicles[a] per day	30	30	9.0	9.0
One entry lane and two exit lanes, without divider	25	40	7.5	12.0
One entry lane and two exit lanes, with divider	25	44[b] – 50[c]	7.5	13.2[b] – 15.0[c]
Two entry lanes and two exit lanes, with divider	25	56[b] – 62[c]	7.5	16.8b[2] – 18.9[c]

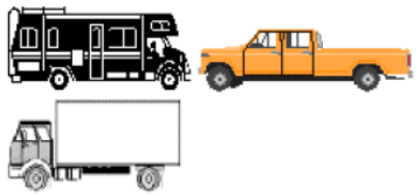
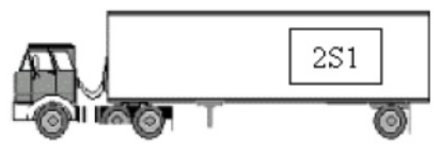
Notes:
[a] Driveway designs for larger vehicles will be considered on a case-by-case basis
[b] 4 ft (1.2 m) wide divider, face-to-face curbs
[c] 10 ft (3.0 m) wide divider, face-to-face curbs

The *Road Design Manual* does not describe or define what "P" or "SU" design vehicles are. The TxDOT *Traffic Data and Analysis Manual* includes sketches of a variety of vehicle classifications (both Texas 6 vehicle classifications and FHWA vehicle classifications) (*33*). Table 35 shows some relevant vehicle classification entries in the *Traffic Data and Analysis Manual* (*33*). As documented in the field visits, a typical water truck used for gas well fracking activities is a five-axle (18-wheel), single trailer truck (Class 9 in Table 35).

The *Access Management Manual* includes some requirements for the design of drainage elements. For example, the manual indicates that highway side ditches should not be altered or impeded, and that the driveway should be designed and built in a manner that will not impede the flow of water away from the highway pavement. The manual also indicates that if the driveway is approved to be constructed at grade through the roadside ditch or natural grade of the roadside, the driveway should be paved with a stabilized all-weather surface material acceptable to TxDOT. However, the manual does not define what a "stabilized all-weather surface material" is or where to find the specifications for such a material.

The *Access Management Manual* indicates that approved safety end treatments can be found at "standard CAD drawing under Bridge Standards for Safety End Treatments" without pointing the reader to the exact location on the TxDOT website where this information could be found. Further, although it provides information about design requirements for safety end treatments, the manual indicates that the most frequently used standard is "Parallel Drainage for 12"–72" Diameter."

Table 35. Texas 6 and FHWA Vehicle Classification Sample (*33*).

Texas 6 Class 4 – 2D, 6-Tire Single Unit FHWA Class 5 – 2D, 6-Tire Single Unit 	Texas 6 Class 5 – 3 Axles, Single Unit FHWA Class 6 – 3 Axles, Single Unit 
Texas 6 Class 6 – 4 or More Axles, Single Unit FHWA Class 7 – 4 or More Axles, Single Unit 	Texas 6 Class 7 – 3 Axles, Single Trailer FHWA Class 8 – 3 to 4 Axles, Single Trailer 
Texas 6 Class 8 – 4 Axles, Single Trailer FHWA Class 8 – 3 to 4 Axles, Single Trailer  	Texas 6 Class 9 – 5 Axles, Single Trailer FHWA Class 9 – 5 Axles, Single Trailer 

In general, the existing manuals are silent on critical related matters, e.g., how to treat the roadway section in the immediate vicinity of the access location to ensure adequate traffic flow conditions, or the need to comply with applicable *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) provisions. The manuals are also silent on strategies to mitigate or prevent damage to the pavement structure in the immediate vicinity of the access location.

The responsibility for specifying driveway permit requirements to individual access permit applicant lies frequently with maintenance supervisors. However, given the lack of clarity, completeness, and detail in the existing manuals, it is not difficult to imagine that officials in the field would have a hard time developing and implementing driveway permit specifications that are not just reasonable but also truly enforceable.

During the field visits to the Abilene, Fort Worth, and Lubbock Districts, the researchers had ample opportunity to examine examples of poor driveway construction practices. Figure 71, Figure 72, and Figure 73 show three such examples.

Figure 71. Drainage Problems and Mud Tracking (Abilene District).

Figure 72. Tire Tracks on Driveway End Treatment and Illegal Left Turns (Fort Worth District).

Note: This driveway is not associated with an energy development, but is useful to illustrate issues related to drainage structures and safety end treatment at driveways subject to heavy truck traffic. This figure shows an entrance to a dairy farm.

Figure 73. Drainage and Safety End Treatment Issues (Lubbock District).

Problems are not just limited to driveway access points. The researchers also noted problems at intersections between county roads and state roads where there is heavy traffic related to energy developments (see Figure 74).

During the field visits, district officials also mentioned situations where energy developers use existing farm or ranch driveways to provide access to their equipment. In those situations, it is common for the energy developer not to request a driveway permit. The *Roadway Design Manual* (*23*) requires a typical farm or ranch driveway to provide a 25-ft return radii and a 20-ft throat width. The manual highlights that the distance from the edge of pavement must be sufficient to store the longest vehicle or combination of vehicles expected (e.g., a truck with a trailer). This type of driveway is insufficient for a typical energy development project.

Alligator cracking Shoulder patches, cracked seals

Figure 74. T-Intersection between County Road and State Road. The Intersection Also Has Visibility Problems (Fort Worth District).

Overall observations related to energy-related access management practices within the state right-of-way include the following:

- There is an urgent need to improve existing manuals at TxDOT to assist energy developers in the process to design, build, and maintain driveways they need to access the state highway network. The revised manuals should include more detailed, appropriate information about geometric design considerations, drainage specifications, and safety end treatments. The manuals should also provide information about traffic flow controls and compliance, as well as strategies to mitigate (or better yet, prevent) damage to the pavement structure in the immediate vicinity of the access points. The overall goal of these strategies should be to construct and operate driveways in connection with energy development in such a way that the state highway network does not suffer any short-term or long-term negative impacts. In connection with improvements in manuals and other documents, there is also a need to develop training materials for district maintenance personnel to implement and enforce the updated requirements.

- Similar improvements are also needed in connection with intersections between county roads and state roads.

MANAGEMENT OF MINERAL RIGHTS WITHIN THE STATE RIGHT-OF-WAY

Of particular interest was to examine issues and opportunities regarding the management of mineral rights owned by the state in areas where there are active energy-related activities. To this end, the researchers reviewed relevant documentation and met with Texas General Land Office (GLO) officials.

The GLO manages state lands and mineral rights covering approximately 20 million acres that include properties in West Texas, Gulf Coast beaches and bays, and all "submerged" lands 10.35 miles out into the Gulf of Mexico. It also manages land and timberlands in East Texas.

A primary GLO responsibility is to manage lands and mineral rights for the benefit of the Permanent School Fund (PSF), i.e., the endowment fund established in 1876 to help support public schools in Texas. State lands dedicated to the PSF include 13 million acres, i.e., approximately 65 percent of the state land and mineral rights the GLO manages. Land management includes sales, trades, leases, and improvements, as well as administration of contracts, mineral royalty rates, and other transactions. Most of the revenue comes from oil and gas leases. The GLO also leases state lands for mining minerals such as limestone, gravel, coal, and sulfur. The State Board of Education distributes the interest earned on PSF investments to school districts in Texas on a per-pupil basis. The GLO also deposits fines on unpaid or late royalties, commercial leasing revenues, and outer continental shelf pipeline fees into the PSF. In 2005, the GLO received the authority to invest in real estate using proceeds received from the sale of PSF lands and revenue from PSF mineral leases and royalties.

The GLO is also responsible for managing mineral rights the state owns within the state highway right-of-way in accordance with Chapters 32 and 52 of the Natural Resources Code (*34*, *35*). All mineral right revenues in this category are dedicated to the State Highway Fund (Category 6). As Table 36 shows, only a small fraction of the total GLO revenue is in connection with the State Highway Fund. Another revenue source at the GLO is the sale of energy to public entities. The GLO sells both natural gas and electricity to schools, cities, and other public-sector agencies.

Table 36. Permanent School Fund versus State Highway Fund Revenue Comparison.

GLO Revenue	2008	2009
State Highway Fund	$4,978,104	$7,525,216
Permanent School Fund	$540,267,695	$387,669,276

According to the GLO, roads that were conveyed to the state prior to around 1940 included mineral rights. After 1940, deeds have generally excluded mineral rights, i.e., grantors keep the mineral rights under the road. If the state, county, or city only obtains an easement to develop the road, the grantor typically retains title to the underlying fee, including minerals. Under these conditions, conveyance of land bounded by a public highway carries with it the fee to the center of the road (*36*).

The GLO has a formal procedure for leasing mineral rights under state highway right-of-way tracts (*37*). In general, a highway right-of-way tract may be leased if the state owns the mineral rights under the tract and if the right-of-way is not within 2,500 ft of a well capable of producing in paying quantities as of January 1, 1985. The 2,500-ft limitation may be deleted if the lease is for drilling a horizontal well. The School Land Board can establish the size and boundaries of each right-of-way tract to be leased or to be exempted from leasing. Right-of-way tracts must extend across the width of the highway right-of-way since the leasing transaction involves adjacent tracts.

The GLO does not have an official record of the state-owned highway right-of-way. As a result, the burden is on lease applicants to provide sufficient documentation of all mineral rights, including those associated with tracts adjacent to the right-of-way. GLO procedures describe steps to follow where the adjacent mineral rights are leased versus not leased. The GLO uses a database to store lease information. However, the database does not include information about how many miles of highway are leased. Leases are described by acreage and by deed reference. The GLO maintains highway lease records. Until about 1995, it used to send copies of these records to the TxDOT Right of Way Division.

Mineral leases are normally issued for three years (or less depending on the situation). Reviewing and approving leases is a quick process. The GLO does not have a record of drilling operations or drilling permits. However, because leasing mineral rights usually takes place well in advance of drilling, lease records at the GLO could be used as an early "warning sign" so that other state agencies, including TxDOT, can become aware of upcoming energy developments and start preparing for them accordingly.

During negotiations with lease applicants, the GLO expects to get the best terms for the tract and, whenever possible, "cherry-picks" the terms based on information available from adjacent leases. Revenue from mineral leases is a function of commodity price and volume. The pricing structure includes the following elements:

- Cash bonus, which is an up-front payment the GLO receives. This payment depends on market conditions. For bidding purposes, the GLO does not accept bids that include a cash bonus of less than $10 per acre (*34*). However, in some cases, it could be substantially higher, e.g., $5,000 per acre or more. In highly desirable areas, this value could easily exceed the value of the surface estate.
- Royalty rate, which is a fraction of what the mineral right produces. For bidding purposes, the GLO does not accept bids with a royalty rate of less than ⅛ of the gross production of oil and gas.
- Rental fee.

The overall implications for TxDOT and financial impact related to the management of mineral rights within the state highway right-of-way are quite minor. Over the last two years, the state has received around only $5 million per year in connection with oil and gas leases on state highways. This level of revenue is not likely to increase any time soon. Unfortunately, the state does not have a good estimate of how much of the highway network the state actually owns in fee simple. However, even if a good estimate existed, it would probably be low (and certainly only a fraction of the estimated 1.1 million acres that occupy the state highway network).

CHAPTER 6. OPERATIONAL AND SAFETY IMPACTS

INTRODUCTION

This chapter describes two analyses the researchers conducted to determine the impact of energy-related developments on roadway operations and safety. The first analysis focused on crash rates in the Abilene, Lubbock, and Fort Worth Districts. The second analysis focused on commercial vehicle enforcement data.

CRASH DATA ANALYSIS

For the crash data analysis, the researchers analyzed 2003–2009 CRIS data. Appendix B shows details of the calculations. For each district, the analyses included a general comparison of crash rates between visited and control corridors, as well as district and state averages. The analysis also included a more detailed review of different crash types (e.g., intersection, driveway, severe). However, the frequency of crashes under those categories was too low to enable a meaningful determination of trends. Similar to the PMIS data analyses, the researchers combined rural major and minor collectors in the analysis, but analyzed rural minor arterials at the Fort Worth District separately.

At first, the researchers calculated crash rates by dividing the number of crashes found by the number of vehicle-miles traveled (VMT) based on traffic information in PMIS. However, because of concerns about the reliability of AADT data in the database (as well as the low frequency of crashes and low traffic volumes that characterize most rural highways where energy developments take place), the researchers decided to use distance (more specifically "100 miles") to estimate crash rates. Although this approach does not explicitly take exposure into consideration, at least it eliminates the issue of traffic volume uncertainty.

As the following subsections show in more detail, crash rates along visited corridors were generally higher than crash rates along control corridors and higher than crash rates for all district corridors. Strictly speaking, it is not possible to conclude that energy developments are responsible for the higher crash rates along the visited corridors because the existing data do not include any data elements connecting energy developments with crashes. It is possible that higher traffic volumes along visited corridors could result in a higher exposure that could explain the higher crash rates. However, even after normalizing crash rates by volume (i.e., by calculating the number of crashes per 100 million VMT), crash rates were still higher along visited corridors than along control corridors. Although circumstantial, this is an indication that corridors where energy developments take place have higher crash rates.

Crash Analysis – Lubbock District

Figure 75 shows 2003–2009 crash rates at the Lubbock District. Figure 76 shows 2003–2009 crash rates for crashes that involved commercial vehicles. Overall, corridors visited in the field exhibited similar crash rates to those along control corridors. Both visited and control corridors showed slightly lower crash rates than all state roads within the district. The crash rate for crashes involving commercial vehicles was low.

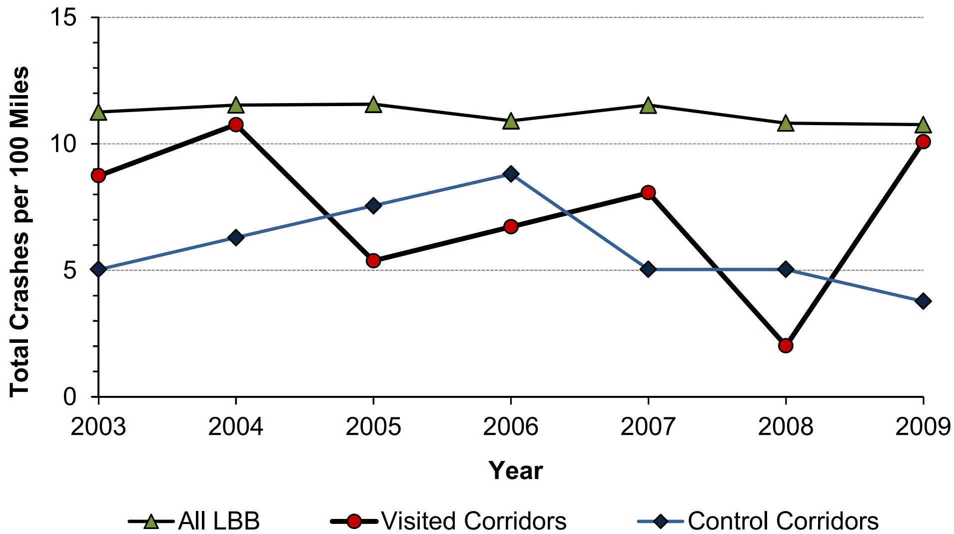


Figure 75. Crash Rates per 100 Miles (Lubbock District).

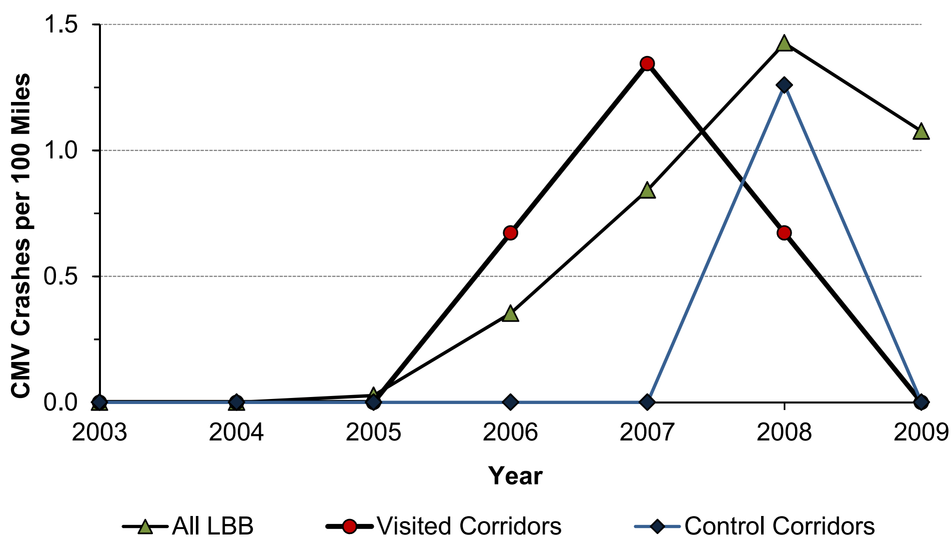


Figure 76. Crashes Involving Commercial Vehicles (Lubbock District).

Crash Analysis – Abilene District

Figure 77 shows 2003–2009 crash rates at the Abilene District. Figure 78 shows 2003–2009 crash rates for crashes that involved commercial vehicles. Overall, corridors visited in the field exhibited higher crash rates than both control corridors and all corridors in the district. These trends also apply to severe crashes, intersection crashes, and driveway crashes (although the number of crashes in these categories was too low to enable conclusive answers). The crash rate for crashes involving commercial vehicles was low. However, Figure 78 suggests a higher crash rate along visited corridors than along control corridors.

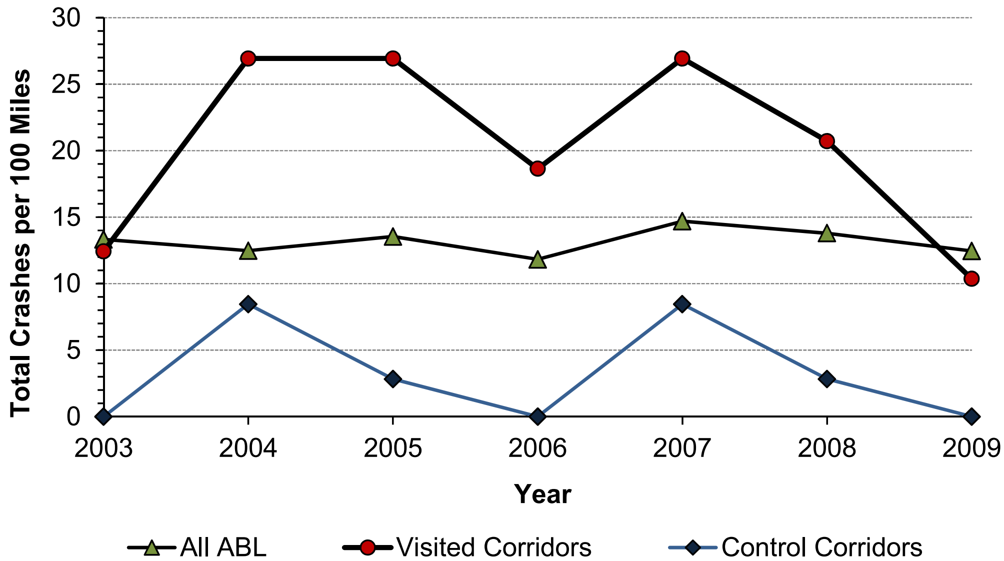


Figure 77. Crash Rates per 100 Miles (Abilene District).

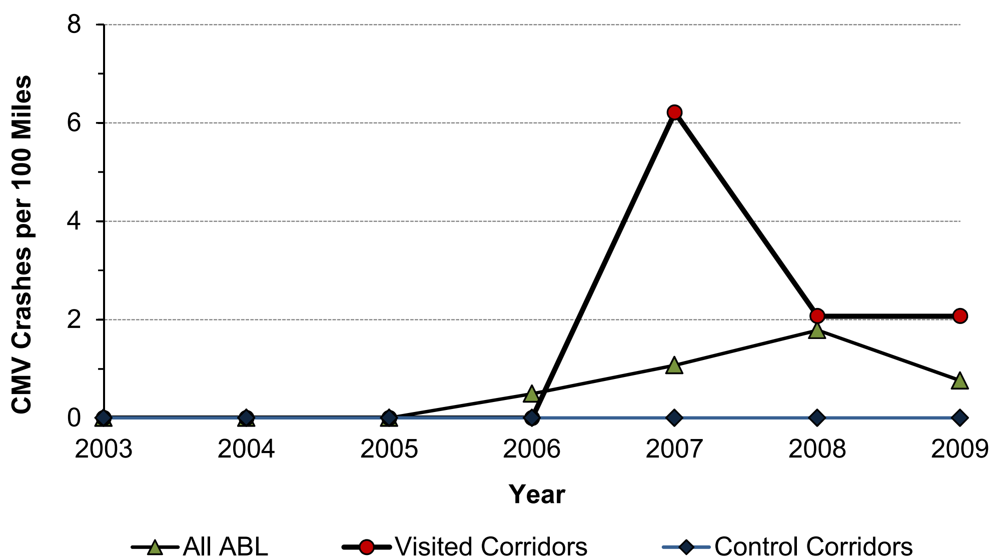


Figure 78. Crashes Involving Commercial Vehicles (Abilene District).

Crash Analysis – Fort Worth District

Rural Collectors

Figure 79 shows 2003–2009 crash rates for rural collectors at the Fort Worth District. Figure 80 shows 2003–2009 crash rates for crashes that involved commercial vehicles. Overall, corridors visited in the field exhibited higher crash rates than both control corridors and all corridors in the district. These trends also apply to severe crashes, intersection crashes, and driveway crashes. The crash rate for crashes involving commercial vehicles was considerably higher along visited corridors than along control corridors and for all state roads within the district.

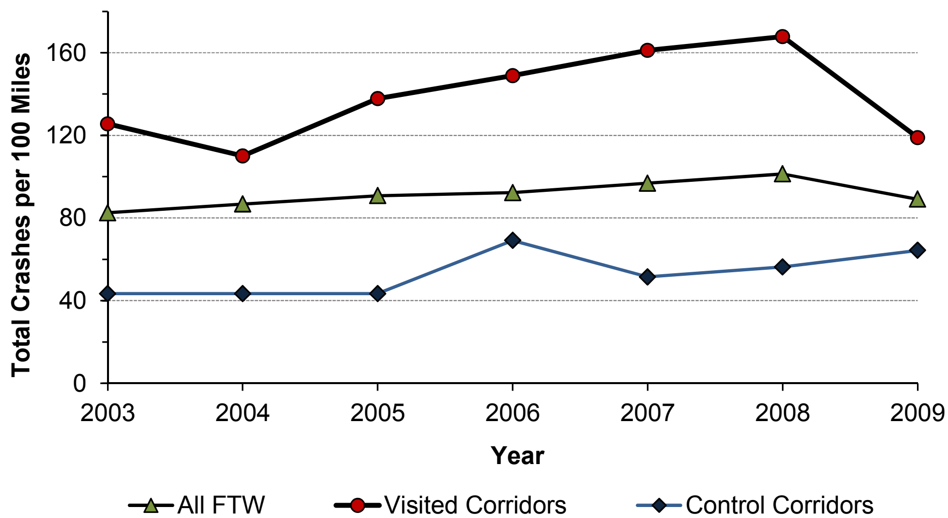


Figure 79. Crash Rates per 100 Miles, Rural Collectors (Fort Worth District).

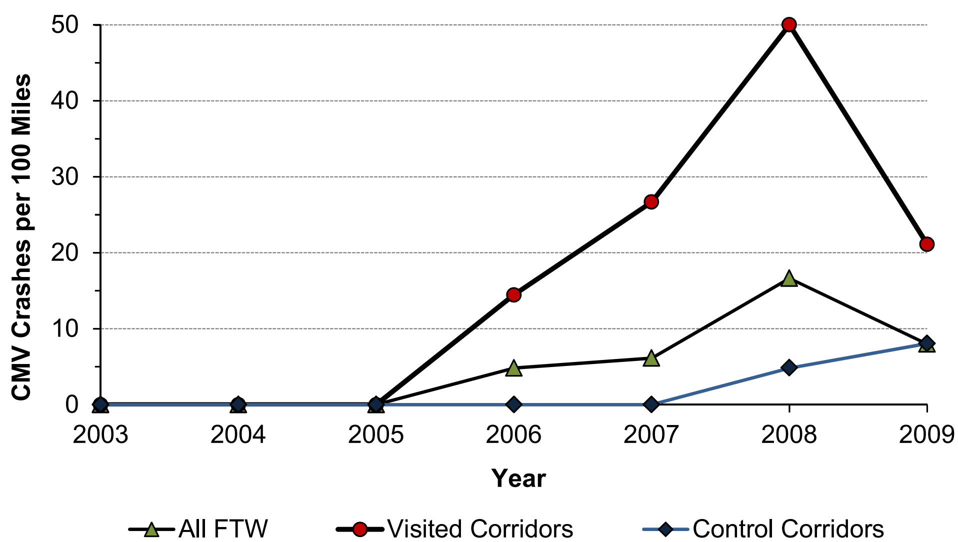


Figure 80. Crashes Involving Commercial Vehicles, Rural Collectors (Fort Worth District).

Rural Minor Arterials

Figure 81 shows 2003–2009 crash rates for rural minor arterials at the Fort Worth District. Figure 82 shows 2003–2009 crash rates for crashes that involved commercial vehicles. Overall, corridors visited in the field exhibited similar crash rates to those along control corridors and all corridors in the district. These trends also apply to severe crashes, intersection crashes, and driveway crashes. The crash rate for crashes involving commercial vehicles was slightly higher along visited corridors than along control corridors and for all state roads within the district.

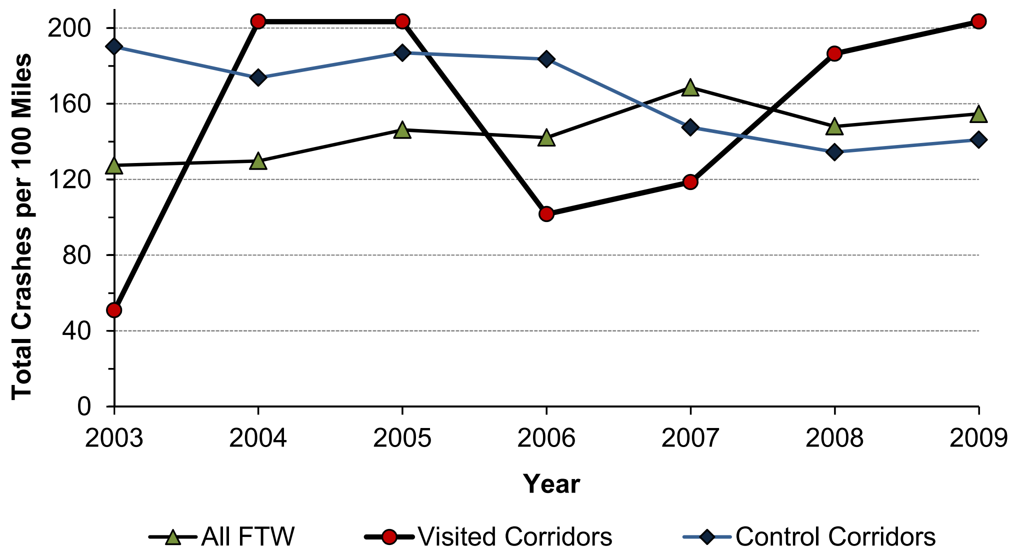


Figure 81. Crash Rates per 100 Miles, Rural Minor Arterials (Fort Worth District).

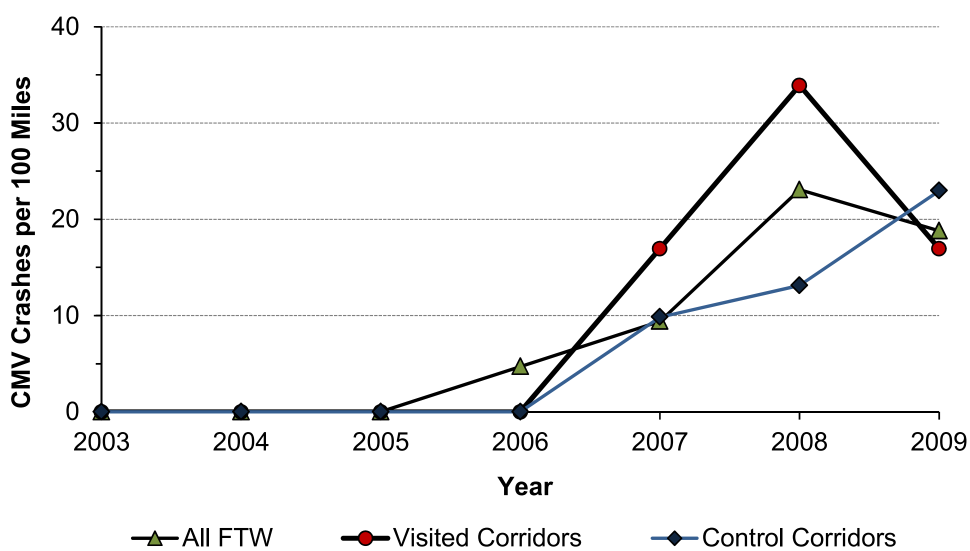


Figure 82. Crashes Involving Commercial Vehicles, Rural Minor Arterials (Fort Worth District).

COMMERCIAL VEHICLE ENFORCEMENT DATA ANALYSIS

The researchers examined 2007–2009 commercial vehicle enforcement data received from TxDPS. The database included detailed information about commercial vehicle inspections associated with violations of traffic laws and regulations. A record in the database indicates there was an inspection of a commercial vehicle and one or more violations of traffic laws and regulations associated with the vehicle in question. Tables in the database included the following:

- **GI_GEN1**. This is the parent table, which contains data about each commercial vehicle inspection, such as time, place, carrier, and driver.
- **CM_COM1**. This table contains brake data and shipping details such as commodity, consignor, consignee, origins, and destinations.
- **CO_COU1**. This table contains data about court date and judge information for records that involve lawsuits.
- **HM_HAZ1**. This table contains hazardous material data.
- **UN_UNI1**. This table contains detailed information about the commercial vehicle involved in the inspection.
- **VT_VIO1**. This table contains violation data.

Inspection Data Analysis

Most TxDPS enforcement activities take place on major highways and ports of entry. Because the database contained only a limited number of inspection records on the corridors examined in this research, it was not possible to conduct a detailed analysis for those corridors. As a result, the researchers decided to conduct a high-level analysis at the inspection type and district levels.

Identification of energy-related records in the database was indirect and involved selecting energy-related keywords in the commodity description, consignee, and consignor fields (table CM_COM1). Identifying commodities and energy-related companies was challenging because, in the database, these fields are free text format. As a result, there were problems such as lack of standardization of naming conventions and misspelled descriptions. Through trial and error, the researchers selected the keywords listed in Table 37 and Table 38.

Energy developments generate a considerable amount of truck traffic during preliminary construction activities, e.g., to haul caliche, gravel, and concrete. The researchers used the keywords in Table 39 to select inspection records that might be construction-related. Readers should note that this approach could result in inspection records that are not related to energy developments. However, the alternative would have been to ignore construction activity records altogether. At the same time, the researchers decided to ignore records with keywords such as

"TANK," "STORAGE TANK," and "LARGE MACHINERY." Finally, the researchers ignored records associated with empty trucks (commodity description was "EMPTY") and for which the consignor and consignee were empty or "SELF."

Table 37. Keywords Used to Identify Energy-Related Inspection Records.

Keyword	Commodity Description Example*	Number of Records in 2009
Petro	Petroleum product; petro. Oil	1,849
Oil & field	Oilfield equ.; oil field tower	1,845
Salt & water	Salt water; saltwater	1,276
Crude & oil	Crude oil; crude oil residue	826
Drill	Oil base drilling waste	728
Oil & base	Oil base; oil base material	92
Brine	Brine; brine water	69
Windmill	Windmill; windmill blade	30
Oil & pro	Oil processing unit; oil product	28
Bio & dies	Bio-diesel; biodiesel	22
Oil & pump	Oil pump jack; oil pump	14
Wind & tower	Windtower; mid section wind tower	13
Wind & turb	Wind turbine; windturb	5

* Examples listed include misspelled names and descriptions found in the database.

Table 38. Keywords Used to Identify Energy-Related Companies.

Keyword	Example*	Number of Records in 2009
Oil	Texas Gas and Oil; TSI Oilfield Services	3,232
Energy	Texas Energy; Tower Energy Group	2,493
Drilling	Pioneer Drilling; Precision Drilling	1,056
Resources	Flint Hills Resources; Pioneer Natural Resources	1,089
Mining	TXU Mining; Luminant Mining	119

* Examples listed include misspelled names and descriptions found in the database.

Table 39. Keywords Used to Identify Records Associated with Construction.

Keyword	Commodity Description Example*	Number of Records in 2009
Calich	Caliche/rock; calichie	836
Concr	Concrete; concreate; concreet	3,588
Gravel	Natural gravel; gravel mix	1,983

* Examples listed include misspelled names and descriptions found in the database.

Table 40 provides a summary of commercial vehicle inspections by inspection type (mainly location base) between 2007 and 2009. The table provides the total number of inspections for each inspection type and year, as well as the total number of inspections corresponding to the keywords identified in Table 37, Table 38, and Table 39. For completeness, the table also provides inspection percentages under each category. For example, for interstate highways and ports of entry, Table 40 shows 217,864 inspection records in 2007, of which 5,963 (or 3 percent) were energy-related according to the keywords established above and 7,985 (or 4 percent) were related to energy and construction activities. Similarly, for FM and RM highways, Table 40 shows 13,763 inspection records in 2007, of which 1,306 (or 9 percent) were energy-related and 2,036 (or 15 percent) were related to energy and construction activities.

Table 40. Summary of Commercial Vehicle Inspections (2007–2009).

Inspection Type	Year	Total Inspections	Energy Only		Energy + Construction	
			Total	Percent	Total	Percent
Interstate highways Ports of entry	2007	217,864	5,963	3%	7,985	4%
	2008	203,470	5,781	3%	7,740	4%
	2009	213,085	5,290	2%	7,109	3%
	Total	**634,419**	**17,034**	**3%**	**22,834**	**4%**
US or SH highways	2007	122,228	8,204	7%	10,867	9%
	2008	123,445	8,566	7%	11,596	9%
	2009	128,428	7,331	6%	10,254	8%
	Total	**374,101**	**24,101**	**6%**	**32,717**	**9%**
FM or RM highways	2007	13,763	1,306	9%	2,036	15%
	2008	13,781	1,318	10%	1,958	14%
	2009	13,113	1,057	8%	1,704	13%
	Total	**40,657**	**3,681**	**9%**	**5,698**	**14%**
Local roads	2007	276	8	3%	23	8%
	2008	2,759	157	6%	293	11%
	2009	3,452	159	5%	299	9%
	Total	**6,487**	**324**	**5%**	**615**	**9%**
Off-road	2007	3,639	133	4%	274	8%
	2008	18,220	427	2%	1,091	6%
	2009	21,537	463	2%	1,194	6%
	Total	**43,396**	**1,023**	**2%**	**2,559**	**6%**
Other Unknown	2007	12,674	479	4%	992	8%
	2008	1,957	20	1%	54	3%
	2009	1,032	21	2%	52	5%
	Total	**15,663**	**520**	**3%**	**1,098**	**7%**
Total	2007	370,444	16,093	4%	22,177	6%
	2008	363,632	16,269	4%	22,732	6%
	2009	380,647	14,321	4%	20,612	5%
	Total	**1,114,723**	**46,683**	**4%**	**65,521**	**6%**

Table 40 is obviously not conclusive regarding the correlation between commercial vehicle inspections and energy developments. However, it is interesting to note that the percentage of energy-related inspections on secondary roads, e.g., FM and Ranch-to-Market (RM) roads, was roughly three times as large as the corresponding percentage for interstate highways, even though the total number of inspections on interstate highways and ports of entry was much higher than on FM and RM roads. The percentage of energy-related inspections on US and SH highways was also higher than the corresponding percentage on interstate highways.

The analysis also included developing a tabulation of inspections at the county level for each of the three districts studied during the research (Abilene, Lubbock, and Fort Worth). Although there were significant differences among counties, the analysis did not shed any additional light regarding a potential correlation between inspections and energy developments. In fact, for some counties where the level of energy development activity was significant (based on the location of facilities such as wells or wind farms), commercial vehicle inspection percentages turned out to be very low. Conversely, for some counties where the level of energy development activity was relatively minor, commercial vehicle inspection percentages turned out to be high. It is possible that regional differences are partially the result of individual efforts (e.g., a local request is made to increase TxDPS presence and enforcement), but the available data were insufficient to identify any conclusive trends.

Traffic Violation Data Analysis

The 2007–2009 commercial vehicle enforcement database contained traffic violation records associated with 1,085 violation types. The number of violation records for most violation types was very small. To facilitate the analysis, the researchers focused on the violation types that accounted for 95 percent of all violation records. The result was 159 violation types, which the researchers grouped into five major categories (Table 41).

Table 41. Traffic Violation Categories.

No.	Category	Description
1	General traffic violation	Violation of applicable traffic laws when a vehicle is in motion, but not related to driver license or vehicle load
2	Vehicle defect	Missing, defective, or improperly installed vehicle component
3	Illegal license, registration, or other required paperwork	Expired, illegal, or without documents, plates, or markings required to operate the vehicle
4	Size, weight, or other related violation	Illegal size, weight, or installation of vehicle and load configuration
5	Other	Other

Table 42 through Table 44 list the most common violations found in the database in 2007, 2008, and 2009. For convenience, the tables include the violation category from Table 41 and the relative frequency of each violation with respect to the total number of records. Notice that records are grouped into energy-related violations and non-energy-related violations (according to the keywords identified in the previous section).

An analysis of the results indicates that many of the top 10 violation types occurred whether the violation was energy-related or not. Further, some of the violation types had a similar ranking, e.g., in the case of brake hose/tubing chafing and/or kinking, as well as no or defective ID lamp. However, some of the results are worth noting. For example, driving over 34,000-lb per tandem axle was ranked consistently higher in the case of energy-related violations than in the case of non-energy-related violations. This is an important finding in light of the implications regarding additional pavement impact resulting from overweight vehicles, particularly because, as shown in Chapter 4 (see, e.g., Table 11), the relationship between vehicle load weight and pavement impact is not linear.

Table 42. Top 10 Energy and Non-Energy Related Violation Types (2007).

	No.	Category	Violation Type Description	Percent
Energy-Related (Total: 57,401)	1	2	Brake hose/tubing chafing and/or kinking	4.6%
	2	4	Oil and/or grease leak	4.1%
	3	2	No/defective ID lamp	4.0%
	4	2	No/defective side marker lamp	3.5%
	5	4	Over 34,000-lb tandem axle	3.3%
	6	2	Defective stop lamps	3.1%
	7	2	Defective turn signal lamp	3.1%
	8	3	No/expired commercial motor vehicle inspection certificate	2.8%
	9	3	Required information not shown on log	2.4%
	10	2	Fire extinguisher violation	2.3%
Non-Energy-Related (Total: 1,604,579)	1	2	Brake hose/tubing chafing and/or kinking	5.2%
	2	4	Oil and/or grease leak	3.8%
	3	2	No/defective ID lamp	3.7%
	4	2	All other tires less than 2/32 of an inch	3.3%
	5	2	No/defective side marker lamp	3.1%
	6	4	Over 34,000-lb tandem axle	3.1%
	7	2	Defective turn signal lamp	3.0%
	8	2	Defective stop lamps	2.9%
	9	3	Required information not shown on log	2.8%
	10	2	No/defective clearance lamp	2.3%

Table 43. Top 10 Energy and Non-Energy Related Violation Types (2008).

	No.	Category	Violation Type Description	Percent
Energy-Related (Total: 58,187)	1	2	Brake hose/tubing chafing and/or kinking	5.2%
	2	2	No/defective ID lamp	3.8%
	3	4	Oil and/or grease leak	3.7%
	4	4	Over 34,000-lb tandem axle	3.3%
	5	2	Brake out of adjustment – clamp/roto	3.1%
	6	2	Defective stop lamps	3.1%
	7	2	No/defective side marker lamp	3.0%
	8	2	Defective turn signal lamp	2.9%
	9	3	No/expired commercial motor vehicle inspection certificate	2.8%
	10	2	Fire extinguisher violation	2.3%
Non-Energy-Related (Total: 1,595,563)	1	2	Brake hose/tubing chafing and/or kinking	8.0%
	2	4	Oil and/or grease leak	7.8%
	3	2	No/defective ID lamp	4.0%
	4	2	Brake out of adjustment – clamp/roto	3.6%
	5	2	All other tires less than 2/32 of an inch	3.4%
	6	2	No/defective side marker lamp	3.0%
	7	2	Defective turn signal lamp	2.4%
	8	2	Defective stop lamps	2.4%
	9	3	Required information not shown on log	2.2%
	10	4	Over 34,000-lb tandem axle	2.2%

Table 44. Top 10 Energy and Non-Energy-Related Violation Types (2009).

	No.	Category	Violation Type Description	Percent
Energy-Related (Total: 47,721)	1	2	Brake hose/tubing chafing and/or kinking	5.7%
	2	4	Oil and/or grease leak	4.2%
	3	4	Over 34,000-lb tandem axle	3.5%
	4	2	No/defective ID lamp	3.5%
	5	2	Defective stop lamps	3.1%
	6	2	Defective turn signal lamp	3.1%
	7	2	No/defective side marker lamp	2.8%
	8	2	Brake out of adjustment – clamp/roto	2.8%
	9	3	No/expired commercial motor vehicle inspection certificate	2.6%
	10	2	Fire extinguisher violation	2.3%
Non-Energy-Related (Total: 1,635,068)	1	2	Brake hose/tubing chafing and/or kinking	9.2%
	2	4	Oil and/or grease leak	8.1%
	3	2	No/defective ID lamp	3.6%
	4	2	All other tires less than 2/32 of an inch	3.6%
	5	2	Brake out of adjustment – clamp/roto	3.2%
	6	2	No/defective side marker lamp	2.7%
	7	2	Defective turn signal lamp	2.3%
	8	2	Defective stop lamps	2.3%
	9	4	Over 34,000-lb tandem axle	2.2%
	10	3	Required information not shown on log	2.1%

CHAPTER 7. ECONOMIC IMPACTS

INTRODUCTION

This chapter summarizes the work completed to provide an assessment of the economic impact to TxDOT in connection with energy development activities in the state. The analysis includes a documentation of funding and expenditure levels at TxDOT, a review of maintenance expenditures along sample corridors, and the development of a methodology to assess the impact due to specific energy developments.

TXDOT FUNDING AND EXPENDITURES

This section includes a high-level review of funding allocations and expenditures at TxDOT, particularly on secondary highways such as FM and RM roads. Although this information is common knowledge inside the department and among stakeholders knowledgeable about transportation funding concepts and issues, it is not widely disseminated, e.g., among energy stakeholders. Such a summary could be useful as part of outreach and coordination efforts with the energy industry.

TxDOT's appropriations come from a number of sources (*39*, *40*). Fund 6 is the state's primary highway funding mechanism. During the 2008–09 appropriation cycle, the level of funding for Fund 6 was approximately $14.2 billion, as follows:

- Federal reimbursements, primarily from the federal Highway Trust Fund ($6.9 billion, or 49 percent). Sources of funding for the federal Highway Trust Fund include a federal motor fuel tax of 18.4 cents per gallon and federal taxes on tires, vehicle weight permits, and truck and trailer sales.

- State motor fuel tax ($4.55 billion or 32 percent). This revenue comes from a state motor fuel tax of 20 cents per gallon on diesel and gasoline and 15 cents per gallon on liquefied gas. The Texas Constitution dedicates 75 percent of the revenue to highway-related purposes (which includes 1 percent to help enforce state motor fuel tax laws) and 25 percent to the Available School Fund. The last time the state motor fuel tax was increased was in 1992 (by 5 cents per gallon).

- Motor vehicle registration fees, sales taxes on motor vehicle lubricants, and other fees ($2.75 billion or 19 percent). Counties collect vehicle registration fees, of which they retain the first $60,000 collected and $350 for each mile of county road the county maintains (up to 500 miles).

Not all Fund 6 appropriations go to TxDOT. For example, during the 2008–09 appropriation cycle, $12.1 billion (or 86 percent) went to TxDOT, $1.0 billion (or 7.1 percent) went to TxDPS, and 0.94 billion (or 6.7 percent) went to other categories.

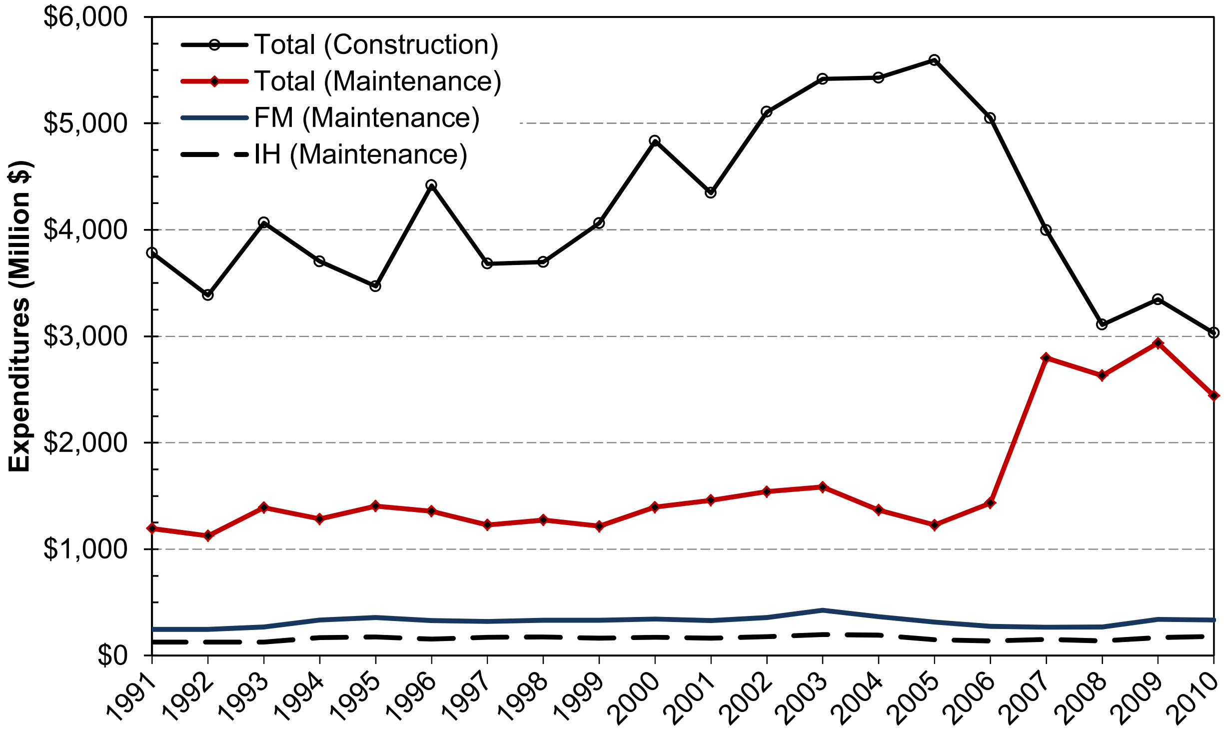
Table 45 summarizes annual TxDOT funding sources and expenditures, based on the legislative appropriation request the department filed with the Legislative Budget Board and the Governor's

Office of Budget, Planning, and Policy in the fall of 2010 (*41*). TxDOT's baseline request for the 2012–2013 biennium was $1.3 billion lower than for the 2010–2011 biennium, which TxDOT attributed mostly to diminishing bond proceeds, lower federal stimulus expenditures, and lower federal reimbursements. However, it is worth noting that TxDOT's latest operating budget report shows $7.44 billion in FY2011 expenditures and $10.38 billion in anticipated FY2012 expenditures (*42*).

Table 45. TxDOT Revenues and Expenditures (*41*).

Item	FY 2009 (Exp.)	FY 2010 (Est.)	FY 2011 (Bud.)	FY 2012 (Req.)	FY 2013 (Req.)
EXPENDITURES:					
Planning and Design	$980,978,900	$974,727,156	$1,098,502,306	$875,172,965	$681,581,973
Construction	$1,902,584,350	$1,980,152,377	$3,970,578,201	$2,538,176,464	$1,844,357,322
Maintenance	$3,135,733,137	$3,007,937,781	$2,746,685,675	$3,077,339,693	$2,819,602,869
Public Transportation	$135,226,240	$119,954,569	$89,684,372	$92,939,660	$92,968,396
Traffic Safety	$49,058,473	$51,697,470	$72,124,927	$71,933,635	$71,996,827
Travel Information	$17,841,584	$17,881,011	$18,481,451	$18,402,863	$18,407,506
Rail Transportation	$5,081,420	$7,442,303	$29,810,464	$73,132,657	$51,094,440
Indirect Administration	$168,432,407	$199,514,580	$234,464,937	$206,109,939	$202,922,554
Debt service payments	$831,972,352	$846,066,890	$732,069,577	$804,902,578	$926,067,045
SH 121 Toll Project Funds	$622,388,083	$279,429,467	$439,676,428	$583,514,825	$574,047,192
SH 130 Toll Project Funds	$9,833,115	$6,000,000	$2,000,000	$2,000,000	$4,300,000
TOTAL	**$7,859,130,061**	**$7,490,803,604**	**$9,434,078,338**	**$8,343,625,279**	**$7,287,346,124**
REVENUES:					
General Revenue Funds:					
General Revenue Fund	$2,907,817	$19,398,412	$33,516,637	$147,059,162	$129,799,556
Insurance Maintenance Tax Fees	$749,908	$750,000	$750,000	$750,000	$750,000
Highway Beautification Account	$364,089	$629,703	$629,703	$629,703	$629,703
Subtotal	$4,021,814	$20,778,115	$34,896,340	$148,438,865	$131,179,259
Federal Funds:					
Federal Recovery and Reinvestment Fund	$150,403,342	$769,630,282	$806,903,414	$533,536,075	$169,039,719
Federal Reimbursements	$2,813,400,726	$2,238,639,551	$2,566,768,006	$2,783,204,121	$2,648,022,650
Subtotal	$2,963,804,068	$3,008,269,833	$3,373,671,420	$3,316,740,196	$2,817,062,369
Other Funds:					
State Highway Fund	$2,312,451,274	$1,979,087,378	$2,262,637,420	$2,679,074,444	$2,633,686,835
Appropriated Receipts	$958,027	$4,013,505	$0	$0	$0
Interagency Contracts	$2,850,331	$6,395,536	$6,395,536	$4,500,000	$4,500,000
Bond Proceeds – General Obligations	$17,855,593	$30,725,920	$24,000,000	$24,000,000	$0
Bond Proceeds – Texas Mobility Fund	$592,633,517	$472,495,634	$151,507,348	$84,355,459	$42,883,104
Bond Proceeds – State Highway Fund	$500,361,887	$733,614,960	$753,942,770	$787,432,569	$303,916,124
State Highway Fund – Debt Service	$569,717,096	$520,103,305	$347,940,243	$282,863,831	$415,464,266
Texas Mobility Fund – Debt Service	$262,255,256	$296,551,510	$315,666,844	$320,948,867	$325,145,628
Highway Fund 6 – Toll Revenue	$622,388,083	$279,429,467	$439,676,428	$583,514,825	$574,047,192
Highway Fund6 – Concession Fees	$9,833,115	$6,000,000	$2,000,000	$2,000,000	$4,300,000
Bond Proceeds – GO Bonds	$0	$133,338,441	$1,721,743,989	$109,756,223	$35,161,347
Subtotal	$4,891,304,179	$4,461,755,656	$6,025,510,578	$4,878,446,218	$4,339,104,496
TOTAL	**$7,859,130,061**	**$7,490,803,604**	**$9,434,078,338**	**$8,343,625,279**	**$7,287,346,124**

Uncertainty about the availability of funds for construction and maintenance of highway facilities is likely to continue or even grow over the next few years (*43*, *44*). Figure 83 shows annual construction and maintenance expenditures at TxDOT from 1991 to 2010, expressed in December 2010 dollars. For completeness, Figure 83 shows overall maintenance expenditures between 1991 and 2010, as well as maintenance expenditures on FM and IH highways.



Notes:

- Construction expenditures include project development costs and right-of-way acquisition.
- Cost data were obtained from TxDOT's District and County Statistics (DISCOS) annual reports. The numbers in this figure are slightly different from those in Table 45, possibly due to differences in the selection of cost categories.
- Expenditures are expressed in millions of December 2010 dollars. For expenditures prior to 1997, a 4 percent annual rate was used to convert those expenditures to 1997 dollars. Beginning with FY 1997, the TxDOT Highway Cost Index was used to convert dollar amounts to December 2010 dollars (*45*).

Figure 83. TxDOT Construction and Maintenance Expenditures.

As Figure 83 shows, construction expenditures have not increased substantially over the last 20 years. Although construction expenditures increased from 1997 to 2005, they decreased significantly after 2005. Further, following the trends in Table 45, it is reasonable to assume that construction expenditures will continue to decrease in the near future. Overall, maintenance expenditures have increased slightly over the years. In 2007, there was a substantial increase in maintenance expenditures, although one reason for this increase is that TxDOT began to report contracted reconstruction maintenance projects as a maintenance category instead of a construction category. Since 2007, maintenance expenditures have remained essentially flat. Overall, maintenance expenditures on FM and IH highways have varied little over the years.

Secondary roads such as FM roads evolved to provide access to rural areas and to enable farmers to bring their goods to market. The first FM road in Texas (a 5.8-mile section) was completed in Rusk County (Tyler District) in 1937. The 1949 Colson-Briscoe Act called for the construction of an extensive FM road network by dedicating $15 million a year from the Omnibus Tax Clearance Fund to build local roads that did not have sufficient traffic volume to justify their construction and maintenance (*46*). Today, the FM road network is about 38,000 miles long.

According to the 2030 Committee report published in 2009, Texas would need $315 billion (in 2008 dollars) from 2009 to 2030 (or $14.3 billion per year) to maintain the transportation infrastructure, mobility, and safety in the state at current levels (*47*). This need translates to $89 billion for pavements (or $4 billion per year), $36 billion for bridges (or $1.6 billion per year), $171 billion for urban mobility (or $7.8 billion per year, and $19 billion for rural mobility and safety (or $0.9 billion per year). However, during the same period, TxDOT estimates that traditional funding sources would be able to generate only about $155 billion in revenues, leaving a substantial funding gap that would need to be bridged using non-traditional means (*48*).

CONSTRUCTION AND MAINTENANCE EXPENDITURES IN ABILENE, LUBBOCK, AND FORT WORTH

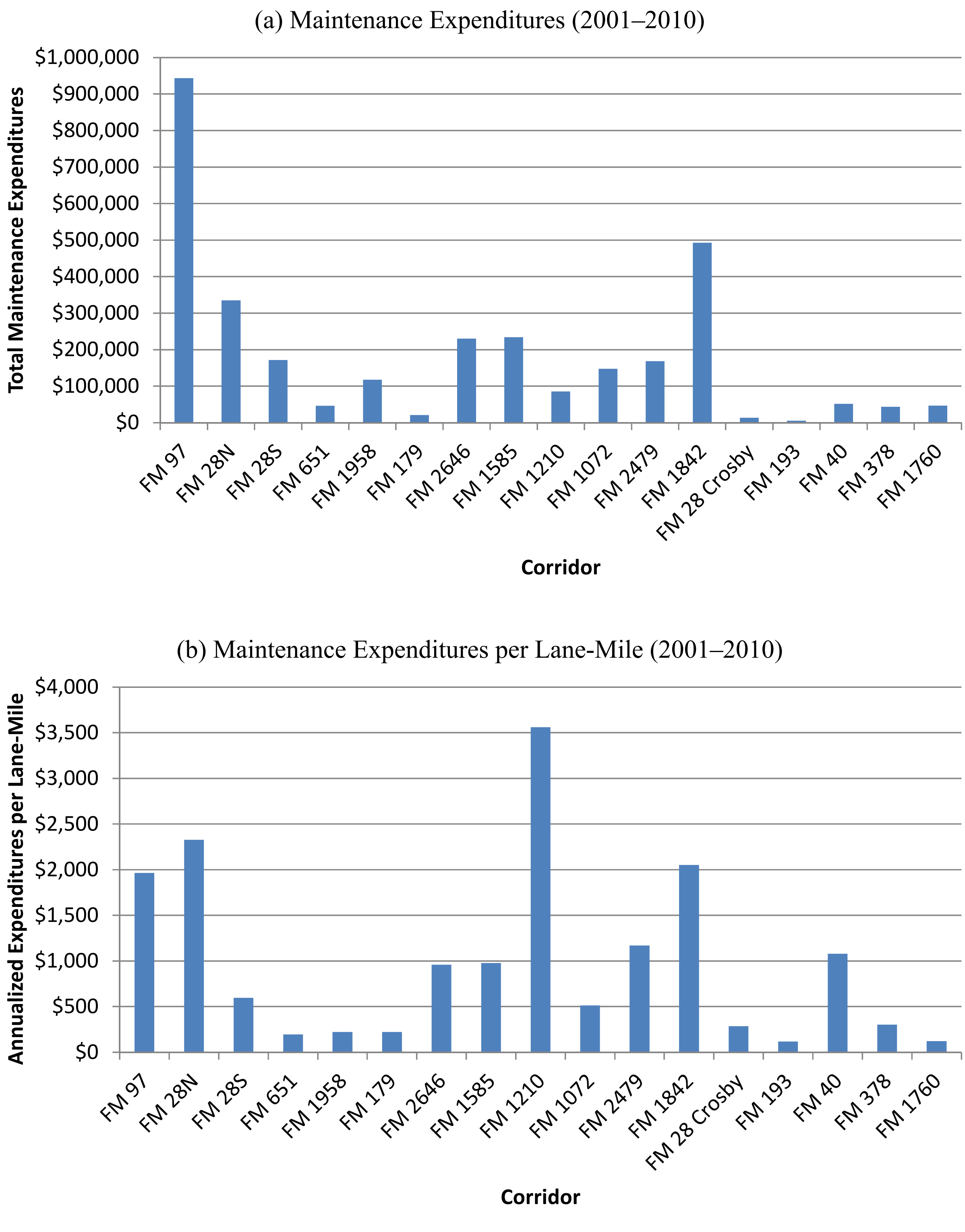
Table 46 summarizes average maintenance expenditures per lane-mile for visited and control corridors, as well as district and state averages at the Lubbock, Abilene, and Fort Worth Districts. In Lubbock, until about 2007, maintenance expenditures for the corridors visited were lower than for the control corridors, rural collectors in general at the district, and throughout the state. There was a spike in maintenance expenditures for visited corridors in 2008, but they decreased again in 2009. In Abilene, maintenance expenditures for visited corridors were consistently higher (except in 2003 and 2004) than for control corridors, as well as rural collectors at the district and throughout the state. In Fort Worth, until about 2005, maintenance expenditures for the corridors visited in the field were roughly the same as for the control corridors, rural collectors in general at the district, and throughout the state. Beginning in 2005–2006, maintenance expenditures for the corridors visited in the field increased dramatically.

The researchers also conducted a more detailed analysis for the corridors visited in the field. To this end, they extracted maintenance expenditure data from PMIS (2001 through 2009), converted the dollar amounts to 2010 dollars assuming a four percent discount rate, and added FY10 maintenance expenditures from data the districts provided. Figure 85, Figure 84, and Figure 86 show both maintenance expenditures and maintenance expenditures per lane-mile for the visited corridors at the Lubbock, Abilene, and Fort Worth Districts. For completeness, the figures also show an average annualized maintenance expenditure value for all the visited corridors combined at each district (blue horizontal line) as well as district-wide (red line).

Overall, average expenditures per lane mile in the Fort Worth District are considerably higher than those in Abilene and Lubbock. However, corridors in the Fort Worth District service substantially higher truck traffic levels compared to the corridors in Abilene and Lubbock (see Table 27). Given the much larger truck volumes on the Fort Worth corridors compared to the corridors in Abilene and Lubbock, it is reasonable to see much higher expenditures spent maintaining the Fort Worth corridors.

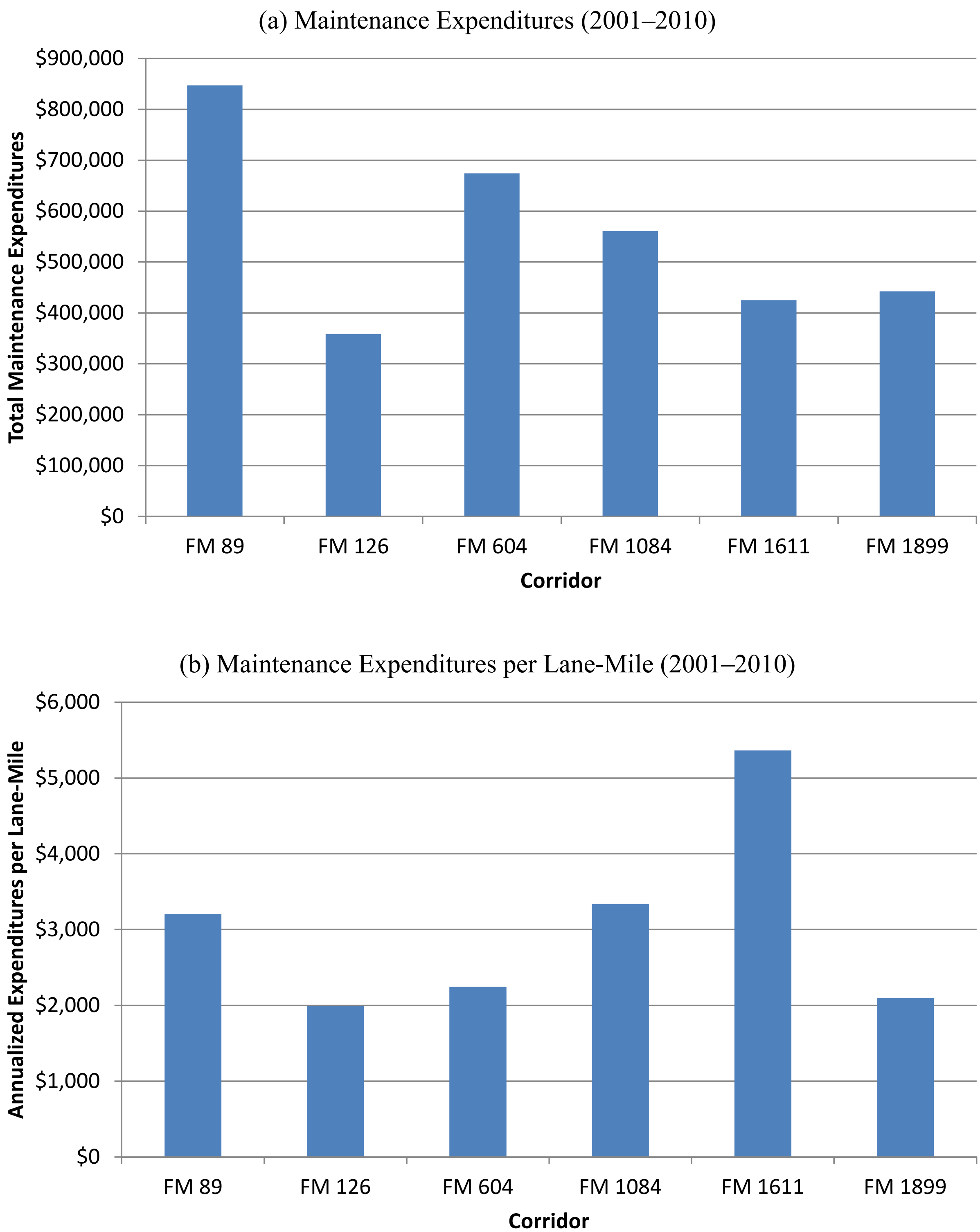
Table 46. Maintenance Expenditures per Lane-Mile in Lubbock, Abilene, and Fort Worth.

Year	Average Maintenance Expenditures per Lane-Mile (2010 dollars)			
	Visited Corridors	Control Corridors	District Average	State Average
Lubbock District (Rural Major and Minor Collectors)				
2001	$865	$1,598	$991	$1,261
2002	$1,221	$1,196	$710	$1,300
2003	$1,326	$3,242	$1,477	$1,645
2004	$699	$1,656	$1,085	$1,447
2005	$591	$1,964	$965	$1,408
2006	$164	$801	$748	$1,183
2007	$177	$239	$576	$2,369
2008	$2,188	$507	$731	$1,281
2009	$510	$127	$852	$1,576
Abilene District (Rural Major and Minor Collectors)				
2001	$1,148	$284	$872	$1,261
2002	$4,202	$686	$1,037	$1,300
2003	$775	$602	$1,035	$1,645
2004	$996	$209	$895	$1,447
2005	$2,403	$1,464	$746	$1,408
2006	$2,907	$1,742	$894	$1,183
2007	$3,095	$1,766	$864	$2,369
2008	$4,625	$961	$810	$1,281
2009	$3,698	$147	$1,083	$1,576
Fort Worth District (Rural Major and Minor Collectors)				
2001	$1,460	$1,007	$1,439	$1,261
2002	$2,752	$4,578	$1,757	$1,300
2003	$1,541	$1,140	$1,801	$1,645
2004	$1,634	$475	$1,109	$1,447
2005	$1,219	$2,003	$1,758	$1,408
2006	$3,817	$1,019	$1,092	$1,183
2007	$6,288	$310	$1,535	$2,369
2008	$9,813	$911	$2,555	$1,281
2009	$2,966	$319	$2,936	$1,576
Fort Worth District (Rural Minor Arterials)				
2001	$269	$1,062	$2,590	$1,350
2002	$127	$1,936	$2,462	$1,328
2003	$85	$2,483	$2,305	$1,495
2004	$4,580	$709	$1,512	$1,330
2005	$128	$337	$2,139	$965
2006	$3,801	$1,363	$1,973	$934
2007	$152	$512	$1,246	$1,002
2008	$14,210	$778	$3,996	$1,016
2009	$57,208	$458	$4,182	$1,419



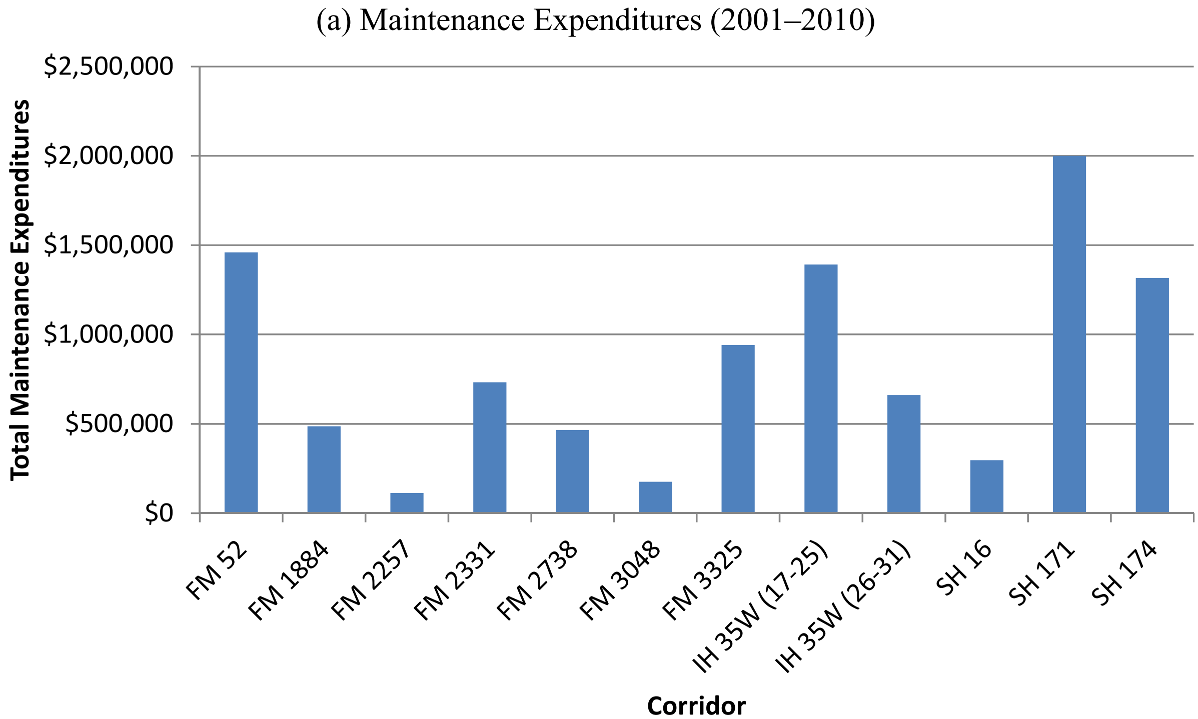
Average annualized expenditures (visited corridors): $980/lane-mile
Average annualized expenditures (district wide): $926/lane-mile

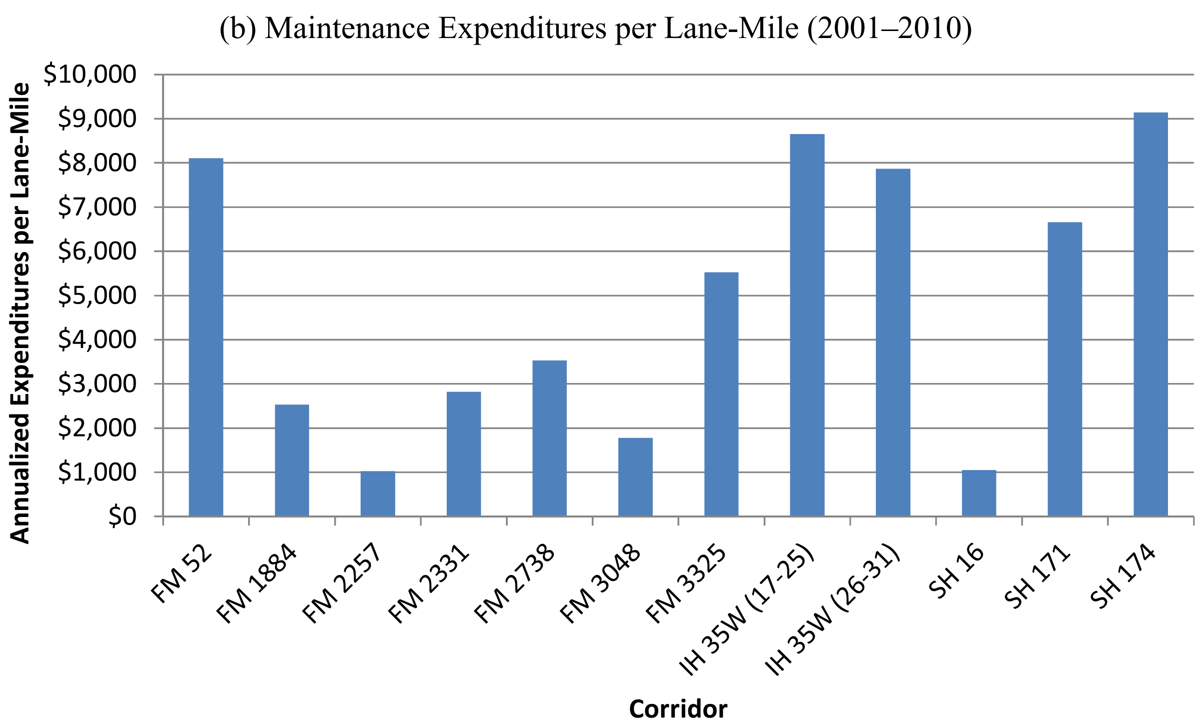
Figure 84. Pavement Maintenance Expenditures at the Lubbock District.



Average annualized expenditures (visited corridors): $3,040/lane-mile
Average annualized expenditures (district wide): $1,115/lane-mile

Figure 85. Pavement Maintenance Expenditures at the Abilene District.





Average annualized expenditures (visited corridors): $4,892/lane-mile
Average annualized expenditures (district wide): $1,979/lane-mile

Figure 86. Pavement Maintenance Expenditures at the Fort Worth District.

In addition to maintenance expenditures, the researchers extracted construction cost data from DCIS to develop an understanding of typical expenditures associated with activities such as seal coats, overlays, restorations, and rehabilitations. To this end, the researchers extracted DCIS data from January 2004 to March 2011, and focused on projects at the Abilene, Lubbock, and Fort Worth Districts for which the bid amount was different from zero. To make the data as homogeneous as possible, the researchers focused on projects on FM roads for which the main purpose of the project and the corresponding billable items were related to seal coats, overlays, restorations, and rehabilitations. Table 47 shows the results of the analysis.

Table 47. Average Construction Cost Trends on FM Roads at the Abilene, Lubbock, and Fort Worth Districts.

Project Class	Description	Project Count	Average Cost	Average Length (miles)	Average Cost per Mile	Average Cost per Lane-Mile
SC	Seal Coat	159	$144,107	6.94	$20,752	$10,376
OV	Overlay	11	$1,227,536	5.32	$230,929	$115,465
RES	Restoration	12	$2,192,582	8.01	$273,694	$136,847
RER	Rehabilitate Existing Road	29	$2,391,426	4.68	$510,759	$255,379

APPROXIMATE METHODOLOGY TO ASSESS THE ECONOMIC IMPACT DUE TO ENERGY DEVELOPMENTS

With the information gathered in the previous chapters regarding the impact of energy developments on the transportation infrastructure (mainly in terms of reduction in pavement remaining life) and average trends in construction and maintenance expenditures, the researchers developed a generic methodology and tool to assess the economic impact due to a typical development. The researchers implemented the tool using a Microsoft Excel spreadsheet, which can be easily disseminated to districts and other stakeholders.

Assumptions behind the methodology and tool include the following:

- 20-year horizon.
- Annual discount rate to take into account the time value of money: 4 percent.
- FM road (rural collector):
  - Maintenance expenditure (no-impact scenario): $1,000 per lane-mile.
  - Maintenance expenditure (impact scenario): $3,000 per lane-mile.
  - Seal coat cost: $10,000 per lane-mile.
  - Overlay: $115,000 per lane-mile.
  - Restoration: $137,000 per lane-mile.
  - Rehabilitation: $255,000 per lane-mile.

The methodology also assumes the analyst has information about the type of energy development, more specifically anticipated truckloads and impact on remaining pavement life, as described in Chapter 4. This knowledge would enable the analyst to forecast when certain activities need to be scheduled to maintain the functionality of the road, e.g., when to schedule a seal coat or an overlay, or when more substantial measures such as restoration or rehabilitation are required.

The methodology involves the following steps:

- Calculate 20-year anticipated expenditures without the energy development in place (i.e., Scenario 1).

- Calculate 20-year anticipated expenditures with the energy development in place (i.e., Scenario 2). As needed, a variety of additional scenarios could be run to develop a better understanding of the range of potential impacts.

- Calculate the additional cost associated with Scenario 2 with respect to Scenario 1. This additional cost is the cost due to the impact of the energy development on the transportation pavement infrastructure.

As an illustration, Table 48 shows anticipated 20-year expenditures per lane-mile associated an FM road without an energy development in place (i.e., Scenario 1). Although not required for the analysis (since Step 3 involves calculating cost differences between each scenario and Scenario 1), Table 48 assumes for simplicity a restoration project at the beginning of the analysis. According to this assumption, the anticipated 20-year expenditure without an energy development in place would be $157,346 per lane-mile.

Table 49 shows anticipated 20-year expenditures per lane-mile associated with a hypothetical scenario (Scenario 2) that involves an energy development and a corresponding impact on pavements that require frequent seal coats and a restoration in year 10. According to this assumption, the anticipated 20-year expenditure would be $284,095 per lane-mile, i.e., an increment of $126,749 (or $6,337 per year) with respect to Scenario 1.

It may be possible to develop a high-level, statewide preliminary estimate of the total impact associated with Scenario 2. By using the geodatabase of oil and gas wells (see Chapter 2) and by defining buffers of different sizes (e.g., 1-mile radius, 2-mile radius, and 5-mile radius) around each well, a surface could be generated and overlaid on the state highway network to identify road segments that fall within each of the buffers. For the three buffers above, the result would be 7,872 miles, 14,191 miles, and 22,000 miles, respectively. Multiplying these values by the additional cost associated with Scenario 2 ($126,749 × 2, to account for both directions of travel) and converting the total to an annual value would result in a total annual cost of $99.8 million (for a 1-mile radius), $180 million (for a 2-mile radius), and $279 million (for a 5-mile radius). Readers should note that this estimate is only a high-level, preliminary estimate. For individual energy developments, a more detailed analysis involving origins and destinations and route assignments would be necessary.

Table 48. Anticipated 20-Year Expenditures *without* Energy Development (Scenario 1).

Year	Maintenance	Seal Coat	Overlay	Restoration	Rehabilitation	Total
0	$0	$0	$0	$137,000	$0	$137,000
1	$1,000	$0	$0	$0	$0	$1,000
2	$1,000	$0	$0	$0	$0	$1,000
3	$1,000	$0	$0	$0	$0	$1,000
4	$1,000	$0	$0	$0	$0	$1,000
5	$1,000	$0	$0	$0	$0	$1,000
6	$1,000	$0	$0	$0	$0	$1,000
7	$1,000	$0	$0	$0	$0	$1,000
8	$1,000	$0	$0	$0	$0	$1,000
9	$1,000	$0	$0	$0	$0	$1,000
10	$1,000	$10,000	$0	$0	$0	$11,000
11	$1,000	$0	$0	$0	$0	$1,000
12	$1,000	$0	$0	$0	$0	$1,000
13	$1,000	$0	$0	$0	$0	$1,000
14	$1,000	$0	$0	$0	$0	$1,000
15	$1,000	$0	$0	$0	$0	$1,000
16	$1,000	$0	$0	$0	$0	$1,000
17	$1,000	$0	$0	$0	$0	$1,000
18	$1,000	$0	$0	$0	$0	$1,000
19	$1,000	$0	$0	$0	$0	$1,000
20	$1,000	$0	$0	$0	$0	$1,000
Present Value	**$13,590**	**$6,756**	**$0**	**$137,000**	**$0**	**$157,346**

Table 49. Anticipated 20-Year Expenditures *with* Energy Development (Scenario 2).

Year	Maintenance	Seal Coat	Overlay	Restoration	Rehabilitation	Total
0	$0	$0	$0	$137,000	$0	$137,000
1	$3,000	$0	$0	$0	$0	$3,000
2	$3,000	$0	$0	$0	$0	$3,000
3	$3,000	$0	$0	$0	$0	$3,000
4	$3,000	$0	$0	$0	$0	$3,000
5	$3,000	$10,000	$0	$0	$0	$13,000
6	$3,000	$0	$0	$0	$0	$3,000
7	$3,000	$0	$0	$0	$0	$3,000
8	$3,000	$0	$0	$0	$0	$3,000
9	$3,000	$0	$0	$0	$0	$3,000
10	$3,000	$0	$0	$137,000	$0	$140,000
11	$3,000	$0	$0	$0	$0	$3,000
12	$3,000	$0	$0	$0	$0	$3,000
13	$3,000	$0	$0	$0	$0	$3,000
14	$3,000	$0	$0	$0	$0	$3,000
15	$3,000	$10,000	$0	$0	$0	$13,000
16	$3,000	$0	$0	$0	$0	$3,000
17	$3,000	$0	$0	$0	$0	$3,000
18	$3,000	$0	$0	$0	$0	$3,000
19	$3,000	$0	$0	$0	$0	$3,000
20	$3,000	$0	$0	$0	$0	$3,000
Present Value	**$40,771**	**$13,772**	**$0**	**$229,552**	**$0**	**$284,095**
					Scenario 1	**$157,346**
					Difference	**$126,749**

Table 50 shows anticipated 20-year expenditures per lane-mile associated with another hypothetical scenario (Scenario 3) that involves an energy development and a corresponding impact on pavements that require more frequent seal coats, and overlay in years 6 and 18 and a restoration in year 12. According to this assumption, the anticipated 20-year expenditure would be $432,463 per lane-mile, i.e., an increment of $275,117 (or $13,756 per year) with respect to Scenario 1.

Table 50. Anticipated 20-Year Expenditures *with* Energy Development (Scenario 3).

Year	Maintenance	Seal Coat	Overlay	Restoration	Rehabilitation	Total
0	$0	$0	$0	$137,000	$0	$137,000
1	$3,000	$0	$0	$0	$0	$3,000
2	$3,000	$0	$0	$0	$0	$3,000
3	$3,000	$10,000	$0	$0	$0	$13,000
4	$3,000	$0	$0	$0	$0	$3,000
5	$3,000	$0	$0	$0	$0	$3,000
6	$3,000	$0	$115,000	$0	$0	$118,000
7	$3,000	$0	$0	$0	$0	$3,000
8	$3,000	$0	$0	$0	$0	$3,000
9	$3,000	$10,000	$0	$0	$0	$13,000
10	$3,000	$0	$0	$0	$0	$3,000
11	$3,000	$0	$0	$0	$0	$3,000
12	$3,000	$0	$0	$137,000	$0	$140,000
13	$3,000	$0	$0	$0	$0	$3,000
14	$3,000	$0	$0	$0	$0	$3,000
15	$3,000	$10,000	$0	$0	$0	$13,000
16	$3,000	$0	$0	$0	$0	$3,000
17	$3,000	$0	$0	$0	$0	$3,000
18	$3,000	$0	$115,000	$0	$0	$118,000
19	$3,000	$0	$0	$0	$0	$3,000
20	$3,000	$0	$0	$0	$0	$3,000
Present Value	**$40,771**	**$21,468**	**$147,653**	**$222,570**	**$0**	**$432,463**
					Scenario 1	**$157,346**
					Difference	**$275,117**

These levels of economic impact are reasonable when compared to estimates that other agencies have prepared. For example, the City of Keller, which is located north of Fort Worth, conducted a study to assess road damages resulting from natural gas well activities within city limits (*9*). Their methodology involved estimating the total number of heavy truck trips associated with developing and operating a gas well, estimating the total number of available ESALs for different types of roads within the city, estimating the reduction in road life due to the development and operation of gas wells, and assigning costs associated with the reconstruction of roads after failure. The result of the methodology is a table (Table 51) that shows road damage in dollars per lane-mile for eight different roadway types and four different roadway use case conditions.

Table 51. Road Damage Assessment at the City of Keller, Texas (*9*).

Road Type	Pavement Type	Assessment Cost per Lane-Mile			
		Case 1[1]	Case 2[2]	Case 3[3]	Case 4[4]
1	10" reinforced concrete, 8" lime stabilized soil	$53	$69	$100	$110
2	8" reinforced concrete, 9" lime stabilized soil	$156	$201	$292	$322
3	6" reinforced concrete, 6" lime stabilized soil	$807	$1,039	$1,511	$1,666
4	3" HMAC, 6" cement treated soil	$3,861	$4,972	$7,230	$7,971
5	3" HMAC, 6" flexible base	$3,653	$4,705	$6,841	$7,543
6	2" HMAC, 8" cement treated soil	$8,008	$1,313	$14,997	$16,534
7	2" HMAC, 6" cement treated soil	$9,462	$12,186	$17,720	$19,536
8	2" HMAC, 6" flexible base	$9,676	$12,461	$18,120	$19,977

[1] Case 1: Fracking water piped to site and hauled out by truck. Production water hauled out via pipeline.
[2] Case 2: Fracking water hauled in and out by truck. Production water hauled out via pipeline.
[3] Case 3: Fracking water piped to site and hauled out by truck. Production water hauled out by truck.
[4] Case 4: Fracking water hauled in and out by truck. Production water hauled out by truck.

CHAPTER 8. STRATEGIES AND RECOMMENDATIONS FOR IMPLEMENTATION

INTRODUCTION

This chapter summarizes the work completed to develop strategies and recommendations for implementation that resulted from the identification of impacts in the field and the review of available documentation and data. The recommendations include changes to business practices and procedures, as well as short-term initiatives to facilitate the implementation of the research findings into practice. The strategies and recommendations were grouped into the following categories:

- Early notification and coordination.
- Road maintenance and repair.
- Roadside management.
- Funding.

The following sections describe all the strategies and recommendations within each category.

As part of this activity, the researchers scheduled three meetings with stakeholders to describe the results of field visits, data collection, and analysis completed; and obtain feedback with respect to the potential strategies and recommendations for implementation. The meetings took place in Abilene, Fort Worth, and San Antonio. Figure 87 shows the meeting agenda. Invitations to participate in the stakeholder meetings were sent to state agencies, county and local agencies, metropolitan planning organizations (MPOs), and energy producer and transmission associations. Table 52 summarizes the participation of stakeholders at each of the meetings.

Table 52. Stakeholder Participation.

Stakeholder	Abilene Meeting	Fort Worth Meeting	San Antonio Meeting
TxDOT	4	13	14
Other state agencies	1	2	1
County and local agencies	-	3	1
MPOs	-	2	-
Energy sector	1	4	1
Research team	5	5	5
Total	**11**	**29**	**21**

Texas Transportation Institute

Texas Department of Transportation

Energy Developments and TxDOT – Stakeholder Meeting

May 19, 2011, 8 AM – Noon, Abilene
May 20, 2011, 8 AM – Noon, Fort Worth
May 24, 2011, 8 AM –Noon, San Antonio

Background

In recent years, there has been a boom of energy-related activities in the state. These efforts contribute to enhance the state's ability to produce energy reliably. However, many short-term and long-term impacts on the state's transportation infrastructure and right-of-way are not properly documented. The Texas Department of Transportation has begun to document some of the impacts. However, a comprehensive document that describes impacts, needs, and recommendations is missing. This document is critical for the implementation of sound strategies to address the needs of the state and other energy-related stakeholders.

Meeting Purpose

As part of TxDOT Research Project 0-6498, the Texas Transportation Institute of the Texas A&M University System is conducting research to measure the impact of increased levels of energy-related activities on the state's transportation infrastructure and right-of-way, as well as develop recommendations and strategies to handle stakeholder needs. The purpose of the meeting is to:

- Describe the results of field visits, data collection, and analysis completed as part of the research.
- Obtain feedback from stakeholders with respect to potential strategies and recommendations for implementation.

Agenda

8:00 – 8:15	Welcome, introductions, and stakeholder meeting objectives
8:15 – 9:20	Field visits, data collection, and pavement impacts
9:20 – 9:30	Break
9:30 – 10:20	Roadside impacts, traffic safety, and costs
10:20 – 10:30	Break
10:30 – 11:00	Open discussion and brainstorming about issues, needs, and impacts
11:00 – 11:50	Open discussion and brainstorming about strategies, opportunities, and recommendations
11:50 – 12:00	Next steps and wrap up

For other information about the research, please contact:
Cesar Quiroga, Ph.D., P.E., Texas Transportation Institute, Texas A&M University System
Phone: (210) 979-9411 x 17203
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Figure 87. Stakeholder Meeting Agenda.

EARLY NOTIFICATION AND COORDINATION

Strategies and recommendations for implementation include the following:

- Implement and maintain the geodatabase of energy developments in Texas.
- Implement interagency cooperation agreements with other agencies.
- Improve communication and coordination with energy developers.
- Implement additional proactive mechanisms to learn about energy developments.
- Work with TxDPS to improve traffic safety and protect the transportation infrastructure.

Implement and Maintain the Geodatabase of Energy Developments in Texas

TxDOT should implement and maintain the geodatabase of energy developments that was developed during the research and submitted as Product 0-6498-P1, *Energy Developments and the Transportation Infrastructure in Texas: Geodatabase of Energy Developments in Texas* (*18*). This geodatabase is a GIS-based database that includes both locational data (which places energy developments spatially with respect to other geographic features, including the transportation network) and non-spatial attribute data (which enables the execution of a wide range of attribute-based queries and reports). In some cases, e.g., in the case of oil and gas well permit data, the database includes time attributes, which are useful for determining when drilling happened or is expected to happen in the near future (e.g., up to two years into the future, considering the drilling expiration date is typically two years after the permit approval date).

The geodatabase is only as valuable as the validity of the data included in it. By necessity, the geodatabase delivered to TxDOT is valid as of a certain date. For example, the oil and gas permit data is valid as of June 2011, which corresponds to the date Railroad Commission officials ran the query to generate the last dataset received by the researchers. In some situations, the data included in the deliverable are older, e.g., in the case of datasets (such as wind potential) the researchers requested early during the research, but turned out to be fairly stable or non-critical.

Because critical datasets such as oil and gas permit data change rapidly over time, implementing and maintaining the geodatabase of energy developments will go beyond storing the research deliverable on a TxDOT GIS server waiting to be used. In order to ensure the long-term sustainability of the geodatabase, TxDOT should implement a plan that includes, as a minimum, the following activities:

- Assign a team led by two individuals (e.g., representing the Technology Services Division and the Maintenance Division) the responsibility to manage and ensure the long-term sustainability of the geodatabase, including ensuring the various datasets that make up the geodatabase are always up-to-date. At least one of these individuals should be sufficiently familiar with GIS and database concepts and procedures to guarantee the level of technical expertise needed to acquire, process, store, and publish datasets associated with the geodatabase.

- Add one representative from selected districts within each of the four regions to the team above to ensure the team receives feedback from field offices, e.g., in relation to data completeness or data accuracy issues, as well as new trends that might make it necessary to expand the scope or coverage of the geodatabase. Potential candidates for membership to the team are officials who operate or manage the UIR system at the district level. The reason is that these officials are in a unique position to identify trends, not just in connection with energy development-related utility permit applications, but also because they can easily access information online from other state agencies, such as the RRC, PUCT, GLO, and ERCOT.

- Store the various datasets on a GIS server and make the data available throughout the department. Considering the variety of users who might need access to the data, the researchers recommend implementing both a web-based viewer application (appropriate for casual, "non-power" users) and a service (appropriate for "power" GIS and database users). The data and applications could be deployed on a TxDOT-controlled server or, alternatively, TxDOT could enter into a cooperation agreement with another agency to let that agency manage, maintain, and develop the geodatabase. Issues to consider when making this decision include issues such as data storage needs and fees, flexibility, reliability, scalability, and security.

- Implement a suite of "pre-canned" queries or data views, particularly for large datasets such as oil and gas well locations, to facilitate data access and a variety of analyses. Examples of pre-canned queries include extracting oil and gas permits by year (both the year when the permit was approved and the year when the well was drilled), extracting the location of injection and disposal wells, and extracting the number of oil and gas well permits approved each year (grouped by TxDOT district).

- Implement a program of data acquisition to make sure the geodatabase is always up-to-date. As described below in more detail, this process could entail entering into agreements with other agencies. The data exchange agreements should facilitate data exchange by including provisions and protocols to access the data as automatically and seamlessly as possible. Some of these agencies have developed data and map viewers, which are useful for general data gathering and information purposes. Although TxDOT could benefit from this level of access, a much more useful arrangement would be through data scripts and other mechanisms to enable the automatic extraction and import of data into a database at TxDOT where it can be used for a variety of applications.

Strategy benefits or advantages:

- Coordinated access to a range of spatial and non-spatial datasets that depict energy developments in the state.
- Deeper understanding of spatial and temporal patterns in the development of energy resources in the state and the impact of developments on the transportation network.
- Ability to overlay energy-related datasets on transportation layers in a GIS environment.
- Ability to generate a wide range of maps and reports depicting energy developments throughout the state.

Strategy costs, challenges, or disadvantages:

- Firm commitment and support from the administration to develop and maintain the geodatabase over time.
- Investment to develop and maintain the geodatabase. TxDOT would need to formulate a financial model to ensure the long-term sustainability of the geodatabase.

Implement Interagency Cooperation Agreements with Other Agencies

TxDOT should initiate discussions with other agencies leading to the execution of interagency cooperation agreements to facilitate the acquisition and maintenance of critical energy-related datasets and to learn about energy developments early while these developments are still in the planning phase. The nature and scope of the interagency agreements would vary, depending on the type of data and the frequency with which the data need to be acquired.

As mentioned previously, the list of agencies that provide energy-related datasets is extensive. A sample of agencies associated with the most critical datasets follows.

- **Railroad Commission of Texas**. RRC maintains an extensive database of oil and gas well permits in the state. The database includes both spatial data (i.e., locations of wells in latitude and longitude) and non-spatial data, which include a large number of attributes, including control dates such as permit application and approval date, well completion date, well status, and well type. The database also includes production data. A separate database tracks fluids injected into injection and disposal wells.

  Accessing and using data from RRC is not straightforward. The researchers received data in Esri format (spatial data) and text format (non-spatial data from the master file tape and the drilling permit tape), which required extensive processing before the data could be used. As of June 2011, the database included permit records associated with some 1.2 million oil and gas wells. In order to access the data efficiently, the researchers recommend that information technology (IT) personnel from both TxDOT and RRC meet to discuss and agree on an appropriate set of data access and export protocols. The protocols would also address issues such as data confidentiality and data security. The interagency cooperation agreement would include those protocols by reference. At this point, the researchers do not anticipate a need for real-time data access to the RRC database. Regular data updates, e.g., monthly, would suffice.

  Another reason an interagency agreement with RRC is strategic is to help both agencies understand each other's missions and challenges and collaborate on strategies to address common issues. An example of this need is that, recently, an RRC commissioner announced the establishment of a task force for the Eagle Force Shale. Members of the task force included representatives of a variety of agencies and groups, including local elected officials, community leaders, oil and gas producers, environmental groups, oil services companies, property owners, and a trucking company. However, transportation agencies, either local or state, were not invited to participate in that task force.

As part of the interagency agreement with RRC, the Commission could include a requirement that drilling permit applicants should submit a proposed transportation plan for TxDOT review and comment. The transportation plan could be submitted in phases. For example, Phase I would include a preliminary plan submitted to RRC with a copy to TxDOT at the time the drilling permit application is submitted. This plan would not be detailed, but would include enough information for TxDOT to learn about the proposed energy development, including the approximate location of proposed driveways, and provide feedback to the applicant on specific routing-, access-, or pavement-related issues the developer might face. Phase II would include a more detailed plan submitted to TxDOT before construction starts and would include plans and details associated with all driveways and other critical road-related features.

- **Texas General Land Office**. One of the primary responsibilities of the GLO is to lease land and mineral holdings for energy and mineral development. Leases for oil and gas development occur both onshore and offshore. Most of the revenue from these operations goes into the Permanent School Fund, with highway leasing and other areas playing a minor role.

  The GLO maintains a database of leases. It also maintains a web-based system called the Energy Land Lease Information System (ELLIS), which enables searches of leases by name or number for leases on Texas bays and the Gulf of Mexico. Onshore lease data are not spatially enabled, although it may be possible to manually generate spatial locations from the lease information the GLO keeps.

  As in the case of other property owners, the state receives offers from energy developers for leases involving potential future developments. Approving and executing a lease can take months of preparation and negotiation. However, what is significant is that energy developers pursue mineral leases with property owners, including the state, very early in the process (e.g., three-five years before drilling). It would be strategic for TxDOT and the GLO to enter into an interagency cooperation agreement, which would enable TxDOT to learn about new mineral leases at regular intervals (e.g., every quarter), convert that information to GIS features, and add those features to the energy geodatabase. TxDOT could use this dataset to learn about the general location where energy developments could be taking place in the short- to mid-term (e.g., three-five years into the future).

- **Electric Reliability Council of Texas**. ERCOT manages the flow of electricity to 23 million Texas customers. It covers 85 percent of the state's electric load and 75 percent of the state's land area. It schedules power on an electric grid that connects 40,500 miles of transmission lines and more than 550 generation units. Through a special arrangement, ERCOT makes available files in AutoCAD and PDF formats depicting the location of features such as transmission lines, electric congestion management zones, and electric reliability corporation regions. As explained earlier, the researchers converted this information to georeferenced features that were then overlaid to other features in a GIS environment.

This information is available online without an interagency agreement (although it is necessary to register before accessing the website). However, an interagency agreement with ERCOT would be beneficial because of the type of advance information TxDOT might be able to acquire. For example, wind developers normally do not disclose the location of their leases before they sign an interconnection agreement (IA) with ERCOT. After the IA is signed, the wind farm development is publicly announced. IAs typically take six-eight months to complete. The process includes a request from the wind farm developer and subsequent review by ERCOT of the feasibility to connect to the grid. Through an interagency agreement, TxDOT might be able to learn about the location of a wind farm well in advance of the public announcement.

As part of the agreement with ERCOT, the Council could include a requirement that IA applicants should submit a proposed transportation plan for TxDOT review and comment. The transportation plan could be submitted in phases. For example, Phase I would include a preliminary plan submitted to ERCOT with a copy to TxDOT at the time the IA is submitted. This plan would not be detailed, but would include enough information for TxDOT to learn about the proposed energy development, including the approximate location of proposed driveways, and provide feedback to the applicant on specific routing-, access-, or pavement-related issues the developer might face. Phase II would include a more detailed plan submitted to TxDOT before construction starts describing details associated with driveways and other critical road-related features.

- **West Texas A&M University's Alternative Energy Institute**. AEI maintains a listing of wind farms in the state, including approximate locations in latitude and longitude, as well as the number of wind turbines and the year the farm became online. Unfortunately, the listing does not include polygons or other similar information depicting the approximate geographic extent of each wind farm (i.e., the latitude-longitude coordinates correspond to just one point located somewhere inside the wind farm). In some cases, it may be possible to use recent aerial imagery or online search tools to trace the approximate location of the wind farms. Despite these limitations, the AEI listing is useful for tracking wind farms as they become online. Through AEI, it is also possible to obtain a raster file depicting wind power potential in the state.

- **Public Utility Commission of Texas**. PUCT is responsible for identifying competitive renewable energy zones and developing a plan to provide electric transmission lines to the CREZs. Of 24 potential wind energy development areas, PUCT selected five of those areas as CREZs: McCamey, Central, Central West, Panhandle A, and Panhandle B (*49*).

  ERCOT developed a map that shows power infrastructure needs in the state. This map is available on the PUCT website (*50*). This map shows CREZs and locations within 20 miles (according to information PUCT provided), where ERCOT believes additional transmission lines will be needed to route electric power from wind farms. These locations might also indicate potential locations where TxDOT infrastructure might receive the biggest impact from wind farm developments.

- **Pipeline and Hazardous Materials Safety Administration**. PHMSA maintains the National Pipeline Mapping System, which is a GIS-based inventory of locations and selected attributes of major gas transmission and hazardous liquid transmission pipelines, and LNG plants operating in the United States (*51*). Pipeline operators contribute data annually to the national repository. NPMS data have a target accuracy of ±500 ft horizontally.

  Distribution of NPMS data is limited to pipeline operators and local, state, and federal government agencies. From the information PHMSA provided, it was not possible to ascertain during the research whether pipeline operators provide information about future pipeline installations. However, discussions between TxDOT and PHMSA could (a) help TxDOT to obtain additional information that might not be possible through PHMSA's standard dataset, and (b) help to start a dialog between PHMSA and the industry that would result in pipeline operators providing advance notifications to PHMSA, which would benefit state agencies such as TxDOT.

- **Other agencies**. In addition to these organizations, agencies such as TCEQ might provide supplemental information, e.g., in cases that involve permits. The TCEQ surface casing program, which is related to the protection of groundwater resources from oil and gas activities, is being transferred to RRC. This transfer is the result of HB 2694, which the 82nd Texas Legislature passed recently (*52*).

  Appraisal districts contain a wealth of information about mineral leases. Unfortunately, most of this information is not available electronically, making it necessary to manually gather and process the resulting information. Alternatively, it may be possible to subscribe to a commercial service that specializes in aggregating and selling leasing information. Some of those services generate GIS-based lease features. An obvious disadvantage is that accessing this information would require a financial commitment.

Strategy benefits or advantages:

- Coordinated access to a range of spatial and non-spatial datasets that depict energy developments in the state.
- Deeper understanding of spatial and temporal patterns in the development of energy resources in the state.
- Deeper understanding of the needs and concerns of other agencies that deal with energy developments and increased opportunities for collaboration to address common issues.

Strategy costs, challenges, or disadvantages:

- Firm commitment from the highest levels of the TxDOT administration.
- Some costs involved, particularly at the beginning, in order to set up the agreements.

Improve Communication and Coordination with Energy Developers

TxDOT should develop and maintain effective communication and coordination protocols with energy developers. In the current practice, communications with the energy sector tend to be sporadic and ad hoc. This practice leads to inefficiencies and is partly responsible for the lack of knowledge by department officials about energy developments and how these developments affect the department.

TxDOT could borrow from the experience of interacting with external stakeholders in other areas. For example, in the area of utility adjustments, a wealth of recommended practices exists in the literature, both in Texas and elsewhere, which could be used to develop a list of recommended practices for developing effective communications with the energy sector. Examples of potential practices include the following:

- At the division level, schedule at least one meeting with energy developers every year. The purpose of the meeting would be to establish or renew relationships, highlight major projects and initiatives, discuss topics and issues of mutual interest, and identify items for further discussion or resolution. Memoranda of understanding (MOUs) or more detailed project-level agreements could also be a result from meeting discussions. Invitations to participate in the meeting would include TxDOT officials, other state agencies, energy sector associations, and other stakeholders.

- At the region or district level, schedule regular meetings with energy developers to discuss issues of mutual interest. Depending on the district and the type of energy developments in the region, the frequency of the meetings could vary. However, it is reasonable to assume these meetings to take place semiannually or quarterly. These meetings could be held in conjunction with other existing meetings that stakeholders already attend or host (e.g., cities and counties).

- Develop a website to keep track of meeting schedules, agendas, and minutes. The website would also provide links to additional documents and sites of interest to TxDOT and external stakeholders. A designated official from the Maintenance Division would be responsible for managing the website and ensuring the site contents are current. Designated officials at the region or district level would be responsible for adding content to the website regarding activities and initiatives within their jurisdiction.

- Identify initiatives that can benefit both TxDOT and the energy sector, and pursue those initiatives through MOUs and special-purpose agreements. A potential initiative is the development of outreach and training materials in areas of mutual interest. Examples of training modules could include the following:

    - TxDOT processes (for energy sector representatives).
    - Energy development processes (for TxDOT employees).
    - Energy development technologies.
    - Pavement analysis and deterioration.
    - Estimation of impacts on the transportation infrastructure.

- TxDOT driveway permitting process and standards.
- TxDOT utility accommodation policy and procedures.
- Funding mechanisms and agreements.

For some of the training modules, TxDOT would be responsible for developing and maintaining the content. For other training modules (e.g., in relation to the process to develop energy sites or discussions about technology), the industry would be better suited to develop the content.

Strategy benefits or advantages:

- More effective working relationship between TxDOT and energy developers.
- Increased awareness among energy developers of issues and challenges TxDOT faces in connection with energy developments.
- Increased awareness among TxDOT officials of the planning, development, construction, operation, and maintenance needs associated with energy developments.

Strategy costs, challenges, or disadvantages:

- Buy-in from TxDOT officials at all levels about the need for more effective communication and coordination with the energy sector.
- Cost to develop and maintain training modules.
- Willingness and interest of different stakeholders about the need for outreach and training materials.

Implement Additional Proactive Mechanisms to Learn about Energy Developments

To complement the tools described above, TxDOT should use a variety of additional mechanisms to learn about energy developments early while these developments are still in the planning stages. Examples of additional mechanisms include the following:

- **Review oil and gas drilling permit data**. Developing and maintaining the geodatabase of energy developments is not sufficient. To maximize its potential, districts should use the geodatabase in actual practice. To achieve this objective, one or more designated officials at the district level should be responsible for running queries on the database at pre-specified intervals, e.g., semiannually or quarterly, to generate maps and reports to support trend analysis and forecasting. These queries are particularly critical in the case of oil and gas drilling permits for a number of reasons, including the huge number of locations throughout the state and the rapidly changing nature of the business.

- **Follow, compile, and review local media**. Clues and information about future energy developments frequently appear in a variety of local media. Examples include newspaper articles, radio and television segments, and, increasingly, web-based information sources such as blogs, articles, discussions, and tweets. To facilitate monitoring of electronic information, it is advisable to use web-based aggregators including Really Simple

Syndication (RSS) feed aggregators. Public information officers at the district level should be responsible for tracking this information and generating a digest that could be distributed to district officials on a regular basis, e.g., semiannually or quarterly. They could also prepare regional or statewide summaries from the digests prepared at the district level.

- **Review vehicle routing plans**. Local jurisdictions frequently specify routes and/or impose limitations on the types of routes that truck operators can use. In some cases, e.g., the City of Fort Worth, local ordinances prohibit facilities such as saltwater disposal facilities within city limits. In many cases, these requirements have repercussions beyond city limits, e.g., when the locally permitted routes connect with the state transportation network or when saltwater trucks need to use state roads to access saltwater disposal facilities located outside city limits. Officials at the district level should become familiar with local requirements and their potential impact on the state transportation network.

Strategy benefits or advantages:

- Early knowledge of potential energy developments.
- Early knowledge of potential impacts both on the transportation network and the local communities.

Strategy costs, challenges, or disadvantages:

- Commitment at the district level to acquire and process the additional information.
- Some costs involved in the gathering and distribution of the resulting information.

Work with TxDPS to Improve Traffic Safety and Protect the Transportation Infrastructure

TxDOT should request additional presence from TxDPS on corridors subject to energy developments to enforce traffic safety laws and regulations, and to protect the transportation infrastructure, particularly on secondary roads. Currently, very few inspections take place on these corridors.

Of the various types of violation types, loads in excess of 34,000 lb per tandem axle are of particular interest. A number of tactics to address this critical issue may be feasible, including the following:

- Increase the level of TxDPS enforcement and inspections in areas where heavy trucks operate, e.g., near oil and gas well construction sites and saltwater disposal facilities.

- Use, or increase the use of, portable truck axle scales to monitor truck axle weights. These scales are typically not accurate enough for enforcement, but officials could use the scales to identify problem areas where targeted enforcement should happen. Historically, one reason TxDPS does not inspect more trucks on secondary roads is the lack of space to pull over trucks safely. In rural areas where daily truck traffic is not high, it may be possible to install portable scales on one of the lanes and guide traffic with the help with cones, without severely affecting traffic operations on the road. Alternatively, it may be possible to widen the cross section of the road at targeted locations (e.g., near saltwater disposal facilities) to facilitate the installation of the portable scales at those locations. Changeable message signs (CMSs) could also be used to alert truck drivers about the axle weights measured with the portable device.

- At locations such as well fluid stations and saltwater disposal facilities, reach an agreement with the facility operators to build a pad where TxDPS officials can conduct traffic safety inspections safely. This pad could be either inside the facility or on the state right-of-way next to the driveway.

Strategy benefits or advantages:

- More effective enforcement of traffic and safety laws and regulations.
- Less damage to the transportation infrastructure.

Strategy costs, challenges, or disadvantages:

- Additional resources at TxDPS to conduct inspections.
- Additional resources to develop the infrastructure to conduct inspections safely.
- Resistance by some within the energy sector to additional enforcement levels.

ROAD MAINTENANCE AND REPAIR

Strategies and recommendations for implementation include the following:

- Strengthen the use of triaxial design checks in the current flexible pavement design method.
- Extend the use of nondestructive testing tools.
- Strengthen guidelines for cross sectional elements on rural two-lane highways.
- Examine the feasibility of converting paved roads to gravel surface roads.

Strengthen the Use of Triaxial Design Checks in the Current Flexible Pavement Design Method

Overriding the triaxial design check should not be allowed on corridors affected by energy developments. In the current practice, project engineers are allowed to override the outcome of the triaxial design checks (typically in order to accept a thinner pavement when the check would otherwise result in a thicker pavement) based on evidence of adequate performance on similar pavement structures relative to the pavement design under consideration.

For low-volume roads where the expected number of cumulative 18-kip ESALs is low, it is not unusual to find trucks with heavier wheel loads than those of the standard 18-kip single axle configuration used in pavement design. Although occasional, these overloads could cause subgrade shear failure, particularly where the base or subgrade is wet. The Texas Triaxial Class (TTC) design check enables the project engineer to verify the results from TxDOT's FPS to ensure the design thickness provides adequate cover to protect the subgrade against occasional overstressing (*53*). In cases where the thickness requirement from the triaxial design check is greater than the pavement thickness determined from FPS, the software interface displays a "Design Fails !" message (Figure 88), at which point the recommendation is to modify the pavement design and check again until the design passes (*54*). In common practice, designers add the difference between the triaxial design check thickness and the FPS design thickness to the flexible base thickness. However, the project engineer may also override the outcome of the triaxial design check and accept the original design, taking into consideration the past performance of similar pavements.

This practice is inadequate for corridors subject to energy developments because these corridors do not conform to the traditional low-volume road model. For energy corridors, not overriding the triaxial design check would require the engineer to re-evaluate the existing pavement design using FPS in order to identify alternative designs with thicker layers and/or better materials that would pass the triaxial design check and sustain the expected level of truck traffic associated with energy developments. It would also require the engineer to carefully assess the applicability of past performance to justify using the pavement design from FPS. For affected corridors, past performance on similar pavements might not reflect the level of truck traffic associated with energy developments on the specific corridor under consideration.

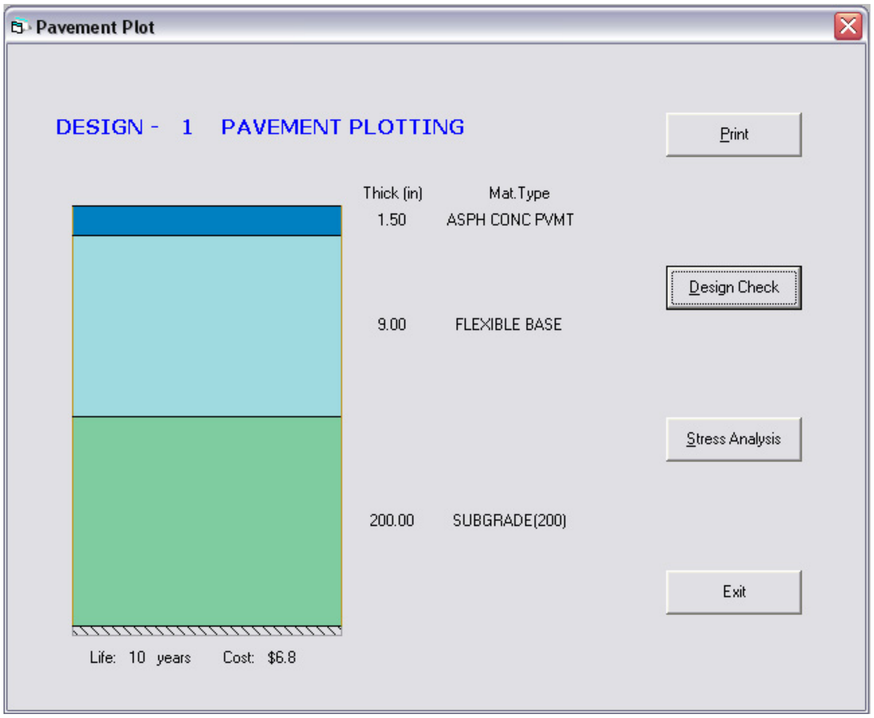
Strategy benefits or advantages:

- Thicker pavement to sustain the increased level of truck traffic associated with energy developments, which, in turn, would reduce the rate of accelerated pavement failure.
- Higher design standard for energy corridors than for "normal" low-volume roads.

Strategy costs, challenges, or disadvantages:

- Higher initial cost associated with the thicker pavement structure from the modified triaxial design check.
- Higher initial cost associated with the higher quality pavement required to pass the modified triaxial design check.

(a) TxDOT's FPS screen



(b) Triaxial design check screen

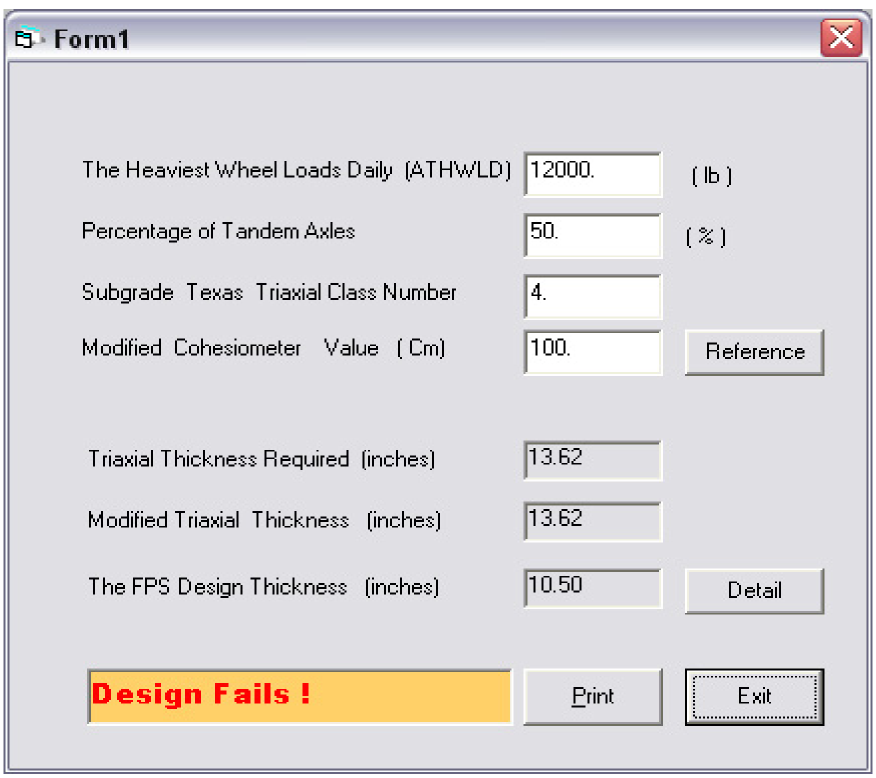


Figure 88. Modified TTC Design Check in FPS 19.0.

Extend the Use of Nondestructive Testing Tools

TxDOT should use nondestructive tools on routes that are subject to energy developments to obtain information that can be used to support maintenance or rehabilitation decisions along those corridors. In particular, the researchers recommend using GPR and FWD to evaluate existing pavement structural conditions and identify weak or potentially problematic sections early when energy developments are still in the planning phase, i.e., to establish "before" conditions. Districts could also take measurements to monitor the degradation of the pavement structure after energy developments begin in order to assist with maintenance and/or policy decisions.

TxDOT pavement engineers use FWD and GPR data to document the cause of pavement failures and to select optimal repair strategies, particularly on projects along corridors that experience premature pavement failure. FWD data enable the calculation of pavement layer moduli, which are used in FPS 19 for flexible pavement design on new construction and rehabilitation projects. FWD data also provide information about the load-carrying capacity of a pavement structure. The department summarizes FWD measurements into a structural strength index (SSI) that ranges from 1 (very weak) to 100 (very strong). PMIS documents which segments have SSI data.

GPR is used to measure layer thickness and to identify subsurface defects in the pavement structure, primarily for gathering information for rehabilitation projects and for flexible pavement monitoring purposes. GPR is also used for bridge deck evaluations. TxDOT operates several GPR test vehicles. GPR services are also available through an interagency agreement between TxDOT and TTI where the technology has been used during the course of forensic investigations to understand the reason for premature pavement failures.

The researchers' understanding is that in the mid-1980s there was an initiative to collect network-wide FWD data, but the practice was made voluntary in the early 1990s because of the perception that the data collection took too much time and effort. In addition, as part of the transition from Dynaflect to FWD for pavement structural evaluation, districts recognized the suitability of FWD for project-level use to support pavement design on rehabilitation projects. Nevertheless, a few districts such as San Antonio, Wichita Falls, and Houston make an effort to collect FWD data extensively.

Given this precedent, collecting FWD and GPR data along corridors affected by energy developments will need to be carefully targeted. For example, having advance knowledge of where energy developments might take place would enable TxDOT to select specific corridors on which to collect data. For planning purposes, the data collection campaign would need to include equipment and staff time for the nondestructive testing as well as traffic control and other related logistical activities. It would also require assigning personnel to the task of processing and interpreting field data and preparing reports.

Using the geodatabase of energy datasets might facilitate the identification of preliminary, high-level data collection needs, and just as importantly, filter out corridors that are not critical. For example, by overlaying the dataset of oil and gas wells completed since 2005 on the state highway centerline dataset and generating a 5-mile buffer (i.e., radius = 5 miles) around each well, the result is that some 22,000 miles of FM roads would intersect that buffer. This extent of data collection would likely not be cost-effective. By reducing the buffer size to 1 mile around each well (i.e., radius = 1 mile), the result would be 7,872 miles of FM roads. Likewise, by only considering oil and gas wells completed in fiscal years 2009, 2010, and 2011, and by using a 2-mile buffer, the result would be 8,807 miles of FM roads. A 1-mile buffer for the same time period would result in 3,874 miles of FM roads. Additional queries could be generated, e.g., to identify corridors within a certain distance of oil and gas wells that have been permitted over the last year but have not been completed.

Strategy benefits or advantages:

- Ability to identify weak, potentially problematic areas along corridors affected by energy developments.
- Ability to translate data into quantifiable indicators such as remaining pavement life, and required maintenance, rehabilitation, or reconstruction costs.

Strategy costs, challenges, or disadvantages:

- Additional cost for conducting nondestructive tests. Based on some limited feedback from energy developers, it is possible for some of those costs to be absorbed by the industry.

Strengthen Guidelines for Cross Sectional Elements on Rural Two-Lane Highways

TxDOT should strengthen the guidelines for cross sectional elements of rural two-lane roads, particularly in the case of lane width, shoulder width, turn lane width, and horizontal clearance of routes with high truck traffic volumes associated with energy developments. Table 4-2 in the *Roadway Design Manual* (*23*) includes design guidelines for rural two-lane highways, but these guidelines do not account for cases where heavy truck traffic is predominant. A disclaimer in the guidelines gives the engineer the flexibility to adopt higher geometric design element values if needed. However, as written, the disclaimer is weak.

To strengthen the design guidelines for cross-sectional elements of rural two-lane roads, the manual should address situations in which heavy truck traffic is predominant and provide specific recommendations or requirements as a function of daily truck traffic thresholds. These recommendations would also apply to frontage roads, whether rural or urban, in situations where heavy truck traffic is predominant on those roads. For example, Table 4-2 in the *Roadway Design Manual* would be expanded to include recommended lane width, shoulder width, turn lane width, and horizontal clearance for different average daily truck traffic ranges.

There is not much in the literature on this topic, particularly for rural corridors with low to medium levels of truck traffic, e.g., less than 1,000 trucks per day. As a reference, in 2003, TxDOT Research Project 0-4364 provided recommendations on lane and shoulder widths for high-speed, heavily-traveled highways with at least 5,000 trucks per day (*55*). Given the lack of specific guidelines for low-volume roads affected by energy developments, there appears to be a need for additional research to establish applicable criteria for these roadways. In the interim, TxDOT should consider using a minimum lane width of 12 ft or a minimum paved shoulder width of 10 ft to determine the amount of widening needed.

Districts should consider widening the cross section of FM roads that are subject to frequent truck traffic to minimize the risk of edge failures, particularly in situations where the absence of a paved shoulder results in overstressing the pavement edge under repeated applications of heavy tire loads. Figure 89 shows typical pavement widening designs using bound and unbound base materials (*20*). In general, the researchers recommend avoiding base materials such as caliche for cross-section widening applications because those materials are susceptible to high moisture. If the decision is to use lower-quality materials due to budgetary constraints, lime stabilization should be applied to reduce susceptibility of the base material to moisture.

(a) Bound base

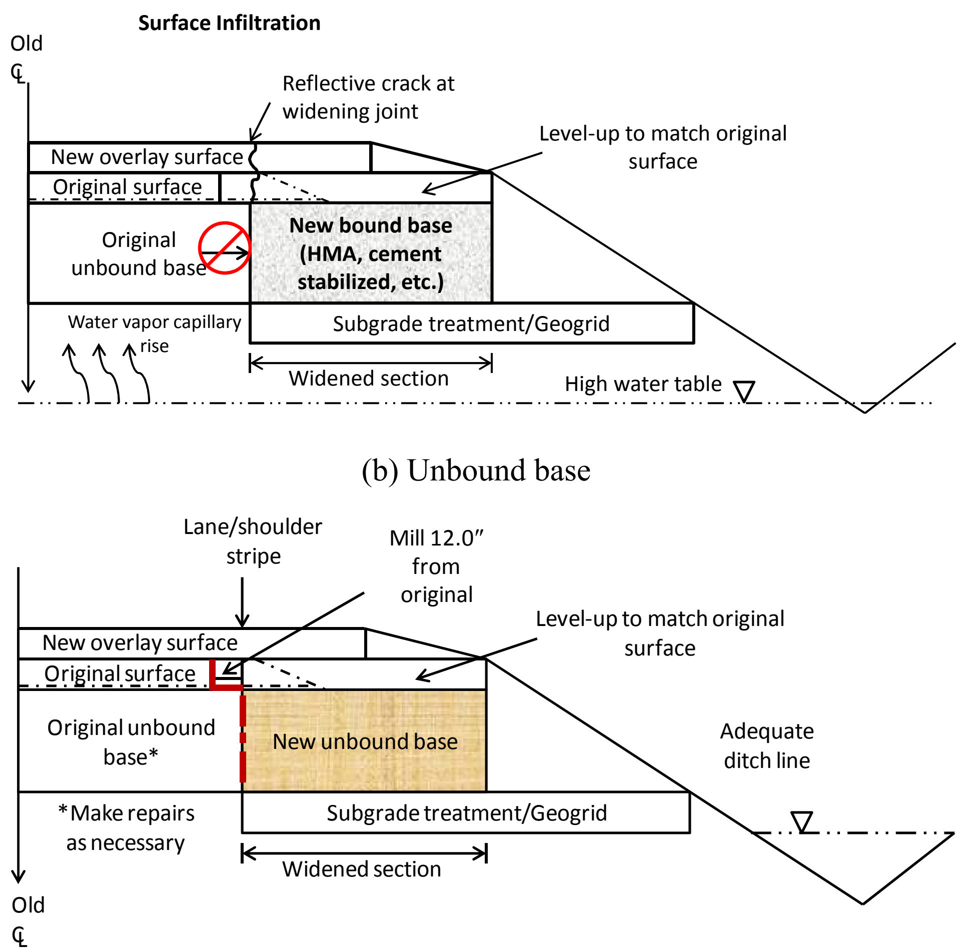


Figure 89. Typical Designs for Pavement Widening at TxDOT (*20*).

Following the *Pavement Design Guide* (*20*), selection of the new flexible base material should be based on a laboratory evaluation of both new and existing materials to compare their moisture susceptibility. Preferably, the moisture susceptibility should be about the same. The reason is that a material that is more susceptible to moisture may draw moisture from both the original section and from outside the structure. Likewise, a material that is less susceptible to moisture may send moisture to the original base, particularly during the original curing process. Part of research project 0-4519 involved conducting laboratory and field tests to evaluate the load-bearing capacity of different base materials built on clay and sand subgrade pavement sections (*53*). The researchers observed that caliche exhibited significant changes in moisture content as the material underwent moisture conditioning, indicating greater moisture susceptibility compared to the other base materials tested in the research.

Strategy benefits or advantages:

- Stronger design guidelines for corridors subject to energy developments.
- Effectiveness in mitigating pavement edge failure by moving tire loads away from the edge.
- Safety improvement, since progressive edge failure narrows the paved roadway width, increasing the risk of vehicular collisions as drivers move away from the pavement edge toward the center of the roadway.

Strategy costs, challenges, or disadvantages:

- Difficulty to allocate funds for pavement widening due to budgetary restrictions.
- Not sufficient for localized conditions, such as driveways to access well drilling operations or saltwater disposal facilities, which require truck drivers to make wide turns. In these cases, even if the driveway width is adequate, edge failures and rutting or shoving of the surface (due to turning and braking maneuvers) are likely to develop on the widened section. Additional measures are needed in these cases (see below).
- Need to acquire right-of-way at some locations if the existing right-of-way is limited.

Examine the Feasibility of Converting Paved Roads to Gravel Surface Roads

Research project 0-6677 aims to identify the conditions under which converting paved roads to unsurfaced roads might be a cost-effective option. The researchers' understanding is that research project 0-6677 will study the methods and costs associated with converting existing paved roads to unsurfaced roads.

The researchers recommend that research project 0-6677 include case studies to investigate the feasibility of implementing this strategy on routes affected by energy developments. During the stakeholder meetings conducted as part of research project 0-6498, several district officials highlighted the inefficiency of spending scarce resources maintaining a paved road that is being ruined by heavy truck traffic in connection with energy development efforts. Those officials highlighted that fixing potholes and applying bandages on those corridors is quite expensive. Under these conditions, a more effective strategy would be to proactively convert the road to a gravel surface road, perform blading operations as necessary to maintain the functionality of the road, and wait until the energy development is complete before restoring the paved surface.

Strategy benefits or advantages:

- Significant cost savings if it turns out the cost to maintain unpaved roads is lower than that for paved roads.
- Potential improvements in safety because of the possibility of fewer potholes and if drivers feel compelled to drive at slower speeds.
- Ability to use limited maintenance funds on other routes.

Strategy costs, challenges, or disadvantages:

- Costs associated with a public awareness campaign to clearly and convincingly illustrate the advantages of converting paved roads to unpaved roads.
- Potential need to partner with affected energy developers to share unpaved road maintenance responsibilities if TxDOT's own resources are not sufficient. Coordination, responsibilities, and liabilities would need to be clearly established to avoid or minimize problems.

ROADSIDE MANAGEMENT

Strategies and recommendations for implementation include the following:

- Strengthen driveway permitting requirements.
- Automate the driveway permitting process.

Strengthen Driveway Permitting Requirements

TxDOT should update manuals, specifications, and guidelines that pertain to the design, construction, inspection, and operation of driveways to address the type of heavy truck traffic used for energy developments. Because of the lack of robust, standardized driveway permitting requirements for energy developments, there is a wide range of practices throughout the department, e.g., in terms of which provisions to specify and the level of coordination and inspection required in the field. Note that many energy developers operate regionally or nationally. Having one set of standardized guidelines, specifications, and requirements that apply throughout the department would facilitate communications and coordination between TxDOT and those energy developers.

Several documents need to be updated to provide clear, standardized information and guidance to energy developers (and, for that matter, any applicant in rural areas who envisions using a substantial number of heavy trucks accessing their facilities from a state highway), including the following:

- *Access Management Manual* (31).
- *Roadway Design Manual* (23).
- Form 1058 (*Permit Construct Access Driveway Facilities on Highway Right of Way*).

The existing documentation includes references to items such as the *Regulations for Access Driveways to State Highways* and Form 1058, neither of which is available on the TxDOT website.

It is common for TxDOT to learn about the existence of energy developments only when it receives the corresponding driveway permit applications (which is frequently at the end of the process for the energy developer right before construction, i.e., too late for TxDOT to start preparing for the resulting traffic). As a result, it will be critical to include in the updated documentation some information about relevant processes within the department (e.g., typical timelines to maintain and upgrade roads) as well as specific requirements about advance notification, frequent coordination, and points of contact. If properly implemented, the updated requirements would, in effect, improve communication and coordination between energy developers and TxDOT, and would enable TxDOT to learn about energy developments earlier in the process.

The researchers also recommend TxDOT to work with counties and other local jurisdictions to address apparent loopholes in the driveway permitting process. For example, anecdotal information suggests that energy developers sometimes plan their facility locations so that access to those facilities is from a county road if they perceive the county permitting process to be more lenient than the TxDOT process. In this case, trucks would first take the county road from a state road and then enter the energy facility from the county road. A problem for TxDOT is that it is still responsible for maintaining the intersection between the county road and the state road, but is not informed about the new development in a timely fashion. Another problem is the difficulty to allocate resources to repair damages to that intersection and the adjacent approaches. Coordination between counties and TxDOT would help to address these two problems.

Strategy benefits or advantages:

- Standardized, strong driveway permitting standards, specifications, and guidelines.
- Less severe damage to adjacent pavement and fewer repairs.
- More adequate drainage control.

Strategy costs, challenges, or disadvantages:

- Initial cost to develop the updated standards, specifications, and guidelines.
- Cost to develop and implement an outreach and training program to make energy developers aware of the updated requirements.

Automate the Driveway Permitting Process

TxDOT should automate the driveway permitting process by developing a web-based system that provides applicants (not just energy developers) with a single portal that includes functionality such as the following:

- Single point of access with information and hyperlinks for all documentation that pertains to the driveway permitting process (e.g., manuals, guidelines, forms, and points of contact). The web page would also include examples of successful driveway permits, companion documentation, and photographs to illustrate the difference between best or recommended practices and questionable practices.
- Interface to enable applicants to submit driveway permit applications online, with the capability to upload attachments in a suitable format depending on the needs of the specific driveway application. For example, the system could accept files in portable document format (PDF), portable network graphics (PNG) (an increasingly used image format), and Bentley MicroStation format.
- Interface to enable TxDOT officials to enter comments and attach files that pertain to a driveway permit application.
- Ability to generate a wide range of map-based and tabular queries and reports.
- Remote wireless access for field personnel.
- User and account management capabilities.

According to Maintenance Division estimates, TxDOT processes some 10,000 driveway permits per year, of which 90 percent are simple driveway permits and the remaining 10 percent are complex driveway permits that require traffic impact statements. Automating the driveway permitting process at TxDOT would make a significant difference in TxDOT's ability to manage the process and the state highway right-of-way.

Strategy benefits or advantages:

- Standardized inventory of driveway permits throughout the department.
- Improved ability to manage the driveway permitting process.
- Centralized web-based access to all documentation and requirements that pertain to the driveway permitting process.
- Accountability.

Strategy costs, challenges, or disadvantages:

- Cost to develop, implement, and maintain the web-based system.
- Need to provide training to TxDOT officials and applicants.

FUNDING

Strategies and recommendations for implementation include the following:

- Assess damages to pavement structures in connection with energy developments.
- Use donation agreements with energy developers.
- Examine the feasibility of establishing driveway permit fees.
- Review maintenance funding allocation formulas.
- Determine the feasibility of using energy-related fees, taxes, and lease revenues for highway repair purposes.

Assess Damages to Pavement Structures in Connection with Energy Developments

The *Maintenance Management Manual* emphasizes the importance of investigating damages and the need to file claims if the responsible party can be identified (*56*). The *Financial Management Policy Manual* (*57*) describes TxDOT's procedure to file damage claims. Unfortunately, this manual is available only on the TxDOT intranet, which means that external parties that cause damage to the state highway system do not have access to this important piece of information. In the interest of transparency and accountability, the *Financial Management Policy Manual* should be published along with other manuals on the TxDOT website.

It is critical to assess damages to pavement structures in connection with energy developments. A practical difficulty for using current procedures is the ability to document the condition of the road prior to the beginning of energy development activities. TxDOT has control over this challenge. For example, TxDOT could take pictures and video of the roadway segments as soon as the department knows or suspects there might be energy-related activities. Previous sections outline a number of strategies to help TxDOT learn about energy developments earlier in the process. TxDOT should also collect FWD and GPR data as soon as possible (even if the data are processed later).

Another challenge is the ability to establish cause and effect, i.e., determine what level of responsibility can be attributed to an individual energy development. A related challenge is the ability to determine when the damage has taken place (since the damage might not be immediately evident). This research demonstrated several tools TxDOT can use to estimate the damage caused by individual energy developments (in excess of what the facility would sustain under "normal" traffic conditions) and how to translate that damage to a monetary value.

A critical challenge is how to identify the party responsible for the damage. This is significant, particularly in situations when an energy developer does not own or operate the trucks or equipment they use. Because energy developers typically contract out many of their activities, including truck movements, separating and assigning levels of responsibility can be difficult—which is convenient for the energy developer.

Strategy benefits or advantages:

- Transfer of a component of the risk associated with causing damage to the transportation infrastructure to energy developers.
- Ability of districts to seek reimbursement for damages caused by individual developments (in excess of what the facility would sustain under "normal" traffic conditions).

Strategy costs, challenges, or disadvantages:

- Commitment from the highest levels of the TxDOT administration.
- Costs associated with the assessment of damages.

Use Donation Agreements with Energy Developers

The *Local Government Project Procedures Manual* (*58*) describes procedures that provide guidance to local governments (LGs) developing transportation projects under TxDOT's oversight. In the manual, the term LG includes municipalities, counties, regional mobility authorities (RMAs), local toll authorities, and private entities. These procedures address both federal and state requirements, and cover a wide range of topics, including the following:

- Planning and programming.
- Advance funding agreements.
- Site identification and survey.
- Environmental compliance.
- Right-of-way and utilities.
- Preliminary engineering, design, and plans, specifications, and estimates (PS&E).
- Building facilities.
- Traffic operations.
- Bridges.
- Construction.
- Procurement of other goods and services.
- Maintenance.
- Finance and project accounting.
- Data submission requirements.
- Audits.

Following the *Construction Contract Administration Manual* (*59*), an advance funding agreement (AFA) or a donation agreement is used when a third party provides some or all of the funding for a project. An AFA typically applies if the third party is a local government (e.g., a city or county), a private or public utility owner, or a railroad. A donation agreement applies if the third party is a private entity. Following the Texas Administrative Code (*60*), donation agreements require a Commission meeting minute order and a vote by the Commission to accept the donation. The Contract Services Section at the General Services Division develops and coordinates AFAs and donation agreements. The *Contract Management Manual* (*61*) contains detailed information about AFAs and donation agreements. Both types of agreements must be amended if a change order expands the scope of the original agreement or the third party contribution is for a fixed amount.

TxDOT districts and local public agencies have cooperated in the maintenance of the state highway system for years (*58*). From a contractual perspective, this is usually done either through a municipal maintenance agreement or through an AFA (for a specific project). The *Local Government Project Procedures Manual* (*58*) includes specific requirements for maintenance agreements.

Entering into a donation agreement to enable a private entity to donate cash is straightforward. The situation is less clear if the private entity is to donate materials or perform work on the state right-of-way as part of a donation agreement. The reason is the requirement in Subchapter A, Chapter 223 of the Transportation Code (*62*) related to the need for competitive bids for contracts for the improvement of a highway or materials to be used in the construction or maintenance of that highway. In some situations, e.g., in the case of land swaps, a private entity has been able to donate materials and work. For example, a coal mining company that owns the land on both sides of the road would offer to build a new road on private property, which is parallel to the existing road, and then complete a swap. The state receives a brand-new road on a new alignment and the mining company is able to mine for coal under the old road.

HB 628, which was enacted into law recently as part of the regular 82nd legislative session (*63*), will enable TxDOT to enter into a contract with the owner of land adjacent to a state highway without complying with the competitive bidding procedures in the Transportation Code. The contract may be used for an improvement on the state right-of-way that is directly related to improving access to or from the owner's land. According to the General Services Division, TxDOT intends to implement this bill through the donation process.

A question that remains is whether an energy developer who is not a landowner, but who has an interest in the property adjacent to the state right-of-way, would comply with the provisions in HB 628. If so, TxDOT could use the donation agreement tool to enter into contracts to enable energy developers to donate cash, materials, and services to maintain or repair pavement structures that are subject to damage by energy-related activities.

Although its legal feasibility would need to be established, it is also possible that an AFA could be used between TxDOT and a local government (e.g., a county) that receives funding from an energy developer for road maintenance and repairs in the region where the energy developer operates. This type of agreement would be a special type of pass-through financing, except the state would not reimburse the local government or the energy developer later. An AFA with the local government could also be used once the local government begins to receive royalty-related taxes from property owners. Potential risks with this type of tool include having to depend on a local governing body to approve the agreement (which could be time consuming) and liabilities if the private donor walks away from its commitments.

Strategy benefits or advantages:

- Transfer of a component of the risk associated with causing damage to the transportation infrastructure to energy developers.
- Ability of districts to seek reimbursement for damages caused by individual developments (in excess of what the facility would sustain under "normal" traffic conditions).

Strategy costs, challenges, or disadvantages:

- Commitment from the highest levels of the TxDOT administration.
- Resistance by energy developers to enter into donation agreements to pay for damages to the transportation infrastructure.

Examine the Feasibility of Establishing Driveway Permit Fees

As mentioned, TxDOT processes some 10,000 driveway permits annually. TxDOT should explore the feasibility of establishing driveway permit fees as a mechanism to recoup the administrative costs associated with the permitting process. In the case of energy developments (or commercial driveways, for that matter), a permit fee would also enable TxDOT to enhance its inspection capabilities and provide a more effective customer service to applicants, particularly if TxDOT automates the permitting process as discussed previously.

The fee schedule would vary, depending on the type of permit and the level of review and involvement of TxDOT officials. An alternative (or complement) to a permit fee could be a deposit the applicant would make, the amount of which depends on the potential damage to the transportation infrastructure. If there is no damage, the deposit is returned. Other state DOTs use this approach, e.g., the Minnesota DOT (Mn/DOT) (*64*).

Strategy benefits or advantages:

- More effective management of the driveway permitting process.
- Ability to recoup some the costs associated with the administration of the permitting process and potential damages to the transportation infrastructure.

Strategy costs, challenges, or disadvantages:

- Resistance by energy developers or decision makers to the establishment of permit fees.

Review Maintenance Funding Allocation Formulas

During the stakeholder meetings and other exchanges with TxDOT officials, there were references to the need to review the formulas TxDOT uses to allocate maintenance funds to districts by assigning a heavier weight to load repetitions and resulting pavement impacts.

In the current process, when the legislature passes an appropriation bill for the biennium, the Maintenance Division uses various funding formulas to determine each district's proposed budget (*56*). The district then coordinates the allocation of funds to each maintenance section, taking into consideration input from the district maintenance office, the area engineers, and the maintenance sections. The district engineer makes the final determination of allocated funds for the sections. In fiscal year 2011, the maintenance budget was distributed as follows: preventive maintenance ($345 million), rehabilitation ($297 million), and routine maintenance ($867 million) (*65*).

The maintenance funding allocation formulas are based on the application of factors that reflect the inventory of physical components and the condition of those components (*65*). For example, for preventive maintenance (preservation), funding allocation is based on average daily traffic levels (<500, 500–10,000, ≥10,000) and seal coat cycles, which are based on average rainfall. For rehabilitation, funding allocation is based on the amount of deep distress, VMT, ESALs, and a factor to adjust the rate of improvement. The weights associated with these factors are 0.325, 0.2, 0.325, and 0.15, respectively. For routine maintenance, funding allocation is based on factors such as number of lane miles, centerline miles, average daily traffic, daily vehicle miles, daily truck miles, rainfall, and pavement condition scores. Routine maintenance allocations also include roadside, traffic operations, bridge maintenance, and extraordinary maintenance (e.g., snow, ice, and flooding assistance).

As discussed in Chapter 4, the number and magnitude of load repetitions play a much more critical role on the reduction of remaining pavement life than traffic volumes alone. A high-level review of the funding allocation structure reveals that rehabilitation is the only area that explicitly considers pavement loads (e.g., ESALs) as a factor. Preventive maintenance relies on average daily traffic, while routine maintenance relies on average daily traffic, daily vehicle miles, daily truck miles, and pavement condition scores (which are indirect, incomplete measures of pavement load).

A determination of the effectiveness of the current funding allocation formulas is beyond the scope of this research. However, it is reasonable to assume that formulas explicitly considering ESALs in all three maintenance categories would likely result in funding allocations that favor corridors with higher heavy truck traffic volumes, including those that are affected by energy developments. The researchers recommend TxDOT to evaluate the feasibility of a revised approach for maintenance funding allocations that emphasizes ESALs and pavement impact.

Strategy benefits or advantages:

- Maintenance funding allocations that reflect actual pavement impacts more equitably than the current funding allocation formulas.

Strategy costs, challenges, or disadvantages:

- Reduction in the allocation of maintenance funds for some districts that do not have as much heavy truck traffic as other districts.

Determine the Feasibility of Using Energy-Related Fees, Taxes, and Lease Revenues for Highway Repair Purposes

The state collects a number of fees and taxes in connection with energy-related activities, as well as some revenue from mineral leases. TxDOT should start or lead a discussion with other state agencies and stakeholders to determine the feasibility of using some of those fees, taxes, and revenues to assist with the maintenance and repair of state roads affected by energy developments.

For example, following the Texas Natural Resources Code (*66*), fees for each new or amended application for a permit to drill, deepen, plug back, or reenter a well are as follows:

- \$200 if the total depth of the well is ≤2,000 ft.
- \$225 if the total depth of the well is >2,000 ft and ≤4,000 ft.

- $250 if the total depth of the well is >4,000 ft and ≤9,000 ft.
- $300 if the total depth of the well is >9,000 ft.
- Additional $200 when requesting a Rule 37 spacing or a Rule 38 density exception review.
- Additional $150 when requesting an expedited review of the application.

These fees are deposited in the state oil-field cleanup fund. During production, the state also charges oil-field cleanup regulatory fees on oil and gas, which are deposited in the oil-field cleanup fund (*67*). In FY11, the state expected to receive $24.7 million for the oil-field cleanup fund (*68*). This amount is expected to increase to $24.9 million in FY12 and $25.1 million in FY13. Slightly more than a third of this amount comes from the oil and gas drilling permit fees.

The state also levies a tax on crude petroleum produced in this state, as well as an occupation tax on the production of crude petroleum (*67*). The tax is deposited in the General Revenue Fund and is used for the administration of the state's oil and gas conservation laws. In FY11, the state expected to receive $1 billion in oil production and regulation taxes (*68*). This amount is expected to decrease to $955 million in FY12 and then increase to $974 million in FY13. Likewise, in FY11, the state expected to receive $621 million in natural gas taxes (*68*). This amount is expected to increase to $702 million in FY12 and $788 million in FY13.

One way to increase natural gas tax revenue is to repeal or limit the tax rate reduction for high-cost gas extraction (*69*). This exemption was expected to cost $962 million in FY11. The exemption applies to natural gas wells that are certified by the Railroad Commission of Texas as high-cost because of high operating expenses or the type of drilling technology used.

In FY09, TxDOT issued more than 500,000 permits and collected over $95 million in OS/OW permit fees (*70*). This revenue was deposited into the State Highway Fund and the General Revenue Fund. Many permits require the execution of surety bonds prior to the movement in case there is damage to the highway. Other permits require a highway maintenance fee that increases with the gross weight of the vehicle. For vehicles heavier than 200,000 lb, the permit fee includes a vehicle supervision fee that includes the cost for a bridge structural analysis, monitoring of trip progress, and movement of traffic control devices.

In the case of mineral leases, as mentioned, one of the primary responsibilities of the GLO is to lease land and mineral holdings for energy and mineral development. Most of the revenue from these operations goes to the Permanent School Fund, with highway leasing and other areas playing a minor role. Revenue from the highway leasing program is dedicated to the State Highway Fund (Category 6). For example, according to information from GLO officials, in fiscal year 2009, leasing for the Permanent School Fund produced $387 million in revenue, while the highway leasing program produced $7 million.

Strategy benefits or advantages:

- Increase in the funding allocated for maintenance and repairs on state highway roads affected by energy developments.

Strategy costs, challenges, or disadvantages:

- Resistance by energy developers or decision makers to the reallocation of fees, taxes, and mineral lease revenues.

CHAPTER 9. CONCLUSIONS

INTRODUCTION

In recent years, Texas has experienced a boom in energy-related activities, particularly in wind power generation and extraction of oil and natural gas. While energy developments contribute to enhance the state's ability to produce energy reliably, many short-term and long-term impacts on the state's transportation infrastructure are unknown. TxDOT has begun to document impacts of energy-related activities on transportation infrastructure through a variety of initiatives. However, a comprehensive document that describes impacts, needs, and strategies is missing. The purpose of the research was to measure the impact of increased level of energy-related activities on the TxDOT right-of-way and infrastructure, as well as develop recommendations to reduce and manage TxDOT's exposure and risk resulting from those activities.

To meet the research objectives, the researchers completed a number of activities, including the following:

- Developed file geodatabases of relevant energy and transportation-related datasets.
- Conducted and documented field visits to develop a more thorough understanding of potential impacts and issues resulting from energy developments.
- Evaluated pavement impacts, roadside impacts, operational and safety impacts, and economic impacts resulting from energy developments in the state.
- Prepared a set of strategies and recommendations for implementation.

GEODATABASES

The researchers developed file geodatabases of relevant energy and transportation-related datasets. The documentation included a detailed description of steps, scripts, and other procedures used, which would be needed to help develop and maintain the geodatabases during implementation. Four categories of energy-related datasets are included in Product 0-6498-P1, as follows:

- Non-renewable energy datasets.
- Renewable energy datasets.
- Energy use datasets.
- Geology-related datasets.

The deliverable includes information about four categories of transportation-related datasets, as follows:

- Oversize/overweight routing and enforcement datasets.
- Crash datasets.
- Transportation infrastructure datasets.
- Transportation planning datasets.

The researchers used these geodatabases to generate a wide range of queries, reports, including the following:

- Wind farms in relation to other energy developments as well as transportation datasets.
- Wind farms, CREZs, and transmission lines.
- Pipelines in relation to oil and gas wells.
- Permitted (and completed) oil and gas wells over time.
- Permitted (but not completed) oil and gas wells.
- OS/OW routes in relation to energy developments.
- Pavement statistics in relation to energy developments over time.
- Crash locations in relation to energy developments.

FIELD VISITS

The field visits enabled the researchers to develop a more thorough understanding of potential impacts and issues resulting from energy developments. They visited a sample of corridors and locations at the Lubbock, Abilene, and Fort Worth Districts. The researchers also collected GPR and FWD data at those districts. Considering the increasing level of activity in connection with the Eagle Ford Formation in South Texas, the researchers also met with officials from the Laredo, San Antonio, and Yoakum Districts.

IMPACTS

The evaluation of impacts of energy developments on the transportation infrastructure covered pavement impacts, roadside impacts, operational and safety impacts, and economic impacts. The pavement impact analysis included a high-level analysis of PMIS data that involved a comparison between the corridors visited in the field and other (control) corridors, as well as a more detailed analysis of pavement characteristics and anticipated pavement remaining life. The roadside analysis focused on the impact of energy developments on the state highway right-of-way, more specifically in the following areas: accommodation of energy-related facilities on the state right-of-way, access to the state right-of-way from adjacent areas undergoing energy-related activities, and management of mineral rights within the state right-of-way. The operational and safety analysis focused on the impact of energy-related developments on roadway operations and safety, more specifically on crash rates and vehicle enforcement data. The economic impact analysis included a documentation of funding and expenditure levels at TxDOT, a review of maintenance expenditures along sample corridors, and the development of a methodology to assess economic impacts resulting from specific energy developments.

RECOMMENDATIONS FOR IMPLEMENTATION

The researchers prepared a set of recommendations for implementation that included changes to business practices and procedures, as well as short-term initiatives to facilitate the implementation of the research findings. The recommendations were grouped into the following categories: early notification and coordination, road maintenance and repair, roadside management, and funding.

Recommendations for implementation in the area of early notification and coordination include the following:

- Implement and maintain the geodatabase of energy developments in Texas.
- Implement interagency cooperation agreements with other agencies.
- Improve communication and coordination with energy developers.
- Implement additional proactive mechanisms to learn about energy developments.
- Work with TxDPS to improve traffic safety and protect the transportation infrastructure.

Recommendations for implementation in the area of road maintenance and repair include the following:

- Strengthen the use of triaxial design checks in the current flexible pavement design method.
- Extend the use of nondestructive testing tools.
- Strengthen guidelines for cross sectional elements on rural two-lane highways.
- Examine the feasibility of converting paved roads to gravel surface roads.

Recommendations for implementation in the area of roadside management include the following:

- Strengthen driveway permitting requirements.
- Automate the driveway permitting process.

Recommendations for implementation in the area of funding include the following:

- Assess damages to pavement structures in connection with energy developments.
- Use donation agreements with energy developers.
- Examine the feasibility of establishing driveway permit fees.
- Review maintenance funding allocation formulas.
- Determine the feasibility of using energy-related fees, taxes, and lease revenues for highway repair purposes.

REFERENCES

1. *The Energy Report 2008*. Texas Comptroller's Office, Austin, Texas. http://www.window.state.tx.us/specialrpt/energy/. Accessed October 10, 2011.
2. Texas Electricity Profile, 2009 Edition. U.S. Energy Information Administration, U.S. Department of Energy, Washington, D.C., April 2011. http://www.eia.gov/cneaf/electricity/st_profiles/texas.html. Accessed October 10, 2011.
3. Young, S. Public Roads and Wind Farms. TxDOT Short Course, College Station, Texas, October 2008.
4. *Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low Permeability Gas Reservoirs*. ICF International, Albany, New York, August 2009.
5. Schiller, R. Barnett Shale Gas Exploration Impact on TxDOT Roadways. TxDOT Short Course, College Station, Texas, October 2008.
6. Water Use in Marcellus Deep Shale Gas Exploration. Chesapeake Energy Fact Sheet, May 2011.
7. Kuhn, D. *Highway Freight Traffic Associated with the Development of Oil and Gas Wells*. Utah Department of Transportation, Salt Lake City, Utah, October 2006.
8. *Unconventional Gas Shales: Development, Technology, and Policy Issues*. Congressional Research Service, Washington, D.C., October 2009.
9. *Road Damage Fee Assessment Study*. City of Keller, Texas, August 2010.
10. *Preparing for Natural Gas Development: Understanding Impacts and Protecting Public Assets*. Sullivan County, New York, February 2009.
11. *Modern Shale Gas Development in the United States. A Primer*. National Energy Technology Laboratory, U.S. Department of the Energy, Pittsburgh, Pennsylvania, April 2009.
12. Moore, T. Roadway Damages Related to the Construction of Wind Generation Farms. TxDOT Short Course, College Station, Texas, October 2008.
13. Crawford, B. Windfarm Construction and Related Pavement Damage – Abilene District Perspective. TxDOT Short Course, College Station, Texas, October 2008.
14. Motor Carrier Division. Texas Department of Transportation, Austin, Texas. http://www.dot.state.tx.us/about_us/administration/divisions/mcd.htm. Accessed October 10, 2011.
15. Transportation Code, Title 7, Subtitle E, Chapter 621. General Provisions Relating to Vehicle Size and Weight. http://www.statutes.legis.state.tx.us/Docs/TN/htm/TN.621.htm. Accessed October 10, 2011.

16. Texas Administrative Code, Title 43, Part 1, Chapter 28. Oversize and Overweight Vehicles and Loads. http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=4&ti=43&pt=1&ch=28. Accessed October 10, 2011.

17. Recommendations of the Overweight/Oversize Work Group. N-E Texas District Engineers, Texas Department of Transportation, undated.

18. Energy Developments and the Transportation Infrastructure in Texas: Geodatabase of Energy Developments in Texas. Product 0-6498-P1, Texas Department of Transportation, Austin, Texas, August 2011. Under Review.

19. National Electrical Safety Code (NESC). IEEE Standards Association, 2011. http://standards.ieee.org/about/nesc/index.html. Accessed October 10, 2011.

20. *Pavement Design Guide*. Texas Department of Transportation, Austin, Texas, January 2011. http://onlinemanuals.txdot.gov/txdotmanuals/pdm/index.htm. Accessed October 10, 2011.

21. Huang, Y. *Pavement Analysis and Design (2nd Edition)*. Prentice Hall, Englewood Cliffs, New Jersey, 2003.

22. Schwartz, C. and R. Carvalho. *Implementation of the NCHRP 1-37A Design Guide. Final Report. Volume 2: Evaluation of Mechanistic-Empirical Design Procedure*. Maryland State Highway Administration, Lutherville, Maryland, February 2007.

23. *Roadway Design Manual*. Texas Department of Transportation, Austin, Texas, May 2010. http://onlinemanuals.txdot.gov/txdotmanuals/rdw/index.htm. Accessed October 10, 2011.

24. Liu, W. and T. Scullion. *PAVECHECK: Training Material Updated User's Manual including GPS*. Product 5-4495-01-P2. Texas Department of Transportation, Austin, Texas, 2009.

25. Michalak, C. and T. Scullion. *Modulus 5.0: User's Manual*. Report No. TX-96/1987-1. Texas Department of Transportation, Austin, Texas, 1995.

26. Scullion, T. *Incorporating a Structural Strength Index into the Texas Pavement Evaluation System*. Research Report 409-3F, Texas Department of Transportation, Austin, Texas, 1988.

27. Fernando, E. and W. Liu. *Development of an Analysis Procedure for Load-Zoning Pavements*. Research Report 0-2123-2, Texas Department of Transportation, Austin, Texas, 2001.

28. Zhou, F., E, Fernando, and T. Scullion. *Development, Calibration, and Validation of Performance Prediction Models for the Texas M-E Flexible Pavement Design System*. Research Report 0-5798-2, Texas Department of Transportation, Austin, Texas, 2010.

29. Fernando E., S. Ramos, J. Oh, J. Ragsdale, Z. Xie, R. Atkins, and H. Taylor. *Characterizing the Effects of Routine Overweight Truck Traffic on SH4/48*. Report No. FHWA/TX-06/0-4184-1. Texas Department of Transportation, Austin, Texas, 2006.

30. Texas Administrative Code, Title 43, Part 1, Chapter 21, Subchapter C. Utility Accommodation. http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=5&ti=43&pt=1&ch=21&sch=C&rl=Y. Accessed October 10, 2011.

31. *Access Management Manual*. Texas Department of Transportation, Austin, Texas, July 2011. http://onlinemanuals.txdot.gov/txdotmanuals/acm/index.htm. Accessed October 10, 2011.

32. Bridge Standards. Texas Department of Transportation, Austin, Texas, 2011. http://www.txdot.gov/insdtdot/orgchart/cmd/cserve/standard/bridge-e.htm. Accessed October 10, 2011.

33. *Traffic Data and Analysis Manual*. Texas Department of Transportation, Austin, Texas, September 2001. http://onlinemanuals.txdot.gov/txdotmanuals/tda/index.htm. Accessed October 10, 2011.

34. Natural Resources Code, Title 2, Subtitle C, Chapter 32. School Land Board. http://www.statutes.legis.state.tx.us/Docs/NR/htm/NR.32.htm. Accessed October 10, 2011.

35. Natural Resources Code, Title 2, Subtitle D, Chapter 52. Oil and Gas. http://www.statutes.legis.state.tx.us/Docs/NR/htm/NR.52.htm. Accessed October 10, 2011.

36. Bredthauer, W. and S. Rinehart. Ownership and Leasing of Minerals under Highways and Rights-of-Way. *Texas Wesleyan Law Review*, September 2009, Vol. 16, Issue 1, pp. 3-15.

37. Suggested Procedures for Leasing State Highway Right-of-Way Tracts. Texas General Land Office, Austin, Texas, September 1991.

38. *Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1)*, Ninth Edition. Research Report No. 82-2, Asphalt Institute, Lexington, Kentucky, 1982.

39. *Highway Funding in Texas: A Status Report*. House Research Organization, Texas House of Representatives, Austin, Texas, February 2009. http://www.hro.house.state.tx.us/pdf/focus/HighwayFund81-5.pdf. Accessed October 10, 2011.

40. *Overview of State Highway Fund 0006 Revenues and Allocations, the Texas Mobility Fund, and the Texas Rail Relocation and Improvement Fund*. Legislative Budget Board, Austin, Texas, April 2008. http://www.lbb.state.tx.us/Other_Pubs/Overview_Highway_Fund_0508.pdf. Accessed October 10, 2011.

41. Legislative Appropriations Request for Fiscal Years 2012 and 2013. Texas Department of Transportation, Austin, Texas, November 2010. http://www.txdot.gov/txdot_library/publications/leg_ap_req.htm. Accessed October 10, 2011.

42. Operating Budget for Fiscal Year 2012. Texas Department of Transportation, Austin, Texas, November 2010. http://www.txdot.gov/txdot_library/publications/finance/reports.htm. Accessed December 8, 2011.

43. Persad, K., L. Loftus-Otaway, R. Harrison, A. Cruz-Ross, P. Singh, S. Chi, and P. Franco. *Evaluation of TxDOT's J.A.C.K. Model for Revenue and Expenditure Projections*. Report No. FHWA/TX-09/0-6395-CT-1, Texas Department of Transportation, Austin, Texas, 2009.

44. The Transportation Revenue Estimator and Needs Determination System (T.R.E.N.D.S.). Texas Department of Transportation, Texas Transportation Institute, Center for Transportation Research, 2009. http://trends-tti.tamu.edu/. Accessed March 21, 2011.

45. Highway Cost Index (1997 Base) – Index Report for January 2011. Texas Department of Transportation, Austin, Texas. ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/hci_binder.pdf. Accessed October 10, 2011.

46. Highway Development. Texas State Historical Association. http://www.tshaonline.org/handbook/online/articles/erh02. Accessed October 10, 2011.

47. Texas Transportation Needs Report. 2030 Committee. February 2009. http://texas2030committee.tamu.edu/documents/final_022609_report.pdf. Accessed October 10, 2011.

48. Saenz, A. The Future is Now, Fifth Annual Transportation Forum, Austin, Texas, January 7, 2010.

49. CREZ Transmission Program Information Center. Public Utility Commission of Texas, Austin, Texas, 2010. http://www.texascrezprojects.com/. Accessed October 10, 2011.

50. Electric Maps. Public Utility Commission of Texas, Austin, Texas, 2010. http://www.puc.state.tx.us/industry/maps/Electricity.aspx. Accessed October 10, 2011.

51. National Pipeline Mapping System. Pipeline and Hazardous Materials Safety Administration, Washington, D.C., 2007. http://www.npms.phmsa.dot.gov. Accessed October 10, 2011.

52. House Bill 2694. 82nd (Regular) Legislative Session, Texas Legislature, Austin, Texas, 2011. http://www.capitol.state.tx.us/BillLookup/Text.aspx?LegSess=82R&Bill=HB2694. Accessed October 10, 2011.

53. Fernando, E., J. Oh, C. Estakhri, and S. Nazarian. *Verification of the Load-Thickness Design Curves in the Modified Triaxial Design Method*. Research Report FHWA/TX-07/0-4519-1, Texas Department of Transportation, Austin, Texas, 2008.

54. Liu, W., and T. Scullion. *Flexible Pavement Design System FPS 19W: User's Manual*. Research Report FHWA/TX-07-1869-1, Texas Department of Transportation, Austin, Texas, 2006.

55. Middleton, D., A. Clayton, C. Quiroga, and D. Jasek. *Truck Accommodation Design Guidance: Final Report*. Report No. FHWA/TX-04/0-4364-1, Texas Department of Transportation, Austin, Texas, October 2003.

56. *Maintenance Management Manual*. Texas Department of Transportation, Austin, Texas, January 2008. http://onlinemanuals.txdot.gov/txdotmanuals/mmt/index.htm. Accessed October 10, 2011.

57. *Financial Management Policy Manual*. Texas Department of Transportation, Austin, Texas, undated.

58. *Local Government Project Procedures Manual*. Texas Department of Transportation, Austin, February 2009. http://www.txdot.gov/business/governments/lgpp_manual.htm. Accessed October 10, 2011.

59. *Construction Contract Administration Manual*. Texas Department of Transportation, Austin, October 2007. http://onlinemanuals.txdot.gov/txdotmanuals/cah/index.htm. Accessed October 10, 2011.

60. Texas Administrative Code, Title 43, Part 1, Chapter 1, Subchapter G. Donations. http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=5&ti=43&pt=1&ch=1&sch=G&rl=Y. Accessed October 10, 2011.

61. *Contract Management Manual*. Texas Department of Transportation, Austin, July 2011.

62. Transportation Code, Title 6, Subtitle B, Chapter 223, Subchapter A. Competitive Bids. http://www.statutes.legis.state.tx.us/Docs/TN/htm/TN.223.htm. Accessed October 10, 2011.

63. House Bill 628. 82nd (Regular) Legislative Session, Texas Legislature, Austin, Texas, 2011. http://www.capitol.state.tx.us/BillLookup/Text.aspx?LegSess=82R&Bill=HB628. Accessed October 10, 2011.

64. Instructions for Completing Applications for Access (Driveway) Permit TP-1721. Minnesota Department of Transportation, St. Paul, Minnesota, December 2008. http://www.dot.state.mn.us/utility/files/pdf/permits/access-form-complete.pdf. Accessed October 10, 2011.

65. Sims, T. Maintenance Funding Allocation Process, Research Project 0-6664 Peer Review Workshop, Texas Department of Transportation, Austin, Texas, October 2010. http://library.ctr.utexas.edu/pdf1/6664.pdf. Accessed October 10, 2011.

66. Natural Resources Code, Title 3, Subtitle B, Chapter 85, Subchapter F, Section 85.2021. Drilling Permit Fee. http://www.statutes.legis.state.tx.us/Docs/NR/htm/NR.85.htm#85.001. Accessed October 10, 2011.

67. Natural Resources Code, Title 3, Subtitle A, Chapter 81, Subchapter E. Tax. http://www.statutes.legis.state.tx.us/Docs/NR/htm/NR.81.htm#81.111. Accessed October 10, 2011.

68. Biennial Revenue Estimate. 2012-2013 Biennium, Texas Comptroller of Public Accounts, Austin, Texas, January 2011. http://www.window.state.tx.us/taxbud/bre2012/96-402_BRE_2012-13.pdf. Accessed October 10, 2011.

69. *Sources of State Revenue in Texas*. 82nd Legislature, No. 82-3, House Research Organization, Texas House of Representatives, Austin, Texas, March 11, 2011. http://www.hro.house.state.tx.us/pdf/focus/Revenue82.pdf. Accessed October 10, 2011.

70. Motor Carrier Division. Texas Department of Transportation, Austin, Texas, undated. http://www.dot.state.tx.us/about_us/administration/divisions/mcd.htm. Accessed October 10, 2011.

APPENDIX A. REMAINING LIFE ANALYSIS RESULTS

ANALYSIS USING MODULUS 6

Figure 90 shows the MODULUS 6 function to estimate remaining life. MODULUS 6 uses measured FWD deflections to predict service life in terms of the allowable number of 18,000-lb cumulative single axle load repetitions. In this analysis, the FWD deflections are first corrected to account for the effect of pavement temperature. The corrected deflections are then used to predict service life based on fatigue cracking and rutting criteria. The program converts the performance predictions to an equivalent service life in years based on the projected 20-year 18-kip ESAL applications the user specified. The program adjusts the performance predictions to account for existing levels of rutting and cracking along the route. The output from the program is an assessment of the remaining life at each FWD test station according to the categories shown in Table 26 (*25*).

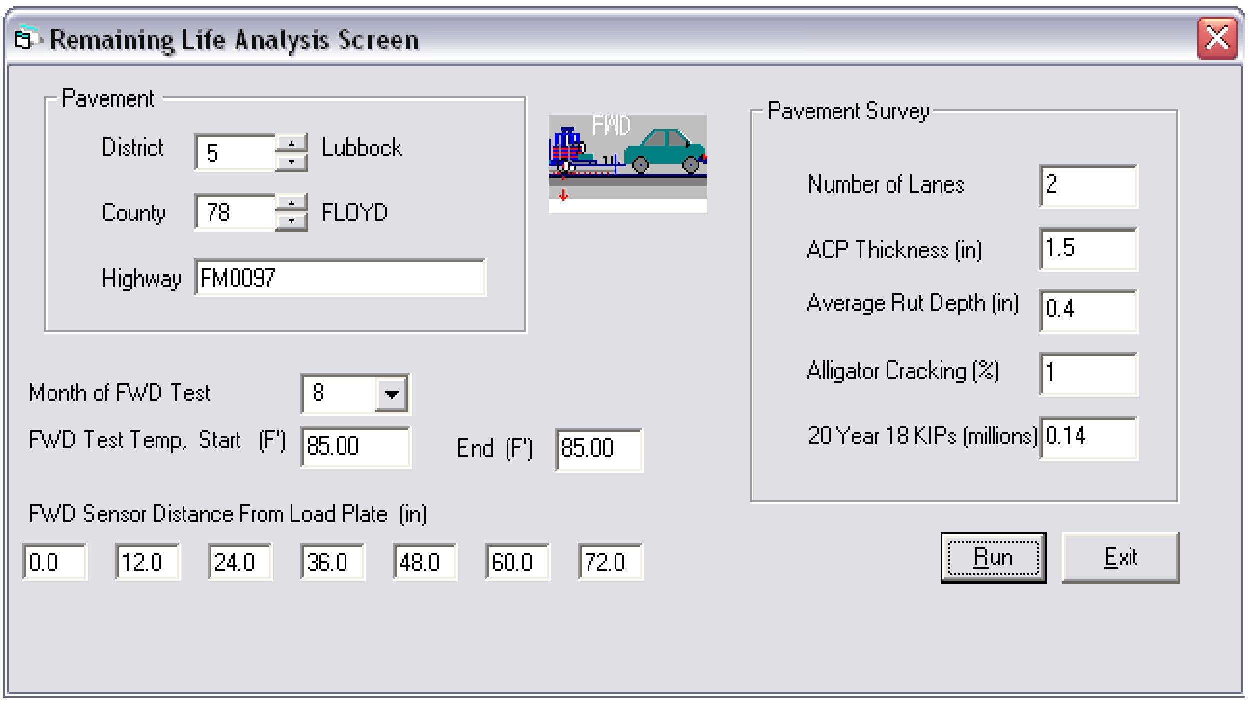


Figure 90. Input Screen for Remaining Life Analysis.

Table 53. Remaining Life Classification Used in MODULUS 6.

Class	Remaining Life (years)	Comments
1	0–2	Failed
2	2–5	Failure in near future
3	5–10	Adequate for now but potential problem in future
4	10+	Structurally sound

For the remaining life analysis, two fundamental assumptions are made:

- The tensile strain (ε_t, expressed in microstrains) at the bottom of the asphalt layer is related to the surface curvature index (SCI) of the pavement. The SCI is calculated by the difference between the FWD sensor 1 and sensor 2 deflections (R_1 and R_2, respectively).

- The vertical compressive strain (ε_v, expressed in microstrains) at the top of the subgrade is correlated to both the peak deflections R_1 (at the center of loading plate) and R_7 (the outermost sensor).

The computation of strains within the pavement layer uses the following regression equations:

$$\varepsilon_v = A + (B \times R_1) + (C \times R_7)$$

$$\varepsilon_t = D + E \times (R_1 - R_2)$$

where *A, B, C, D, E* are regression coefficients, and R_1, R_2, and R_7 are normalized FWD deflections in mils. Using the computed strains, the program calculates service life based on rutting and cracking criteria from the following equations:

$$N_R = \frac{1.94 \times 10^5}{(\varepsilon_v/1000)^4}$$

$$N_C = 10^{[A_0 - 3.291 log(\varepsilon_t) - 0.854 log(E_{AC}/1000)]}$$

$$A_0 = 16.086 + ACP/15$$

where,

N_R = number of 18 kip ESALs to produce a 0.47-inch rut.
N_C = number of 18 kip ESALs to produce 30-percent cracking in the wheel paths.
E_{AC} = stiffness of the asphalt mix.
ACP = thickness of the asphalt layer in inches.

Given the anticipated 18-kip ESALs for 20 years, the program calculates the remaining life in years using the equations above. The number of months to failure also is adjusted by the existing levels of cracking and rutting.

Figure 62 shows an example output file from the remaining life analysis. The figure includes columns that show layer strength classifications. To determine layer strength, the program computes the SCI and base curvature index (BCI = $R_2 - R_3$) based on normalized deflection basins. The SCI, BCI, and R_7 are used to determine the UPR, LWR and SGR strength classifications. UPR is the strength of the *upper* pavement layers (top 8 inches), LWR corresponds to the strength of the *lower* pavement layers (8 to 16 inches), and SGR is the subgrade strength. Table 54 shows the scheme to determine the strength classifications based on

SCI, BCI, and R_7. In the example output shown in Figure 62, the route analyzed has 1.5 inches of asphalt surface. The BCI at station 0.289 is 33.74 − 12.28 = 21.46 mils. Given that the SCI = 32.83 and R_7 = 2.84 mils on this station, the UPR, LWR and SGR strength classifications are all VP (very poor), as shown in Figure 62.

```
                              *****************
                              *  R E L A P S  *
                              *****************

           TTI FLEXIBLE PAVEMENT DEFLECTION BASIN ANALYSIS PROGRAM

--------------------------------------------------------------------------------
  FWD TESTED FILE NAME :   C:\backup\backup\C\OJH\6498\Lubbock\078F0097.FWD
--------------------------------------------------------------------------------
  DISTRICT                :    5--Lubbock            ASPH. THICKNESS  :  1.50
  COUNTY                  :   78--FLOYD              MONTH TESTED     :  AUG
  HIGHWAY                 :   FM0097                 DESIGN LOAD (lbs):  9000
  TEMPERATURE("F) start:      85.0 Rnd:   85.0       20 year 18 KIP(m):    0.14
  AVERAGE RUT DEPTH(in):       0.4                   LANES            :   2
  ALLIGATOR CRACKING   :       1.0 %                 SENSORS: 0 12 24 36 48 60 72
--------------------------------------------------------------------------------
                                                   ASPH DESIGN   LAYER     REMAINING
           ** NORMALIZED DEFLECTION (mils) **       TEMP  SCI   STRENGTHS  LIFE (yrs)
   STATION    R1      R2      R3      R4      R7   DEF F  MILS UPR LWR SGR  RUT   CRK
--------------------------------------------------------------------------------
     0.289  66.58   33.74   12.28    6.81    2.84  85.0 32.83  VP  VP  VP  0-2   10+
     1.113  77.12   33.54    8.24    4.08    2.10  85.0 43.57  VP  VP  PR  0-2   10+
     2.001  53.84   21.01    7.10    4.25    2.03  85.0 32.84  VP  PR  PR  0-2   10+
     2.668  58.66   24.14    8.29    4.90    2.05  85.0 34.51  VP  PR  PR  0-2   10+
     4.246  45.02   22.46    8.73    4.72    2.22  85.0 22.56  MD  PR  VP  2-5   10+
     5.105  21.11   12.14    6.74    4.59    2.51  85.0  8.97  VG  GD  VP  10+   10+
     6.324  54.48   24.31    9.14    4.69    2.02  85.0 30.17  VP  PR  PR  0-2   10+
     7.111  86.10   36.45   13.50    7.39    3.29  85.0 49.64  VP  VP  VP  0-2   10+
     8.449  17.75   13.73    8.40    5.86    2.94  85.0  4.02  VG  GD  VP  10+   10+
    10.026  61.22   23.83    7.98    4.54    2.17  85.0 37.39  VP  PR  PR  0-2   10+
    12.008  63.38   24.66    8.87    4.90    2.34  85.0 38.72  VP  PR  VP  0-2   10+
    12.110  58.25   23.87    8.33    4.71    2.16  85.0 34.38  VP  PR  PR  0-2   10+
    13.039  58.77   26.20   10.71    6.07    2.79  85.0 32.57  VP  PR  VP  0-2   10+
    14.217  53.98   26.57   10.98    6.90    3.74  85.0 27.41  PR  PR  VP  0-2   10+
    15.632  69.17   33.32   14.24    8.45    3.90  85.0 35.85  VP  VP  VP  0-2   10+
    16.348  46.06   22.29    8.84    5.23    2.88  85.0 23.77  MD  PR  VP  0-2   10+
    17.281  68.62   35.01   13.01    7.34    3.80  85.0 33.61  VP  VP  VP  0-2   10+
    18.376  50.42   23.01    9.83    5.65    1.69  85.0 27.41  PR  PR  MD  2-5   10+
    19.787  21.89    5.93    2.48    1.82    0.97  85.0 15.96  GD  VG  VG  10+   10+
--------------------------------------------------------------------------------
     MEAN:  54.34   24.54    9.35    5.42    2.55       29.80  PR  PR  PR
  STD DEV:  18.18    7.97    2.73    1.51    0.76       11.13
  COF VAR:  33.46   32.48   29.18   27.93   29.85       37.36
--------------------------------------------------------------------------------
*   0~2:Failed     2~5:Problem     5~10:OK for Now     10+:Good
```

Figure 91. Output Screen of Remaining Life Analysis on FM 97.

Table 54. MODULUS Layer Strength Classification Scheme (*25*).

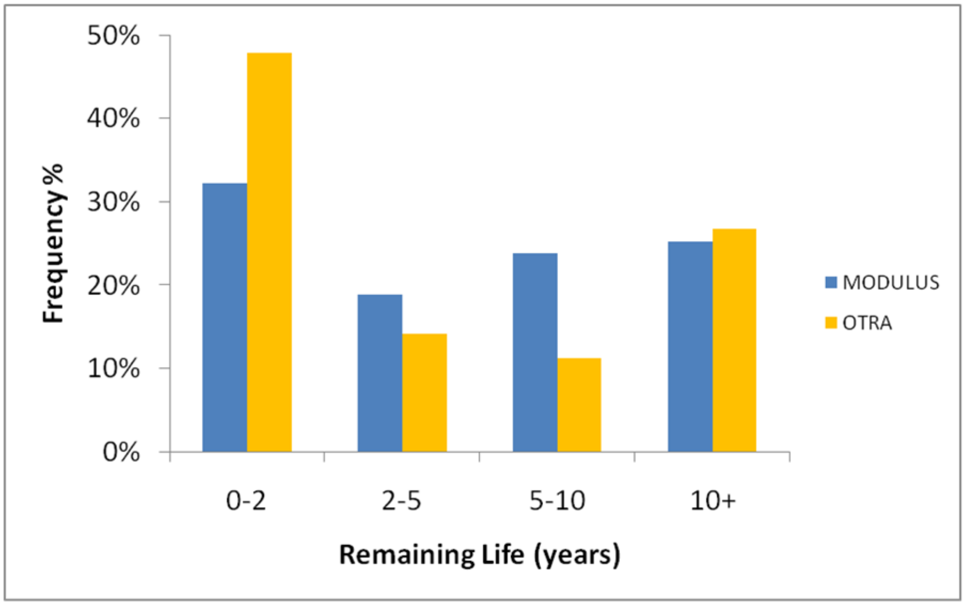
Asphalt thickness (inches)		>5	2.5–5	1–2.5	<1
SCI (mils)	VG (Very good)	<4	<6	<12	<16
	GD (Good)	4–6	6–10	12–18	16–24
	MD (Moderate)	6–8	10–15	18–24	24–32
	PR (Poor)	8–10	15–20	24–30	32–40
	VP (Very poor)	>10	>20	>30	>40
BCI (mils)	VG	<2	<3	<4	<8
	GD	2–3	3–5	4–8	8–12
	MD	3–4	5–8	8–12	12–16
	PR	4–5	8–10	12–16	16–20
	VP	>5	>10	>16	>20
R_7 (mils)	VG	<1	<1	<1	<1
	GD	1–1.4	1–1.4	1–1.4	1–1.4
	MD	1.4–1.8	1.4–1.8	1.4–1.8	1.4–1.8
	PR	1.8–2.2	1.8–2.2	1.8–2.2	1.8–2.2
	VP	>2.2	>2.2	>2.2	>2.2

The researchers ran the MODULUS 6 remaining life analyses using the available FWD data on all routes tested. The anticipated ESALs in 20 years and existing performance data on rutting and cracking were extracted from the PMIS database (Table 55). With respect to the traffic data, the researchers noted the available data in the FY10 PMIS database correspond to FY08 traffic conditions unlike the pavement condition data, which are based on the FY10 PMIS surveys. For the remaining life analyses, the researchers decided to use the FY10 PMIS traffic data, assuming that traffic conditions have not changed significantly between FY08 and FY10. They also based the remaining life analyses on rutting given the predominantly thin pavements along the impacted routes. To predict remaining life, the researchers used the asphalt concrete thickness determined from the GPR analysis summarized in Table 24.

Table 55. Summary of Traffic and Performance Data Extracted from PMIS.

District	Highway	AADT	AADTT	ESALs (×10^6)	Rutting (in)
Lubbock	FM 97	297	44	0.14	0.42
	FM 1958	152	27	0.08	0.42
	FM 28-N	120	18	0.05	0.44
	FM 28-S	127	31	0.09	0.38
	FM 28-Crosby	124	21	0.07	0.38
	FM 651	160	30	0.14	0.38
	FM 1958	152	27	0.08	0.42
	FM 179	303	68	0.34	0.38
	FM 193	80	16	0.05	0.30
	FM 40	500	87	0.39	0.43
Abilene	FM 126	295	61	0.27	0.52
	FM 604	510	56	0.20	0.40
	FM 89	562	94	0.43	0.41
	FM 1899	115	18	0.05	0.40
	FM 1611	394	53	0.25	0.40
Fort Worth	FM 52	266	74	0.29	0.60
	FM 2331	3355	150	0.68	0.38
	FM 2738	3718	435	1.76	0.47
	FM 3048	3200	406	1.79	0.38
	FM 3325	5133	1416	8.59	0.60
	IH35W-1	1979	63	2.26	0.90
	IH35W-2	470	15	0.5	0.50
	SH 16	742	233	0.98	0.40
	SH 171	9488	2613	15.7	0.40
	SH 174	8083	1912	10.9	0.45
	FM 2257	2850	920	3.7	0.38

Figure 92 summarizes the remaining life predictions using MODULUS 6. In Figure 92, the vertical axis represents relative frequency with respect to the total number of ½-mile segments used for the analysis (710). The highest frequency of remaining life predictions (32 percent) fell within the 0–2 year bin (i.e., the pavement on those segments is considered failed). About 19 percent of the pavements tested fell within the 2–5 year bin (i.e., the pavement on those segments is expected to fail in the near future). In other words, at least 50 percent of the segments tested have pavements that have failed or are expected to fail within 5 years.



Note: The relative frequency is given with respect to the total number of ½-mile segments used for the analysis (710).

Figure 92. Summary of Remaining Life Analysis Using MODULUS and OTRA.

ANALYSIS USING OTRA

OTRA is used to evaluate the structural adequacy of an existing route to sustain overweight truckloads over a specified design period (*29*). OTRA includes a layered elastic pavement model for predicting the induced response under surface wheel loads given the modulus, thickness, and Poisson's ratio of each pavement layer.

The predicted horizontal strain at the bottom of the asphalt layer and the vertical strain at the top of the subgrade are used to determine the service life for a given pavement structure and loading condition using the following equations (*38*):

$$N_{AR} = \frac{1.365 \times 10^{-9}}{(\varepsilon_{vs})^{4.477}}$$

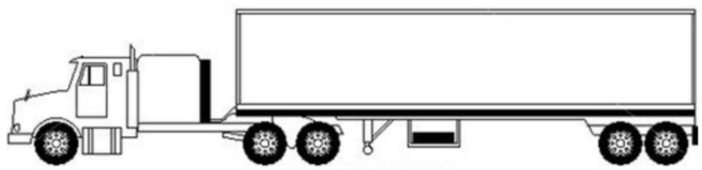
$$N_{AC} = 7.9488 \times 10^{-2} \left(\frac{1}{\varepsilon_{ts}}\right)^{3.29} \left(\frac{1}{E_{AC}}\right)^{0.854}$$

where,

N_{AR} = allowable number of load repetitions based on rutting.
N_{AC} = allowable number of load repetitions based on rutting.
ε_{vs} = vertical compressive strain, expressed in strains.
ε_{ts} = tensile strain, expressed in strains.

The ratio of the expected number of yearly load applications to the allowable number of repetitions prior to failure provides an estimate of the life consumed per year of the design period for each axle configuration (single, tandem, and triple). This ratio is an estimate of the life consumed per year of the design period for the given axle configuration and load and for the given failure criterion (fatigue cracking or rutting). The computed damage ratios for the axle configurations are added to determine the yearly service life consumption for each failure criterion.

Figure 93 illustrates the calculation of service life consumed per truck application. The service life predictions for the route analyzed are then used to compute the probability P_{fail} that the service life is less than the specified design period. Pavement reliability R is then evaluated as $1 - P_{fail}$. The reliability from OTRA is used to determine whether an existing route is structurally adequate to sustain the expected axle load applications over the design period.



Axle group load	P_s	P_d	P_t
Predicted allowable repetitions to failure	$(N_f)_s$	$(N_f)_d$	$(N_f)_t$
Service life consumed for one axle group application	$\frac{1}{(N_f)_s}$	$\frac{1}{(N_f)_d}$	$\frac{1}{(N_f)_t}$
Service life consumed for one truck application		$\frac{1}{(N_f)_s} + \frac{1}{(N_f)_d} + \frac{1}{(N_f)_t}$	

Figure 93. Concept of Estimating Service Life in OTRA Program.

Figure 92 summarizes the remaining life predictions using OTRA. As in the case of the MODULUS analysis, the vertical axis represents relative frequency with respect to the total number of ½-mile segments used for the analysis (710). The highest frequency of remaining life predictions (48 percent) fell within the 0–2 year bin (i.e., the pavement on those segments is considered failed). About 14 percent of the pavements tested fell within the 2–5 year bin (i.e., the pavement on those segments is expected to fail in the near future). In other words, according to the analysis using the OTRA program, at least 60 percent of the segments tested have pavements that have failed or are expected to fail within 5 years.

REMAINING LIFE ANALYSIS TABLES

Table 56, Table 57, and Table 58 show the detailed analysis results of the remaining life analysis using MODULUS and OTRA.

Table 56. Remaining Life Analysis Results (Lubbock District).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 1958	0.445	9018	47.7	15.0	5.7	3.7	2.5	2.2	1.8	2–5	1.3
	1.379	8891	41.5	12.5	4.1	2.8	1.8	1.6	1.4	5–10	2.7
	3.217	9073	38.3	13.2	5.3	3.3	2.1	1.8	1.6	5–10	2.6
	5.749	8871	56.3	18.9	6.5	3.4	1.8	1.8	1.7	2–5	0.7
	8.055	8958	59.3	19.5	6.3	3.6	2.3	2.0	1.9	0–2	0.6
	9.43	8751	71.7	32.9	14.1	8.9	5.8	5.3	4.5	0–2	0.1
	10.772	9288	19.4	10.7	5.1	2.9	1.9	1.7	1.5	10+	30.9
	12.649	8970	45.6	17.7	6.4	3.9	2.5	2.2	1.8	2–5	1
	14.955	8898	47.0	20.2	8.0	4.9	3.2	2.7	2.3	2–5	0.9
	16.801	8875	52.6	20.4	6.0	3.7	2.4	2.0	1.7	2–5	0.7
	17.957	8811	55.7	22.2	8.5	4.8	2.8	2.5	2.1	2–5	0.4
	19.848	8895	44.9	19.6	8.0	4.8	3.0	2.6	2.2	2–5	1
FM 97	0.289	9498	70.3	35.6	13.0	7.2	4.3	3.6	3.0	0–2	0.2
	1.113	9522	81.6	35.5	8.7	4.3	2.9	2.6	2.2	0–2	0.3
	2.001	9459	56.6	22.1	7.5	4.5	2.9	2.4	2.1	0–2	0.7
	2.668	9304	60.6	25.0	8.6	5.1	3.2	2.7	2.1	0–2	0.5
	4.246	9423	47.1	23.5	9.1	4.9	3.3	3.0	2.3	2–5	1
	5.105	9621	22.6	13.0	7.2	4.9	3.4	3.0	2.7	10+	19.4
	6.324	9248	56.0	25.0	9.4	4.8	2.9	2.5	2.1	0–2	0.5
	7.111	8851	84.7	35.9	13.3	7.3	4.7	3.8	3.2	0–2	0.1
	8.449	9506	18.8	14.5	8.9	6.2	4.2	3.8	3.1	10+	20.7
	10.026	9065	61.7	24.0	8.0	4.6	2.9	2.6	2.2	0–2	0.5
	12.008	9030	63.6	24.7	8.9	4.9	3.2	2.7	2.4	0–2	0.4
	12.11	9141	59.2	24.2	8.5	4.8	3.7	2.7	2.2	0–2	0.5
FM 97	13.039	8902	58.1	25.9	10.6	6.0	4.0	3.4	2.8	0–2	0.4
	14.217	8938	53.6	26.4	10.9	6.9	4.6	4.4	3.7	0–2	0.5
	15.632	8799	67.6	32.6	13.9	8.3	5.3	4.6	3.8	0–2	0.2
	16.348	9125	46.7	22.6	9.0	5.3	3.6	3.4	2.9	0–2	1.0
	17.281	8906	67.9	34.6	12.9	7.3	5.0	4.4	3.8	0–2	0.2
	18.376	8902	49.9	22.8	9.7	5.6	3.0	2.2	1.7	2–5	0.7
	19.787	9232	22.5	6.1	2.5	1.9	1.4	1.2	1.0	10+	40
FM 28-N	0.449	9034	49.7	18.7	7.4	4.5	2.9	2.6	2.4	5–10	N/A*
	1.795	8867	56.0	21.2	7.9	4.9	3.1	2.7	2.3	2–5	N/A*
FM 28-S	0.223	9093	39.8	17.3	5.0	2.8	2.0	1.8	1.4	5–10	1.4
	1.555	8998	41.1	18.3	6.7	3.8	2.3	1.9	1.5	2–5	1.1
	2.876	8982	34.2	18.3	7.7	4.3	2.7	2.3	1.9	5–10	3.3
	3.982	8938	37.3	13.5	5.3	3.3	2.2	2.0	1.5	5–10	1.8
	4.862	8962	47.4	19.4	7.8	4.6	2.7	2.4	2.4	0–2	0.6
	5.979	9081	40.2	18.3	7.4	4.3	2.8	2.2	1.8	2–5	1.4
	7.762	9061	38.7	15.0	5.8	3.7	2.4	2.0	1.7	5–10	1.6
	9.359	8736	53.1	25.3	9.9	5.8	3.6	2.9	2.3	0–2	0.4
	10.695	8914	50.9	23.3	8.0	4.5	2.9	2.6	2.1	0–2	0.4
FM 179	0.438	8906	47.7	19.9	8.6	4.7	2.5	2.0	1.7	2–5	N/A*
	1.97	8839	56.4	22.8	8.6	4.8	2.6	2.1	1.8	0–2	N/A*
	2.038	8736	61.4	19.4	6.8	3.7	2.2	1.9	1.6	0–2	N/A*
	3.133	8767	66.1	33.4	12.3	5.4	2.7	2.4	2.4	0–2	N/A*

Table 56. Remaining Life Analysis Results (Lubbock District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 651	0.248	8879	59.6	23.6	7.9	4.3	2.6	2.3	1.9	0–2	0.6
	1.809	8978	45.5	19.3	6.8	4.1	2.6	2.3	1.8	2–5	1.4
	3.08	8895	34.4	14.9	5.4	3.3	2.2	2.0	1.7	5–10	4.3
	4.601	8835	34.4	12.6	5.8	3.8	2.5	2.2	1.8	5–10	4.6
	5.613	9030	42.4	16.1	7.7	5.2	3.5	3.1	2.5	2–5	2
	6.881	8946	46.0	14.6	6.2	3.9	2.6	2.2	1.9	2–5	2.1
	8.64	8676	77.2	32.4	12.5	7.1	4.5	3.8	3.1	0–2	0.2
FM 193	0.453	8962	55.1	28.3	11.8	6.9	4.4	3.7	3.0	2–5	N/A*
	2.026	8759	84.8	43.1	15.6	8.8	5.7	5.1	4.2	0–2	N/A*
FM 40	0.198	8918	52.4	21.1	7.3	4.4	3.1	2.7	2.2	0–2	N/A*
	1.619	8930	42.5	17.1	6.6	4.0	2.5	2.1	1.7	0–2	N/A*

*OTRA analysis not available due to the small number of FWD stations on this short corridor.

Table 57. Remaining Life Analysis Results (Abilene District).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 89	0.445	9,466	11.0	6.7	3.8	2.6	1.6	1.4	1.1	10+	16.6
	1.833	9,017	31.2	11.8	4.3	2.9	1.9	1.8	1.5	5–10	1
	2.761	9,132	18.3	8.4	2.2	1.0	0.7	0.6	0.6	10+	8.9
	4.803	8,929	42.3	14.8	3.7	2.4	1.5	1.3	0.9	2–5	0.5
	5.496	9,092	28.8	9.2	2.3	1.1	0.5	0.4	0.3	10+	3.4
	6.183	9,148	19.4	5.6	1.3	0.7	0.4	0.4	0.3	10+	14.9
	7.078	8,921	52.2	22.9	6.5	3.0	1.9	1.6	1.0	0–2	0.1
	7.982	9,176	23.6	10.8	4.3	2.4	1.3	1.1	0.8	10+	2.3
	8.881	9,021	34.4	17.4	8.4	5.7	3.9	3.4	2.9	2–5	0.4
	9.893	8,711	54.4	28.7	11.1	5.4	2.6	1.8	1.2	0–2	0.1
	0.445	9,466	11.0	6.7	3.8	2.6	1.6	1.4	1.1	10+	16.6
FM 126	0.219	8863	38.0	24.1	14.1	9.3	6.0	5.1	4.6	2–5	0.9
	0.883	9069	27.0	10.4	3.8	2.2	1.5	1.3	1.0	10+	3.7
	1.991	8938	35.8	18.3	7.3	3.7	2.1	1.6	1.2	5–10	0.7
	2.67	9153	17.0	11.2	6.3	3.8	2.2	1.6	1.2	10+	4.1
	3.999	8966	32.4	14.5	5.5	2.6	1.6	1.5	1.3	10+	1.1
	5.15	9077	25.4	17.3	10.6	7.2	4.7	3.9	3.0	10+	2.5
	6.26	8660	50.9	27.5	11.6	6.6	4.4	4.0	3.6	0–2	0.1
	7.365	9101	34.5	14.5	5.2	2.4	1.1	0.6	0.4	10+	0.8
	7.832	8891	42.6	27.2	13.2	7.8	5.1	4.5	3.9	2–5	0.5
	8.696	8811	65.0	33.3	10.3	4.4	2.4	1.9	1.2	0–2	0.1
	9.1	8823	44.8	23.7	9.7	4.8	2.7	1.9	1.4	2–5	0.2
	9.791	9069	30.3	17.7	7.7	3.8	1.9	1.4	0.9	10+	1.5
	10.226	8887	41.6	23.6	9.5	4.7	2.5	1.8	1.3	5–10	0.3
FM 604	0.216	9161	27.6	9.2	4.3	2.9	2.0	1.8	1.5	10+	11.3
	0.672	8970	38.8	14.9	6.5	4.4	2.7	2.4	1.9	2–5	2.2
	1.118	9030	38.8	18.4	7.6	4.6	2.9	2.6	2.3	2–5	1.5
	1.556	8875	28.7	10.7	4.1	2.5	1.7	1.3	1.1	10+	9.2
	1.997	9184	12.1	3.9	2.1	1.3	0.8	0.7	0.6	10+	40
	2.64	8827	41.1	13.2	5.3	3.0	1.8	1.5	1.2	2–5	3.1
	3.067	8910	26.5	9.0	2.7	1.5	1.1	1.0	0.9	10+	24.3
	3.282	9022	20.7	3.3	1.5	1.0	0.7	0.6	0.5	10+	40
	4.151	9041	24.6	15.2	6.4	3.0	1.4	1.0	0.6	10+	7
	4.585	8608	68.7	17.7	5.3	3.8	2.4	2.0	1.5	0–2	1.1
	5.238	8346	81.6	29.2	11.4	7.3	4.4	3.3	2.3	0–2	0.2
	6.334	8748	35.2	12.7	4.3	2.1	1.0	0.9	0.5	10+	5.2
	6.774	8863	27.7	10.5	4.3	2.6	1.7	1.5	1.2	10+	8.7
	7.203	8891	31.7	11.6	4.1	2.2	1.3	1.1	0.8	10+	7.4
	7.863	8370	81.0	25.7	8.8	5.0	2.9	2.2	1.7	0–2	0.4
	8.506	8692	50.0	24.4	6.9	3.9	2.6	2.2	1.7	0–2	0.8
	8.679	8831	35.9	16.4	7.5	4.8	3.0	2.7	2.2	2–5	2
	9.336	8871	31.9	16.1	6.0	3.2	2.0	1.6	1.3	10+	2.9
	10.428	8493	78.7	30.8	10.4	6.3	3.4	2.5	1.7	5–10	0.3

Table 57. Remaining Life Analysis Results (Abilene District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 1611	0.887	8755	48.0	16.0	5.1	3.2	1.9	1.8	1.6	0–2	0.3
	1.236	8775	48.3	15.9	4.6	2.9	2.0	1.9	1.7	0–2	0.4
	1.554	8966	29.4	11.7	4.4	2.6	1.6	1.4	1.1	10+	2.1
	1.976	9014	42.1	17.5	6.9	3.8	2.0	1.9	1.5	2–5	0.5
	1.992	9077	30.3	11.6	4.2	2.5	1.5	1.4	1.2	10+	1.8
	2.351	8879	52.8	18.5	4.7	2.5	1.5	1.3	1.1	0–2	0.3
	3.014	9053	17.3	11.6	6.7	4.1	2.4	2.2	1.8	10+	9.8
FM 1899	0.44	8970	39.22	18.8	8.7	5.2	3.2	2.9	0.4	0–2	1.7
	0.894	8942	42.83	17.9	6.3	3.3	1.8	1.7	0.9	2–5	0.9
	1.335	8978	30.24	14.4	6.5	3.9	2.2	2.0	1.3	5–10	4.8
	1.781	8950	32.62	14.8	6.2	4.1	2.5	2.3	1.8	2–5	3.1
	2.223	8811	34.75	16.1	6.3	4.0	2.5	2.4	2.2	2–5	2.1
	2.437	8906	40.14	14.9	5.2	3.1	1.8	1.7	2.4	2–5	1.2
	2.882	8827	44.35	23.0	11.2	6.9	4.1	3.7	2.9	0–2	1.2
	3.783	8962	29.24	12.6	6.1	4.0	2.6	2.4	3.8	2–5	6
	4.228	8966	28.27	11.7	5.8	3.8	2.3	2.1	4.2	5–10	6.4
	4.671	8942	32.12	13.7	5.6	3.3	1.9	1.7	4.7	5–10	3
	5.339	9200	27.41	12.9	5.3	3.3	2.0	1.9	5.3	10+	7.4
	6.228	8895	34.34	14.4	5.5	3.6	2.2	2.2	6.2	2–5	2.2
	6.474	8759	50.44	18.0	6.1	3.8	2.5	2.3	6.5	0–2	0.4
	6.917	9022	26.49	13.9	5.6	3.3	2.0	1.9	6.9	5–10	8.2
	7.362	8807	62.85	25.3	6.7	3.7	2.3	2.1	7.4	0–2	0.2
	7.822	9101	15.72	9.9	5.2	2.9	1.6	1.3	7.8	10+	33.6
	8.265	8740	50.9	25.4	9.9	5.7	3.4	3.0	8.3	0–2	0.4

Table 58. Remaining Life Analysis Results (Fort Worth District).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 16	0	8692	25.5	18.2	8.5	4.5	2.2	1.9	1.3	5–10	1.5
	0.1	8954	9.5	8.3	6.3	5.0	3.5	3.1	2.0	10+	11.3
	0.2	8978	11.1	7.0	4.5	3.6	2.4	1.9	1.1	10+	25.2
	0.305	8974	6.1	5.7	4.5	3.4	2.3	1.8	1.1	10+	40
	0.373	8934	10.9	5.5	2.7	1.7	1.1	0.9	0.6	10+	40
	0.94	8485	38.6	21.6	10.4	6.1	3.6	2.9	1.9	0–2	0.2
	1.006	8700	25.9	15.3	7.0	4.1	2.6	2.2	1.6	5–10	1.5
	1.1	8628	19.8	10.0	3.2	1.5	1.2	1.0	0.8	10+	6.3
	1.204	8406	37.7	22.4	10.1	5.6	3.4	2.9	2.1	0–2	0.2
	1.305	8597	23.9	12.2	5.1	3.0	2.2	2.1	1.6	5–10	2.2
	1.405	8577	26.4	10.6	3.9	2.5	1.7	1.6	1.2	5–10	2.2
	1.51	8398	31.5	15.6	6.1	3.6	2.4	2.2	1.7	2–5	0.6
	1.603	8537	35.3	18.3	8.7	5.4	3.4	2.9	2.1	0–2	0.4
	1.703	8632	27.5	14.1	7.0	4.4	2.8	2.3	1.6	2–5	1.2
	1.802	8533	32.4	18.1	8.2	4.4	2.5	1.7	1.2	2–5	0.5
	1.899	8716	18.9	11.1	5.7	3.6	2.2	1.8	1.3	10+	6.5
	2.005	8684	21.1	9.7	4.0	2.4	1.5	1.2	0.8	10+	4.5
	2.106	8656	25.9	14.2	5.9	3.2	1.9	1.5	1.1	5–10	1.5
	2.209	8573	23.6	14.5	7.3	4.6	3.0	2.7	2.0	5–10	2.4
	2.302	8438	49.2	22.3	7.8	3.6	1.9	1.5	1.2	0–2	0.2
	2.41	8636	20.8	11.3	5.4	3.3	2.2	1.9	1.4	10+	4.1
	2.508	8406	30.2	19.1	8.4	5.0	3.4	2.9	2.2	2–5	0.7
	2.648	8569	14.7	8.7	4.2	2.4	1.5	1.3	1.0	10+	13.3
	2.719	8549	36.6	19.0	7.9	4.4	2.7	2.3	1.7	0–2	0.3
	2.802	8549	21.3	11.7	5.2	3.0	1.9	1.7	1.3	10+	3.3
	2.912	8481	41.9	24.1	11.7	6.8	4.2	3.3	2.5	0–2	0.2
	3.017	8926	9.0	6.0	3.7	2.2	1.3	1.1	0.8	10+	40
	3.121	8235	38.8	20.5	8.9	5.1	3.2	2.8	2.1	0–2	0.2
	3.203	8875	14.3	8.5	5.0	3.2	2.1	1.8	1.2	10+	12.2
	3.329	8918	11.3	5.1	2.7	1.9	1.4	1.3	1.0	10+	40
	3.413	8875	8.6	3.8	1.9	1.2	0.8	0.6	0.5	10+	40
	3.514	8835	8.6	5.7	2.7	1.9	1.3	1.1	0.7	10+	40
	3.618	8318	39.2	19.1	5.8	3.1	2.0	1.9	1.5	0–2	0.3
	3.712	8338	22.2	10.4	4.3	2.6	1.7	1.5	1.1	10+	2.9
	3.814	8160	39.4	16.3	5.4	3.1	2.3	2.2	1.7	0–2	0.4
	3.926	8708	15.0	7.2	2.9	1.9	1.3	1.1	0.8	10+	18.1
	4.007	8553	12.9	5.2	1.8	0.9	0.5	0.3	0.2	10+	40
	4.102	8322	35.6	19.0	8.5	4.8	2.9	2.3	1.5	0–2	0.3
	4.208	8755	22.2	15.2	8.3	4.7	2.8	2.4	1.7	5–10	2.6
	4.302	8128	28.6	15.9	7.5	4.7	3.1	2.5	1.7	2–5	0.8
	3.712	8338	22.2	10.4	4.3	2.6	1.7	1.5	1.1	10+	2.9
	3.814	8160	39.4	16.3	5.4	3.1	2.3	2.2	1.7	0–2	0.4
	3.926	8708	15.0	7.2	2.9	1.9	1.3	1.1	0.8	10+	18.1
	4.007	8553	12.9	5.2	1.8	0.9	0.5	0.3	0.2	10+	40
	4.102	8322	35.6	19.0	8.5	4.8	2.9	2.3	1.5	0–2	0.3
	4.208	8755	22.2	15.2	8.3	4.7	2.8	2.4	1.7	5–10	2.6
	4.302	8128	28.6	15.9	7.5	4.7	3.1	2.5	1.7	2–5	0.8
	4.401	8533	20.2	11.2	6.1	4.2	3.0	2.5	1.8	10+	5.5

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 16	4.513	8195	45.9	21.1	7.8	4.0	2.5	2.2	1.8	0–2	0.2
	4.638	8485	31.3	13.8	6.3	4.0	2.7	2.4	1.8	2–5	0.7
	4.822	8291	33.1	16.0	6.7	3.8	2.5	2.1	1.6	2–5	0.5
	4.913	8386	33.1	15.6	5.6	2.9	2.0	1.7	1.3	2–5	0.6
	5.012	8410	28.1	12.8	5.5	3.2	1.9	1.5	1.1	5–10	1.1
	5.101	8461	15.8	7.9	3.5	2.1	1.3	1.0	0.6	10+	12.2
	5.205	8406	31.2	15.4	6.3	3.6	2.3	2.0	1.6	2–5	0.7
	5.301	8672	14.2	9.5	5.7	3.8	2.6	2.2	1.6	10+	8.7
	5.401	8716	14.2	9.5	5.5	3.7	2.5	2.0	1.4	10+	9
	5.504	8481	24.2	13.2	6.8	4.5	2.8	2.3	1.4	5–10	2.2
	5.606	8624	18.6	9.3	4.2	2.3	1.4	1.2	0.9	10+	6.6
	5.709	8362	28.2	15.1	6.9	4.2	2.8	2.5	1.8	2–5	0.9
	5.806	8612	26.0	12.9	4.6	2.3	1.4	1.3	1.0	5–10	1.8
	5.919	8370	46.5	20.6	6.1	2.6	1.7	1.6	1.2	0–2	0.3
	6.014	8299	54.1	23.7	6.2	2.4	1.3	1.1	0.7	0–2	0.2
	6.119	8072	43.4	22.5	9.0	4.6	2.7	2.2	1.4	0–2	0.1
	6.204	8263	23.0	12.5	6.1	3.7	2.4	2.1	1.5	5–10	2.2
	6.312	8477	28.4	14.5	7.0	4.6	3.0	2.5	1.7	2–5	1
	6.413	7989	48.6	28.4	12.6	7.0	4.3	3.6	2.5	0–2	0.1
	6.509	8279	25.3	8.0	2.4	1.1	0.5	0.4	0.4	10+	7.6
	6.643	8326	32.3	17.7	8.3	4.6	2.5	1.8	1.1	2–5	0.5
	6.71	8561	33.8	17.3	6.9	3.6	2.0	1.5	1.0	2–5	0.5
	6.813	8303	57.6	26.4	8.0	2.5	1.1	1.1	0.9	0–2	0.2
	6.911	8191	36.2	20.0	8.2	4.4	2.7	2.4	1.7	0–2	0.3
	7.111	8318	29.3	14.7	6.2	3.7	2.2	1.9	1.2	2–5	0.8
	7.205	8418	19.0	7.9	3.1	1.7	0.9	0.9	0.7	10+	8.2
	7.303	8235	26.8	6.7	2.0	1.4	1.1	1.1	0.8	5–10	8
	7.421	8207	24.3	7.9	3.5	2.4	1.7	1.6	1.2	5–10	3.3
	7.511	8259	36.1	12.0	4.4	2.3	1.3	1.1	0.7	2–5	1
	7.617	8493	20.1	8.8	4.4	2.8	1.8	1.5	1.1	10+	5
	7.718	8581	19.0	12.8	7.0	4.2	2.6	2.2	1.4	10+	5.5
	7.817	8219	42.3	20.0	6.3	3.0	1.8	1.6	1.1	0–2	0.3
	7.913	8307	37.7	16.2	5.9	3.2	1.9	1.6	1.1	0–2	0.4
	8.034	8469	17.2	8.5	4.5	3.0	2.0	1.7	1.2	10+	9.5
	8.109	8342	24.9	11.0	4.6	2.9	1.9	1.7	1.3	5–10	1.9
	8.212	8624	11.7	7.0	3.0	1.7	0.9	0.8	0.6	10+	32.4
	8.332	8537	16.9	9.7	5.4	3.4	2.2	1.8	1.2	10+	7.8
	8.413	8672	13.9	7.3	4.0	2.8	1.9	1.6	1.1	10+	15
	8.521	8271	19.6	11.2	5.5	3.5	2.4	2.2	1.6	10+	5
	8.607	8398	26.8	10.2	5.0	3.3	2.2	1.9	1.4	5–10	1.6
	8.72	7818	29.8	9.9	3.2	2.4	1.7	1.7	1.3	2–5	1.6
	8.808	8179	22.4	8.1	1.8	0.6	0.2	0.3	0.3	10+	19.8
	8.9	8259	14.5	6.2	2.6	1.6	1.1	1.0	0.8	2–5	1.1
	9.006	8263	28.1	12.9	5.1	2.9	1.9	1.7	1.2	2–5	0.9
	9.109	8215	36.7	16.1	4.1	1.6	0.9	0.9	0.8	0–2	0.2
	9.199	8013	42.6	21.6	7.4	3.5	1.9	1.4	0.9	0–2	0.4
	9.323	7965	34.7	16.7	6.1	3.7	2.5	2.3	1.6	2–5	0.3
	9.404	8124	34.0	19.2	7.8	4.0	2.3	1.9	1.3	0–2	0.2

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 16	9.501	8223	38.3	22.6	8.8	3.7	1.8	1.5	1.1	0–2	1
	9.627	8287	40.4	15.2	4.1	1.5	0.7	0.6	0.5	10+	39.7
	9.706	8561	9.5	7.0	4.4	2.7	1.6	1.3	0.9	0–2	0.1
	9.823	8175	55.5	28.3	8.7	3.2	1.6	1.5	1.3	10+	0.1
	9.909	7818	45.0	26.8	10.4	4.7	2.8	2.6	2.0	0–2	0.1
	10.018	8450	19.4	11.7	5.3	3.0	1.9	1.5	1.1	10+	4.6
	10.117	8303	27.0	17.4	8.8	4.6	2.7	2.3	1.7	2–5	1
	10.203	8366	21.4	12.7	6.6	3.7	2.1	1.7	1.2	10+	3.1
	10.305	8291	32.2	17.6	6.0	2.8	1.7	1.6	1.2	2–5	0.6
	10.408	8533	15.4	13.0	8.6	5.6	3.4	2.7	1.8	10+	5.5
	10.513	8040	45.7	28.3	12.2	6.0	3.2	2.6	1.9	0–2	0.1
	10.609	8179	28.2	15.2	6.5	3.4	1.6	1.3	1.0	2–5	0.8
	10.732	8374	20.8	15.8	11.2	7.4	4.1	2.9	1.8	5–10	1.2
	10.821	8239	24.2	12.8	5.4	2.7	1.3	1.1	0.9	5-10	1.7
	10.91	8326	24.1	13.2	5.1	2.4	1.4	1.2	0.9	5–10	1.8
	11.003	8017	44.6	24.7	12.2	7.5	4.8	4.0	2.8	0–2	0.1
	11.126	8346	22.5	15.1	7.4	3.8	2.1	1.7	1.2	5–10	2.2
	11.216	8370	21.1	13.4	7.3	4.1	2.3	1.7	1.2	10+	3.3
	11.314	8199	47.4	21.5	6.8	2.9	1.7	1.5	1.1	0–2	0.2
	11.418	8223	22.1	16.3	9.1	5.1	2.8	2.1	1.4	5–10	1.7
	11.509	8704	9.6	8.3	5.9	4.0	2.4	1.9	1.2	10+	11.3
	11.622	8803	6.6	6.4	5.1	4.0	2.8	2.4	1.7	10+	40
	11.747	8815	4.5	4.5	3.5	2.4	1.6	1.3	0.9	10+	40
FM 2331	0	8,548	36.2	18.1	7.6	4.9	3.3	2.4	1.9	5–10	0.9
	0.4	9,092	9.3	6.7	3.1	1.7	0.8	0.4	0.3	10+	40
	0.8	8,504	29.7	16.3	5.7	3.3	2.3	1.7	1.3	10+	2
	1.2	8,917	16.2	6.4	2.2	1.0	0.5	0.3	0.2	10+	40
	1.6	8,909	24.9	17.2	8.6	5.1	2.9	1.7	1.1	10+	3
	2	8,576	32.4	19.1	9.0	5.6	3.4	2.2	1.4	5–10	1
	2.4	8,750	27.5	14.9	7.0	4.7	3.1	2.2	1.6	10+	2.4
	2.8	8,600	31.5	18.6	8.6	5.4	3.5	2.5	1.8	5–10	1.1
	3.2	8,520	36.1	17.0	6.5	4.1	2.7	1.9	1.5	5–10	1.2
	3.6	8,604	39.5	17.7	6.7	3.7	2.2	1.6	1.2	2–5	1.2
	4	8,957	11.7	6.3	3.1	1.8	1.1	0.7	0.5	10+	40
	4.4	8,564	34.7	16.9	6.3	2.9	1.6	1.1	0.8	5–10	1.8
	4.8	9,251	15.1	10.4	6.1	4.5	3.0	2.2	1.6	10+	40
	5.2	8,504	23.0	12.0	4.2	1.9	1.0	0.7	0.5	10+	8.1
	5.6	8,286	38.8	15.5	4.9	2.4	1.4	0.8	0.6	2–5	2.3
	6	8,993	35.0	16.5	6.2	3.3	2.2	1.4	1.0	5–10	1.9
	6.4	8,627	44.7	12.9	5.3	3.8	2.7	2.0	1.4	2–5	1.8
	6.8	8,190	40.8	15.0	4.4	2.3	1.4	0.9	0.7	2–5	2.4
	7.2	8,349	32.4	14.4	5.4	3.3	1.8	1.1	0.7	10+	2.2
	7.6	8,858	38.4	19.3	8.9	5.8	3.8	2.7	2.0	5–10	0.7
	8	9,060	25.3	9.4	3.5	2.2	1.5	1.0	0.8	10+	13.6
	8.4	9,056	27.4	19.1	9.2	5.6	3.2	2.1	1.5	10+	2.1
	8.8	9,275	20.6	13.6	6.7	4.0	2.7	2.1	1.5	10+	9.5
	9.2	8,230	45.5	14.7	4.5	2.7	2.1	1.6	1.3	2–5	1.9
	9.6	8,492	36.8	15.4	6.3	3.9	2.5	1.8	1.4	5–10	1.4

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
IH 35W-1	0	9010	19.7	13.4	7.7	4.7	2.9	2.6	2.0	0–2	5.5
	0.11	9045	19.2	13.0	7.7	4.9	3.1	2.6	1.9	0–2	6.7
	0.228	8930	27.0	16.9	8.3	4.7	3.0	2.7	2.1	0–2	1.3
	0.311	9010	21.8	17.4	10.8	6.5	3.6	2.8	2.0	0–2	3.2
	0.404	8978	23.1	18.1	11.4	6.9	4.1	3.2	2.2	0–2	2.7
	0.504	8990	22.3	14.1	7.3	4.2	2.4	2.0	1.5	0–2	3
	0.604	9101	17.6	11.4	6.4	4.0	2.6	2.3	1.7	2–5	10
	0.708	8958	21.1	13.5	7.5	4.6	3.0	2.7	2.1	0–2	4.1
	0.802	8954	22.5	13.0	6.9	4.4	3.0	2.7	2.0	0–2	3.3
	0.879	8827	38.5	23.2	10.7	6.2	4.0	3.7	2.8	0–2	0.2
	1.015	9049	21.1	11.9	6.1	3.6	2.2	1.8	1.3	2–5	4.5
	1.247	8692	26.5	19.5	11.7	6.8	3.6	2.5	1.6	0–2	1.1
	1.303	8946	22.8	14.1	7.4	4.5	2.9	2.4	1.7	0–2	2.8
	1.42	9141	16.0	14.2	10.7	7.6	5.0	4.2	2.8	0–2	5.7
	1.504	8755	33.1	16.1	7.3	4.7	3.3	3.2	2.4	0–2	0.6
	1.604	8664	23.2	13.3	6.7	4.2	2.7	2.4	1.7	0–2	2.4
	1.709	8775	45.4	23.0	7.7	4.6	3.4	3.2	2.4	0–2	0.2
	1.808	8497	40.3	22.8	9.6	5.4	3.5	3.2	2.5	0–2	0.2
	1.915	8469	47.2	28.0	11.2	5.7	3.7	3.5	2.8	0–2	0.1
	2.004	8652	44.8	27.0	12.3	6.5	3.9	3.4	2.5	0–2	0.1
	2.103	8597	39.1	27.1	13.7	6.7	3.5	3.0	2.3	0–2	0.2
	2.218	8676	25.6	15.2	6.9	3.7	2.4	2.1	1.6	0–2	1.5
	2.307	9101	12.6	11.9	9.4	6.9	4.7	3.8	2.4	2–5	8.5
	2.406	8688	40.0	25.7	12.0	6.4	4.0	3.8	2.9	0–2	0.2
	2.523	9288	5.0	4.5	3.7	2.9	2.1	1.8	1.2	10+	40
	2.62	8859	15.1	13.0	9.4	6.5	4.0	3.2	2.1	2–5	7.3
	2.725	8712	42.1	16.8	3.5	1.8	1.0	0.9	0.6	0–2	1
	2.824	7933	67.7	32.1	11.9	7.4	4.7	4.2	3.0	0–2	0
	2.91	8787	37.6	16.3	5.1	2.5	1.5	1.3	0.8	0–2	0.7
	3.023	8255	39.4	17.8	5.3	3.1	2.0	1.7	1.1	0–2	0.4
	3.126	8676	36.1	14.5	4.5	2.5	1.4	1.2	0.8	0–2	0.9
	3.23	8442	54.6	26.6	9.4	4.9	3.3	2.9	2.2	0–2	0.1
	3.333	8871	11.0	9.6	7.3	5.3	3.6	3.1	2.1	2–5	13.2
	3.416	9065	11.6	9.8	7.1	4.9	3.1	2.6	1.7	5–10	19
	3.513	9002	14.4	12.5	9.2	6.3	3.8	2.8	1.6	2–5	8.1
	3.606	8493	55.7	26.4	7.2	3.0	1.7	1.4	1.0	0–2	0.2
	3.718	8779	42.1	22.2	8.9	4.1	2.5	2.3	1.7	0–2	0.2
	3.804	8815	27.9	18.0	8.3	4.0	2.3	2.0	1.4	0–2	1

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
IH 35W-2	0	8815	26.8	14.3	7.1	4.2	2.7	2.3	1.6	0–2	0.8
	0.104	8859	38.6	18.0	5.3	2.9	2.2	2.0	1.7	0–2	0.2
	0.206	8827	61.6	26.9	6.1	2.1	1.3	1.2	0.9	0–2	0.1
	0.302	8716	34.5	16.9	7.0	3.9	2.3	1.9	1.3	0–2	0.2
	0.345	8787	26.1	10.8	4.2	2.3	1.5	1.3	0.9	2–5	1
	0.418	8700	45.8	17.6	5.5	3.0	2.0	1.8	1.3	0–2	0.1
	0.518	8255	54.3	25.3	6.9	3.7	2.5	2.5	1.6	0–2	0
	0.617	8513	38.1	15.2	5.4	3.0	1.8	1.6	1.2	0–2	0.2
	0.712	8338	51.3	22.3	7.9	5.2	3.5	3.2	2.4	0–2	0
	0.811	8628	35.0	16.3	6.4	4.0	2.7	2.5	1.9	0–2	0.2
	0.909	8525	34.3	15.6	6.9	4.5	3.2	2.9	2.2	0–2	0.2
	1.015	8370	45.6	26.4	11.0	6.4	4.4	4.0	3.0	0–2	0.1
	1.114	8597	38.2	22.4	8.8	5.0	3.5	3.3	2.6	0–2	0.1
	1.222	7599	89.1	37.7	9.7	5.1	3.4	3.8	3.0	0–2	0
	1.225	7635	68.1	32.7	9.5	5.2	3.8	3.7	2.7	0–2	0
	1.302	9407	10.2	9.2	7.2	5.5	4.0	3.6	2.6	5–10	14.7
	1.362	9610	8.3	7.6	6.0	4.7	3.5	3.1	2.2	10+	25.3
	1.411	8541	35.8	18.0	8.1	5.1	3.4	3.1	2.3	0–2	0.2
	1.508	7985	60.8	28.2	10.1	6.2	4.3	3.9	3.1	0–2	0
	1.604	8644	43.6	24.1	10.4	6.2	4.1	3.6	2.7	0–2	0.1
	1.71	8338	59.8	32.7	11.5	5.9	4.1	3.9	3.2	0–2	0
	1.805	8469	31.7	17.7	8.4	5.1	3.5	3.2	2.4	0–2	0.3
	1.904	8565	34.6	18.2	8.8	5.5	3.7	3.4	2.7	0–2	0.2
	2.01	8295	79.1	34.7	9.9	5.1	3.7	3.5	2.7	0–2	0
	2.116	8922	10.5	9.2	7.5	5.9	4.2	3.8	2.6	2–5	10.4
	2.206	8704	28.4	14.0	6.0	3.6	2.3	2.1	1.6	0–2	0.5
	2.308	10114	7.7	7.4	5.5	4.4	3.3	3.0	2.2	10+	34.1
	2.405	8342	69.6	36.7	15.8	8.8	5.6	4.9	3.7	0–2	0
	2.514	8740	36.5	20.4	8.8	4.6	2.6	2.0	1.4	0–2	0.2
	2.609	8585	46.8	21.2	8.2	4.6	3.2	3.0	2.3	0–2	0.1
	2.703	9192	7.2	6.2	5.3	4.4	3.4	3.3	2.5	5–10	32.7
	2.805	9375	9.9	8.8	7.0	5.4	3.7	3.2	2.4	5–10	16.1
	2.908	9975	8.7	7.6	6.1	4.7	3.4	3.0	2.1	10+	26.2
	3.004	8597	34.8	17.2	7.3	4.3	3.0	2.7	2.0	0–2	0.2
	3.112	8509	41.6	22.9	9.6	5.3	3.6	3.4	2.6	0–2	0.1
	3.209	8585	45.9	24.9	9.7	5.3	3.8	3.6	2.7	0–2	0.1
	3.316	8612	36.1	17.2	7.3	4.5	3.2	3.0	2.2	0–2	1.2
	3.38	8938	24.5	14.4	6.8	4.0	2.7	2.5	1.9	0–2	0.1
	3.5	8517	46.7	22.8	8.1	4.1	2.8	2.6	1.9	0–2	0.1
	3.608	8469	57.2	33.9	15.6	8.7	5.3	4.3	3.0	0–2	0
	3.701	8601	35.2	16.6	7.3	4.6	3.3	3.0	2.3	0–2	0.2
	3.806	8608	33.9	14.2	5.9	3.5	2.4	2.2	1.7	0–2	0.3
	3.919	8620	69.6	25.1	5.3	2.5	1.9	1.8	1.3	0–2	0.1
	4.012	8827	33.2	15.3	4.5	1.7	0.8	0.6	0.4	0–2	0.5
	4.108	8589	32.4	18.4	7.7	4.1	2.4	2.1	1.6	0–2	0.3
	4.231	8910	81.5	8.1	2.7	1.9	1.3	1.2	0.8	0–2	0.5
	4.32	8573	56.6	34.7	15.5	7.6	4.3	3.5	2.6	0–2	0
	4.406	8863	22.5	10.9	4.5	2.6	1.6	1.4	1.0	2–5	1.6

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
IH 35W-2	4.475	8942	17.4	10.4	5.0	2.9	1.7	1.5	1.1	5–10	3.7
	4.622	8898	24.1	11.5	5.3	3.3	2.1	1.8	1.4	0–2	1.3
	4.711	8795	26.4	13.2	5.7	3.5	2.3	2.1	1.7	0–2	0.8
	4.812	8934	21.7	13.4	6.5	3.7	2.4	2.1	1.5	2–5	2
	4.914	8748	40.4	23.8	9.1	4.2	2.2	1.8	1.3	0–2	0.1
	5.013	8970	18.2	10.3	5.4	3.2	2.0	1.8	1.2	5–10	3.5
	5.114	8744	33.2	15.2	5.6	3.2	2.1	1.9	1.5	0–2	0.3
	5.21	8863	23.9	12.2	5.3	3.0	1.8	1.5	1.1	2–5	1.2
	5.308	8648	44.3	25.5	10.4	5.1	3.1	2.7	2.0	0–2	0.1
FM 52	0	8608	6.3	3.2	1.5	0.9	0.4	0.3	0.2	10+	40
	0.107	8700	10.6	8.7	6.3	4.7	3.3	2.8	2.0	10+	40
	0.203	8473	20.9	10.0	3.6	1.6	0.8	0.7	0.5	10+	29.5
	0.31	8700	11.0	7.1	3.6	1.9	1.0	0.7	0.4	10+	40
	0.405	8636	11.2	8.3	5.4	3.6	2.2	1.8	1.2	10+	40
	0.504	8545	17.5	9.9	4.1	1.9	0.9	0.8	0.6	10+	40
	0.613	8545	8.3	5.7	3.1	1.7	0.9	0.7	0.6	10+	40
	0.716	8461	20.2	11.4	4.9	2.1	0.8	0.5	0.3	10+	24.1
	0.814	8450	30.0	21.0	12.2	7.3	4.3	3.3	2.2	5–10	3
	0.915	8644	9.3	7.5	5.6	4.0	2.6	2.1	1.5	10+	40
	1.002	8652	14.0	10.5	6.6	4.4	2.8	2.4	1.7	10+	40
	1.123	8450	19.5	11.2	5.1	2.9	1.9	1.7	1.4	10+	21.5
	1.206	8628	11.5	8.7	5.7	3.8	2.4	2.1	1.5	10+	40
	1.31	8605	11.6	8.7	5.9	4.0	2.6	2.1	1.5	10+	40
	1.415	8612	11.9	8.8	5.3	3.5	2.3	2.0	1.5	10+	40
	1.51	8620	12.7	8.9	5.5	3.5	2.2	1.8	1.3	10+	40
	1.615	8632	9.9	7.1	4.9	3.4	2.3	2.0	1.5	10+	40
	1.703	8469	15.9	9.4	5.2	3.1	1.9	1.6	1.2	10+	40
	1.811	8525	14.2	10.2	6.5	4.3	2.8	2.4	1.7	10+	40
	1.913	8620	8.8	7.1	5.4	4.1	2.9	2.5	1.9	10+	40
	1.986	8422	24.3	15.3	7.7	4.4	2.8	2.3	1.6	10+	7.2
	2.113	8525	11.7	7.4	3.5	1.7	0.9	0.8	0.7	10+	40
	2.215	8708	4.9	2.9	1.3	0.6	0.3	0.2	0.2	10+	40
	2.307	8708	9.2	6.1	3.8	2.3	1.2	0.7	0.4	10+	40
	2.405	8688	9.4	7.8	5.6	3.8	2.4	1.7	1.0	10+	40
	2.513	8569	16.3	11.2	6.8	4.1	2.2	1.4	0.7	10+	40
	2.609	8465	15.6	10.6	6.4	4.0	2.3	1.7	1.0	10+	40
	2.723	8605	14.7	10.7	7.1	4.8	3.0	2.4	1.6	10+	31.2
	2.816	8684	6.1	2.7	1.3	0.7	0.4	0.2	0.2	10+	40
	2.915	8589	19.3	8.5	4.7	2.9	1.7	1.2	0.7	10+	40
	3.018	8601	13.7	6.1	2.3	1.2	0.7	0.6	0.4	10+	40
	3.121	8577	18.0	6.3	2.4	1.3	0.8	0.7	0.5	10+	40
	3.216	8803	7.5	4.9	2.9	1.8	1.1	0.8	0.5	10+	40
	3.325	8748	7.1	3.5	1.7	1.0	0.6	0.4	0.3	10+	40
	3.416	8736	8.6	3.9	1.8	1.1	0.6	0.5	0.4	10+	40
	3.518	8736	10.9	4.8	2.1	1.2	0.7	0.5	0.4	10+	3.5
	3.629	8692	11.7	8.4	5.5	3.6	2.2	1.6	1.0	10+	40
	3.727	8267	32.3	15.7	6.0	2.8	1.4	1.0	0.7	5–10	40
	3.813	8664	7.6	4.3	2.4	1.5	0.9	0.7	0.5	10+	40
	3.908	8605	10.2	6.7	4.1	2.4	1.4	1.0	0.7	10+	40

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 52	4.008	8656	9.9	7.3	4.8	3.1	2.0	1.6	1.2	10+	7.8
	4.116	8648	6.4	3.1	1.7	1.0	0.6	0.4	0.3	10+	40
	4.217	8450	24.4	14.9	8.3	5.1	3.2	2.7	2.0	10+	40
	4.302	8632	11.3	6.5	3.1	1.6	0.8	0.5	0.4	10+	40
	4.417	8473	10.9	7.3	4.0	2.3	1.2	0.8	0.4	10+	40
	4.503	8664	8.2	4.5	2.3	1.3	0.6	0.5	0.3	10+	40
	4.604	8601	9.3	3.9	1.6	0.8	0.4	0.3	0.2	10+	40
	4.716	8585	12.4	4.9	1.7	0.8	0.4	0.3	0.2	10+	40
	4.813	8680	8.3	4.3	2.1	1.1	0.6	0.4	0.2	10+	40
	4.915	8779	5.1	3.1	1.7	1.0	0.5	0.4	0.3	10+	40
	5.022	8791	6.8	5.5	4.2	3.1	2.1	1.7	1.1	10+	40
	5.116	8640	9.8	7.6	5.6	4.2	2.9	2.5	1.7	10+	40
	5.22	8513	17.0	11.0	6.3	4.1	2.7	2.3	1.6	10+	32.1
	5.326	8585	10.5	7.5	5.0	3.4	2.2	1.9	1.4	10+	40
	5.425	8473	18.1	12.8	7.8	4.7	2.9	2.4	1.7	10+	40
	5.51	8648	10.5	7.0	4.5	3.1	2.1	1.8	1.3	10+	40
	5.609	8656	11.0	9.0	6.8	5.0	3.4	2.8	2.0	10+	40
	5.711	8605	14.0	10.5	7.0	4.7	3.0	2.5	1.7	10+	40
	5.815	8664	9.9	7.5	5.3	3.8	2.5	2.1	1.5	10+	40
	5.913	8644	11.0	9.0	6.3	4.3	2.7	2.0	1.2	10+	40
	6.029	8489	22.1	14.9	9.1	5.7	3.4	2.5	1.6	10+	12.5
	6.114	8561	17.8	12.6	7.9	4.9	3.0	2.2	1.4	10+	37.6
	6.21	8446	21.1	14.9	8.8	5.3	3.1	2.3	1.4	10+	15.5
	6.313	8414	22.5	15.1	8.9	5.5	3.2	2.4	1.5	10+	10.5
	6.412	8307	27.6	19.5	11.6	7.1	4.3	3.3	2.1	5–10	4.1
	6.504	8402	21.5	14.1	7.9	4.9	3.0	2.4	1.7	10+	12.7
	6.61	8402	18.1	7.5	3.8	2.5	1.8	1.6	1.2	10+	40
	6.716	8398	26.8	14.7	6.9	4.2	2.5	1.9	1.4	10+	5.2
	6.803	8243	31.1	11.5	5.3	3.0	1.9	1.6	1.2	5–10	5.1
	6.915	7905	72.3	34.5	12.5	6.2	3.8	3.2	2.3	0–2	0.2
	7.016	7981	64.5	27.4	9.3	5.1	3.0	2.6	1.9	0–2	0.3
	7.111	8227	41.7	19.3	8.9	5.5	3.4	2.7	1.8	2–5	0.8
	7.2	8080	58.9	26.3	9.8	5.8	3.8	3.2	2.3	0–2	0.3
	7.314	8283	37.4	18.3	7.3	3.5	1.7	1.1	0.8	5-10	1.8
	7.403	7889	69.9	19.7	5.7	3.0	1.2	1.0	0.6	0–2	1
	7.506	8199	41.5	22.8	8.6	3.9	2.0	1.5	1.1	2–5	0.9
	7.583	8219	45.7	26.0	10.7	5.7	3.4	2.9	2.1	0–2	0.5
SH 174	0	8736	16.6	7.0	2.7	1.5	0.9	0.8	0.6	5–10	0.8
	0.113	8704	20.5	10.2	3.9	1.8	0.9	0.7	0.4	2–5	0.2
	0.219	8767	17.3	8.4	3.1	1.4	0.8	0.5	0.3	5–10	0.5
	0.312	8644	16.2	7.2	2.3	1.0	0.5	0.4	0.3	5–10	0.7
	0.407	8751	14.7	6.0	2.1	1.1	0.6	0.5	0.3	10+	1.3
	0.504	9038	5.5	3.9	2.4	1.5	0.8	0.6	0.4	10+	17.8
	0.611	8505	23.0	10.1	2.8	1.2	0.7	0.6	0.4	2–5	0.2
	0.712	8533	35.7	15.6	4.5	2.2	1.5	1.3	1.0	0–2	0
	0.818	8549	32.4	11.3	3.0	1.5	0.8	0.7	0.5	0–2	0.1
	0.907	8648	31.0	13.0	3.3	1.3	0.7	0.5	0.3	0–2	0.1
	1.019	8434	37.2	16.3	6.4	3.7	2.2	1.7	1.1	0–2	0
	1.11	8573	23.4	7.7	1.8	0.9	0.5	0.5	0.3	2–5	0.3

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 174	1.219	8851	13.2	7.1	3.8	2.7	1.8	1.4	1.0	10+	0.7
	1.307	8807	17.6	9.6	4.9	3.5	2.5	2.2	1.6	5–10	0.4
	1.405	8390	41.6	20.8	7.7	4.4	2.9	2.2	1.6	0–2	0
	1.525	8807	17.7	8.0	3.4	2.2	1.4	1.1	0.7	5–10	0.5
	1.617	8469	38.7	17.0	5.3	2.8	1.7	1.3	0.9	0–2	0
	1.718	8628	25.3	11.0	3.5	1.9	1.2	1.0	0.6	0–2	0.1
	1.821	8684	23.0	10.4	3.9	2.0	1.2	0.9	0.6	2–5	0.1
	1.915	8644	23.6	12.6	5.2	2.8	1.6	1.3	0.8	2–5	0.1
	2.029	8465	35.5	15.5	4.8	2.5	1.5	1.0	0.7	0–2	0
	2.124	8275	28.9	15.1	7.4	4.4	2.8	2.2	1.5	0–2	0
	2.219	8612	30.1	17.8	8.1	4.5	2.7	1.9	1.2	0–2	0
	2.308	8755	15.6	7.3	2.5	1.1	0.6	0.5	0.3	10+	0.8
	2.419	8561	26.5	12.6	3.5	1.6	1.0	0.7	0.4	0–2	0.1
	2.507	8700	24.5	12.1	3.8	1.8	1.1	0.9	0.6	2–5	0.1
	2.612	8628	23.4	12.3	5.8	3.9	2.6	2.3	1.6	0–2	0.1
	2.725	8446	36.1	16.4	6.6	4.1	2.5	1.9	1.3	0–2	0
	2.809	8632	24.5	12.1	5.6	3.7	2.5	2.1	1.4	0–2	0.1
	2.916	8529	26.0	9.5	2.8	1.4	0.9	0.7	0.6	0–2	0.1
	3.01	8799	13.4	9.3	5.7	3.9	2.6	2.2	1.6	10+	0.4
	3.121	8704	17.1	6.6	2.3	1.1	0.7	0.6	0.4	5–10	0.7
	3.211	8636	17.6	6.8	2.6	1.4	0.9	0.6	0.4	5–10	0.6
	3.317	7937	34.7	7.7	2.2	1.5	1.2	1.1	0.8	0–2	0.1
	3.413	8640	25.1	12.5	5.3	2.5	1.1	0.7	0.3	2–5	0.1
	3.52	8517	31.0	14.6	5.4	2.6	1.5	1.1	0.7	0–2	0
	3.618	8406	33.2	14.0	4.1	1.8	0.9	0.6	0.4	0–2	0
	3.715	8517	32.1	15.3	5.2	2.5	1.4	1.0	0.7	0–2	0
	5.716	8465	34.2	17.0	5.1	2.0	1.0	0.9	0.6	0–2	0
	5.803	8406	29.4	12.4	3.7	1.6	1.0	0.9	0.7	0–2	0
	5.899	8454	31.1	14.5	4.8	2.3	1.4	1.1	0.8	0–2	0.1
	5.95	8640	23.4	11.5	5.3	3.1	1.8	1.3	0.9	2–5	0
FM 2738	0	8954	16.0	9.2	4.7	2.9	2.0	1.8	1.2	10+	20
	0.102	8914	16.2	11.6	6.8	4.6	3.2	2.6	1.8	10+	17.7
	0.205	8922	21.3	13.2	7.0	4.5	3.0	2.6	1.9	5–10	4.2
	0.306	8867	32.3	20.0	10.4	6.6	4.4	3.9	2.9	0–2	0.7
	0.405	8982	19.5	12.9	8.0	5.7	4.0	3.5	2.5	2–5	9.5
	0.511	8839	20.2	15.1	9.4	6.4	4.4	4.1	3.0	2–5	8
	0.617	8946	21.3	16.8	10.9	7.3	5.0	4.5	3.4	2–5	7.1
	0.705	8744	35.7	25.4	13.9	7.9	5.2	4.6	3.4	0–2	0.3
	0.804	8962	39.0	19.4	11.4	7.0	4.6	4.1	3.1	0–2	0.3
	0.914	9141	10.0	8.7	7.0	5.4	4.0	3.7	2.6	10+	22.7
	1.03	9053	17.2	12.1	7.1	4.6	3.2	2.9	2.2	5–10	14.3
	1.116	8906	19.8	12.3	7.7	5.1	3.4	3.1	2.1	5–10	7.2
	1.213	8827	21.2	13.7	8.9	6.3	4.3	3.9	2.8	2–5	6.4
	1.306	9220	18.2	12.3	7.8	5.4	3.7	3.2	2.4	5–10	14.7
	1.414	8775	24.9	16.7	9.4	6.0	4.1	3.6	2.6	2–5	2.1
	1.516	8811	27.0	20.5	12.4	7.5	4.6	3.8	2.8	0–2	1.4
	1.604	8779	21.1	13.6	8.3	5.7	3.9	3.3	2.2	2–5	5.1
	1.714	8966	10.9	7.5	5.3	4.0	2.8	2.4	1.8	10+	22.7
	1.815	9041	19.5	12.6	7.9	5.6	3.9	3.5	2.5	5–0	20

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 2738	1.912	9026	21.2	15.0	10.4	6.9	4.6	3.9	2.6	2–5	7.3
	2.018	8680	20.7	14.9	10.5	7.3	4.7	3.9	2.7	2–5	7.4
	2.129	9113	15.3	10.3	6.8	4.9	3.4	3.1	2.2	10+	20.5
	2.205	8732	21.1	13.8	8.5	5.9	3.6	2.8	1.8	5–10	4.7
	2.316	8986	17.0	11.8	7.7	5.5	3.6	3.2	2.2	5–10	14.7
	2.422	8799	18.8	12.3	7.5	5.1	3.4	2.9	2.0	5–10	8.3
	2.517	8930	17.4	11.0	7.1	5.0	3.4	3.1	2.2	5–10	15.8
	2.614	8815	18.9	12.4	8.2	5.9	4.0	3.5	2.5	2–5	11.4
	2.718	9010	13.2	7.9	4.4	2.9	1.9	1.6	1.0	10+	22.7
	2.816	9038	8.3	5.6	4.0	3.1	2.2	2.1	1.5	10+	22.7
	2.919	8974	14.4	9.4	6.5	4.8	3.3	2.9	2.1	10+	22.4
	3.015	8930	14.4	9.4	5.9	4.2	2.9	2.8	2.0	10+	22.7
	3.106	8902	15.3	10.2	6.1	4.6	3.4	3.1	2.3	5–10	20.8
	3.23	8906	25.0	17.2	10.9	7.4	4.9	4.4	3.3	0–2	2.9
	3.311	9030	11.3	9.4	7.2	5.3	3.8	3.4	2.5	10+	21.2
	3.415	9026	7.7	6.9	5.8	4.7	3.6	3.3	2.3	10+	22.7
	3.501	8926	18.1	15.1	11.0	7.6	5.0	4.3	2.9	2–5	8.8
	3.582	8533	31.9	19.6	10.8	6.7	4.5	4.0	2.9	0–2	0.6
	3.707	8593	50.3	19.8	11.9	7.6	5.0	4.6	3.3	0–2	7.3
	3.81	9073	15.5	11.0	7.6	5.9	4.4	4.1	3.1	5–10	14.2
	3.922	9125	15.9	11.7	8.3	6.1	4.4	4.0	2.9	5–10	13.5
	4.003	8283	86.3	25.9	15.2	9.0	5.8	5.1	3.7	0–2	0.1
	4.109	8998	15.7	10.1	6.9	5.1	3.6	3.3	2.4	5–10	18.2
	4.205	9097	16.1	11.1	7.4	5.4	3.9	3.7	2.7	5–10	16
	4.325	9018	16.4	12.9	9.5	7.1	5.0	4.3	3.0	5–10	11
	4.417	8918	22.9	14.1	8.5	5.8	4.0	3.7	2.8	2–5	3.8
	4.508	8783	26.6	16.2	9.6	6.5	4.4	3.9	2.7	0–2	1.7
	4.606	8771	29.4	19.3	11.1	7.2	4.9	4.4	3.2	0–2	1
	4.715	9026	21.6	14.9	9.0	6.0	4.2	3.8	2.8	2–5	5.4
	4.817	8748	31.7	20.8	12.2	8.1	5.4	4.9	3.5	0–2	0.8
	4.928	9117	13.1	8.8	6.8	5.3	3.9	3.6	2.7	10+	21.2
	5.009	9057	16.2	11.7	8.4	6.3	4.3	3.8	2.6	5–10	14
	5.102	8755	21.4	14.0	9.2	6.2	4.1	3.7	2.7	2–5	5.5
	5.211	8779	23.2	16.9	12.1	8.6	5.6	4.8	3.3	0–2	5.2
	5.335	8672	22.2	14.4	9.3	6.3	4.2	3.8	2.5	2-5	4.2
FM 3048	0	8485	34.7	15.5	6.1	3.5	2.2	2.0	1.4	0–2	0.2
	0.118	8370	26.4	10.8	3.9	2.6	1.8	1.6	1.3	2–5	0.7
	0.218	8545	20.9	8.9	4.2	2.9	2.0	1.8	1.4	5–10	2
	0.282	8676	15.7	8.3	3.7	2.0	1.2	0.8	0.7	10+	6.9
	0.418	8318	30.5	10.1	3.9	2.6	1.8	1.6	1.2	2-5	0.6
	0.511	8414	26.7	10.8	4.2	2.3	1.4	1.1	0.7	5–10	0.7
	0.619	8350	31.1	12.9	5.0	3.2	2.1	1.9	1.5	0–2	0.3
	0.717	8330	33.6	13.0	4.8	3.2	2.2	2.0	1.4	0–2	0.3
	0.822	8537	26.8	4.6	1.3	1.0	0.9	0.8	0.7	5–10	6.5
	0.917	8680	22.7	10.3	5.2	3.8	2.6	2.4	1.7	5–10	1.8
	1.012	8644	21.7	9.0	4.3	2.9	2.0	1.8	1.3	5–10	1.8
	1.141	8720	17.7	7.9	3.8	2.6	1.7	1.5	1.2	10+	4.8
	1.218	8628	20.7	9.8	4.1	2.3	1.6	1.3	1.0	10+	2
	1.315	8450	26.2	5.9	2.3	1.9	1.4	1.4	1.1	2–5	3.1

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 3048	1.409	8422	24.5	14.8	6.6	4.2	2.7	2.4	1.7	2–5	0.9
	1.513	8748	10.7	5.5	3.2	2.5	1.8	1.6	1.2	10+	22.7
	1.607	8620	11.5	6.0	2.8	1.7	1.1	0.9	0.6	10+	22.5
	1.7	8664	11.9	6.4	2.6	1.5	0.8	0.7	0.5	10+	22.1
	1.822	8326	26.6	12.1	4.5	2.8	1.9	1.8	1.4	2–5	0.6
	1.929	8406	21.8	10.4	4.9	3.2	2.1	1.9	1.4	0–2	1.6
	2.011	8517	20.5	10.6	4.3	2.3	1.5	1.4	1.1	5–10	1.9
	2.055	8537	23.0	12.8	5.3	3.0	1.9	1.7	1.2	10+	1.1
	2.205	8561	22.5	11.2	4.6	2.8	1.9	1.5	1.1	5–10	1.3
	2.302	8505	25.7	16.5	8.1	4.6	2.8	2.6	1.9	5–10	0.8
	2.403	8485	31.0	18.9	8.4	4.7	2.9	2.6	1.9	2–5	0.3
	2.519	8048	35.4	20.6	8.1	4.2	2.8	2.6	2.0	0–2	0.1
	2.608	8680	12.4	7.7	3.7	2.1	1.3	1.2	0.9	0–2	13.4
	2.716	8044	30.9	18.0	6.8	3.4	2.0	1.7	1.3	10+	0.2
	2.829	8084	27.3	12.3	4.3	2.6	1.8	1.6	1.2	0-2	0.5
	2.919	8644	22.8	11.9	4.5	2.4	1.5	1.3	1.0	2–5	1.2
	3.013	8573	17.0	7.0	1.8	0.9	0.6	0.5	0.4	5–10	8.2
	3.117	8422	25.8	14.6	7.1	4.8	3.4	3.0	2.2	10+	0.9
	3.218	8597	20.5	11.4	5.3	3.3	2.3	1.9	1.4	2–5	2.3
	3.311	8597	28.7	15.6	6.2	3.0	1.8	1.6	1.2	5–10	0.4
	3.408	8569	25.0	13.3	5.3	3.1	2.1	2.0	1.6	2–5	0.8
	3.509	8644	23.6	12.4	4.7	2.5	1.6	1.5	1.1	2–5	1.1
	3.609	8684	17.7	9.9	4.3	2.7	1.8	1.6	1.1	5–10	4.4
	3.681	8708	16.8	8.7	3.1	2.0	1.3	1.2	0.9	10+	5
	3.756	8636	27.4	13.5	4.5	2.3	1.4	1.2	0.9	10+	0.6
FM 3325	0	9077	12.3	7.0	3.6	2.3	1.6	1.4	1.0	5–10	7.2
	0.114	9045	13.7	7.8	3.5	1.8	0.9	0.7	0.4	5–10	3.2
	0.208	9093	12.6	9.1	6.0	3.9	2.5	2.1	1.5	5–10	4.7
	0.307	9057	11.1	8.3	5.6	3.7	2.5	2.1	1.6	5–10	5.7
	0.404	9030	12.6	9.4	5.9	3.7	2.1	1.8	1.3	5–10	4.5
	0.51	8990	13.1	9.4	5.8	3.5	2.1	2.0	1.5	5–10	4.1
	0.625	9026	11.2	6.8	3.7	2.4	1.7	1.4	1.1	5–10	9.4
	0.714	9014	11.8	8.0	4.7	2.8	1.9	1.5	1.2	5–10	6.8
	0.821	8942	16.5	9.6	5.0	2.9	1.8	1.5	1.2	5–10	1.8
	0.918	9026	10.7	5.4	2.5	1.4	0.9	0.8	0.7	5–10	14.7
	1.013	9133	10.2	4.4	0.9	0.1	0.2	0.1	0.1	5–10	13
	1.103	9038	11.6	5.9	2.5	1.3	0.8	0.6	0.4	5–10	8.4
	1.203	9065	8.0	5.1	2.7	1.4	0.7	0.4	0.1	5–10	28.5
	1.309	9053	11.3	6.7	3.8	2.6	1.8	1.6	1.1	5–10	9.6
	1.415	9169	7.5	3.2	1.3	0.8	0.5	0.5	0.5	5–10	28
	1.511	9109	12.5	6.6	3.1	1.8	1.0	0.8	0.6	5–10	7.8
	1.609	9077	8.1	5.0	2.7	1.6	0.9	0.8	0.7	5–10	29.2
	1.706	8982	14.8	7.5	2.7	1.3	0.7	0.6	0.4	5–10	3.2
	1.827	9022	11.5	8.6	6.2	4.4	3.1	2.8	2.0	5–10	3.7
	1.915	9125	10.2	7.2	4.5	2.9	1.9	1.6	1.2	5–10	8.9
	1.989	9053	9.1	6.1	3.5	2.0	1.2	0.9	0.7	5–10	17
	2.106	8859	18.4	8.7	2.3	0.4	0.0	0.0	0.0	5–10	5
	2.203	9085	12.9	9.0	5.0	2.6	1.3	0.7	0.4	5–10	2.9

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 3325	2.302	9101	11.3	7.2	4.1	2.2	1.2	0.7	0.4	5–10	7
	2.407	8998	17.8	13.4	8.6	5.4	3.3	2.5	1.6	2–5	0.9
	2.495	9089	12.5	8.3	5.4	3.5	2.0	1.5	0.9	5–10	5.4
	2.616	9089	15.7	11.1	7.0	4.8	3.1	2.6	1.7	5–10	2.2
	2.713	9093	14.0	10.3	7.1	4.8	2.8	2.2	1.3	5–10	3.2
	2.813	9006	17.5	10.0	4.8	2.9	1.9	1.8	1.3	2–5	1.5
	2.915	8962	19.9	15.2	9.9	6.3	3.7	2.8	1.8	2–5	0.5
	3.014	9085	12.8	9.9	6.8	4.7	2.9	2.4	1.6	5–10	3.2
	3.113	9184	8.9	6.9	5.3	4.0	2.6	2.1	1.3	5–10	9.5
	3.212	8998	18.0	11.2	6.0	3.7	2.3	1.9	1.2	2–5	1.3
	3.309	8871	28.7	16.9	7.5	3.9	2.1	1.6	1.0	0–2	0.1
	3.413	8787	32.8	16.7	5.3	2.0	1.0	0.9	0.6	0–2	0.1
	3.502	8978	21.0	11.3	4.6	2.2	1.3	1.0	0.7	2–5	0.5
	3.602	8771	27.0	14.9	6.1	2.9	1.5	1.0	0.6	0-2	0.1
	4.008	8696	41.7	23.6	10.5	5.4	2.8	1.8	1.0	0–2	0
	4.106	8891	24.2	14.5	6.8	3.5	1.9	1.4	0.8	0–2	0.2
	4.215	9018	18.4	11.6	6.9	4.5	2.8	2.4	1.7	2–5	1.3
	4.323	9077	14.0	9.3	5.8	4.1	2.8	2.4	1.8	5–10	4
	4.412	8895	18.5	12.6	7.4	4.4	2.3	1.7	0.9	2–5	0.7
	4.497	8974	16.8	10.6	5.0	2.6	1.3	0.9	0.5	5–10	1
	4.605	9153	8.8	5.3	2.8	1.6	0.8	0.6	0.4	5–10	24
	4.704	8994	22.8	15.6	9.0	5.0	2.4	1.3	0.5	2–5	0.2
	4.802	9041	10.9	6.7	3.3	2.1	1.1	0.8	0.5	5–10	10
	4.914	9093	8.7	5.4	3.1	1.8	1.0	0.6	0.3	5–10	23.3
	5.01	9153	12.6	8.8	5.5	3.6	2.4	2.0	1.4	5–10	5.3
	5.114	8906	28.2	18.5	10.2	5.7	2.9	1.9	1.0	0–2	0.1
	5.207	9061	16.2	11.2	6.9	4.5	2.8	2.2	1.4	5–10	1.9
	5.312	9165	4.7	3.0	2.0	1.4	0.9	0.8	0.5	5–10	40
	5.418	8990	19.3	10.5	3.9	1.4	0.5	0.1	0.1	2–5	1.4
	5.514	9129	11.3	8.1	5.1	3.3	2.1	1.9	1.4	5–10	6.4
	5.609	8910	31.1	20.6	11.0	5.7	2.6	1.3	0.4	0–2	0.1
	5.721	9030	15.7	9.3	5.5	3.7	2.4	2.2	1.6	5–10	2.7
	5.803	9065	11.1	7.3	4.4	2.9	1.8	1.6	1.1	5–10	8.3
	5.901	9169	12.1	7.1	3.7	2.3	1.5	1.1	0.8	5–10	7.4
	6.002	9041	12.0	7.5	4.0	2.2	1.3	1.0	0.7	5–10	6.1
	6.033	8998	13.7	7.7	3.5	1.7	0.9	0.7	0.5	5–10	3.1
SH 171	0	9030	20.5	12.3	6.0	3.5	2.1	1.7	1.1	0–2	0.9
	0.107	8902	19.2	11.6	5.5	3.2	2.1	1.8	1.3	0–2	1.1
	0.206	8926	18.2	11.1	5.6	3.4	2.2	2.0	1.4	2–5	1.4
	0.302	8875	21.6	12.4	5.6	3.1	1.7	1.6	1.2	0–2	0.9
	0.408	9010	19.1	12.8	7.5	5.0	3.3	3.1	2.3	0–2	1.1
	0.509	8740	16.0	10.5	6.1	4.0	2.8	2.5	1.9	2–5	2.3
	0.61	8807	15.5	10.1	5.7	3.7	2.5	2.2	1.7	2–5	2.6
	0.704	8656	19.3	12.8	7.3	4.7	3.1	2.8	2.1	0–2	0.8
	0.801	8823	72.8	11.07	6.88	4.73	3.2	2.91	2.16	0–2	0.1
	0.915	8779	18.06	12.06	6.41	3.95	2.49	2.32	1.67	0–2	1.2
	1.016	9002	12.24	7.93	4.88	3.43	2.44	2.18	1.65	5–10	10.1

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 171	1.111	8934	15.5	10.1	5.7	3.7	2.4	2.1	1.6	2–5	2.7
	1.204	9244	6.4	5.7	4.4	3.5	2.4	2.3	1.7	5–10	36.6
	1.302	8986	13.4	8.2	4.7	3.1	2.2	1.8	1.3	5–10	5.9
	1.401	8982	15.0	9.6	5.4	3.5	2.3	1.9	1.4	2–5	3.2
	1.503	8974	13.2	8.2	4.7	3.1	2.1	1.7	1.2	5–10	6.1
	1.608	8982	13.8	9.1	5.2	3.5	2.3	2.0	1.5	2–5	5
	1.714	8783	9.6	7.1	5.0	3.5	2.3	2.0	1.5	5–10	12.8
	1.812	9141	7.1	5.8	4.6	3.7	2.6	2.4	1.8	5–10	23.8
	1.904	8851	17.3	11.5	6.4	4.1	2.6	2.4	1.8	0–2	1.5
	2.053	9113	9.7	7.9	5.8	4.3	2.9	2.6	1.9	5–10	8.6
	2.119	9085	9.9	6.7	4.0	2.7	1.8	1.7	1.2	5–10	18.8
	2.206	9101	8.5	5.1	2.6	1.7	1.0	0.8	0.6	5–10	40
	2.325	8883	9.8	8.2	6.3	4.7	3.2	2.7	1.8	5–10	12
	2.413	9212	8.1	6.6	4.6	3.4	2.2	1.8	1.1	5–10	15.8
	2.509	8879	12.1	8.9	5.7	4.0	2.5	2.1	1.4	5–10	7.2
	2.614	8847	15.6	10.6	6.8	4.9	3.2	2.8	1.8	2–5	2.8
	2.705	8986	10.5	7.9	5.3	3.8	2.5	2.1	1.5	5–10	8.6
	2.807	9212	9.3	7.0	4.7	3.4	2.3	2.0	1.5	5–10	13.5
	2.91	9085	10.2	7.8	5.2	3.6	2.4	2.1	1.5	5–10	12.2
	3.009	9403	10.8	8.1	5.3	3.5	2.2	1.8	1.2	5–10	12.6
	3.112	8581	23.7	15.6	8.3	5.1	3.2	3.0	2.2	0–2	0.3
	3.201	8597	28.8	18.0	8.8	4.8	2.7	2.4	1.5	0–2	0.2
	3.302	9026	13.2	9.6	5.5	3.3	1.8	1.3	0.8	5–10	6.1
	3.403	9252	6.8	5.9	4.8	4.0	2.8	2.5	1.7	5–10	24.3
	3.506	8962	17.1	9.9	4.4	2.2	1.0	0.7	0.4	2–5	3.8
	3.609	8847	10.3	6.2	3.3	2.2	1.5	1.3	0.9	5–10	17.1
	3.704	8887	20.7	14.4	8.4	5.3	3.1	2.6	1.7	0–2	0.6
	3.805	8859	28.3	16.7	7.9	4.5	2.5	2.2	1.4	0–2	0.2
	3.91	9117	10.2	5.8	3.5	2.3	1.4	1.0	0.6	5–10	21.7
	4.008	8843	16.4	10.7	6.1	4.1	2.7	2.2	1.4	2–5	2.1
	4.11	8811	20.3	10.8	4.9	2.8	1.5	1.3	0.7	0–2	1.3
	4.204	8958	16.2	10.3	5.8	3.8	2.4	2.0	1.4	2–5	2.3
	4.319	9105	10.5	6.3	4.8	3.8	2.6	2.4	1.7	5–10	12.3
	4.413	9073	7.7	4.5	2.8	1.9	1.1	1.0	0.7	5–10	40
	4.515	9236	4.2	1.5	0.9	0.5	0.3	0.3	0.2	5–10	17.8
	4.616	9129	8.9	5.2	4.1	3.3	2.4	2.3	1.7	5–10	17.8
	4.705	9069	10.8	5.7	3.4	1.9	1.1	0.7	0.3	5–10	17.7
	4.807	8946	18.1	11.6	6.8	4.7	3.2	3.0	2.1	0–2	1.6
	4.914	9141	12.1	8.2	5.8	4.2	2.7	2.3	1.6	5–10	8.4
	5.004	9034	13.1	8.1	5.2	3.4	2.1	1.6	0.9	5–10	6.8
	5.111	9022	14.9	8.5	5.3	3.5	2.1	1.7	1.0	2–5	3.9
	5.218	8835	19.9	12.5	6.4	3.9	2.3	1.9	1.2	0–2	0.8
	5.312	8902	17.9	11.1	6.5	4.2	2.7	2.3	1.6	2–5	1.5
	5.42	9049	10.0	5.6	3.6	2.6	1.6	1.4	0.9	5–10	23.8
	5.518	8914	17.3	9.7	5.5	3.8	2.6	2.3	1.6	2–5	2
	5.613	9085	13.2	7.1	4.5	3.3	2.3	2.0	1.5	5–10	8.3
	5.704	9034	10.8	5.7	4.1	3.2	2.2	1.9	1.3	5–10	16.2

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 171	5.815	8771	23.8	14.8	7.5	4.6	2.7	2.4	1.5	0–2	0.4
	5.914	8887	25.2	16.1	8.1	4.6	2.5	1.8	1.0	0–2	0.3
	6.019	8811	23.7	15.2	8.5	5.5	3.3	2.7	1.7	0–2	0.4
	6.118	8787	24.3	12.0	4.3	1.9	0.9	0.6	0.4	0–2	1.5
	6.213	8990	13.5	6.9	3.8	2.2	1.2	0.8	0.5	5–10	7.3
	6.321	8851	19.3	11.6	6.4	4.2	2.8	2.6	1.9	0–2	1.1
	6.432	8898	13.5	8.8	4.9	3.0	1.7	1.4	0.9	5–10	4.7
	6.509	8914	16.5	9.9	5.6	3.4	2.1	1.7	1.1	2–5	2.1
	6.613	8990	11.6	6.4	3.3	2.0	1.3	1.0	0.7	5–10	11.8
	6.711	8954	13.6	9.0	5.8	3.9	2.3	1.9	1.2	5–10	5.3
	6.803	8898	18.5	11.5	6.1	3.8	2.5	2.1	1.5	0–2	1.2
	6.91	8950	16.9	10.2	5.3	3.3	2.0	1.8	1.3	2–5	2
	7.004	8946	17.5	11.1	6.3	4.1	2.4	2.2	1.5	2–5	1.6
	7.105	8895	17.6	11.1	5.6	3.2	1.8	1.4	1.0	2–5	1.5
	7.207	8835	13.6	8.1	3.8	2.3	1.6	1.4	1.1	5–10	5.2
	7.303	9014	11.7	6.0	3.6	2.5	1.6	1.4	1.0	5–10	12.9
	7.411	8807	19.1	11.7	6.2	3.9	2.5	2.2	1.6	0–2	1
	7.503	8871	17.3	9.7	5.4	3.6	2.3	2.1	1.5	2–5	1.8
	7.605	9041	11.0	5.3	3.1	2.1	1.3	1.2	0.8	5–10	19.2
	7.706	8926	11.7	5.7	2.7	1.5	0.9	0.7	0.5	5–10	17
	7.804	8986	11.8	5.9	3.5	2.1	1.2	0.9	0.5	5–10	12
	7.908	8883	15.6	8.7	5.0	3.5	2.4	2.3	1.7	2–5	3.1
	8.016	9006	9.9	5.0	3.0	2.0	1.2	1.0	0.7	5–10	26.5
	8.111	8946	9.1	4.4	2.3	1.6	1.1	0.8	0.6	5–10	40
	8.204	8783	15.6	8.1	3.6	1.9	1.1	0.8	0.6	5–10	4.6
	8.311	8775	22.1	11.8	5.1	2.9	1.7	1.4	1.0	0–2	1
	8.411	8946	12.9	5.9	2.2	1.1	0.6	0.5	0.3	5–10	23.9
	8.506	8839	19.1	9.6	4.8	2.8	1.5	1.3	0.9	2–5	1.7
	8.61	8477	21.0	12.5	6.1	3.9	2.4	2.2	1.5	0–2	0.6
	8.707	8863	17.2	9.3	4.7	2.9	1.7	1.5	1.0	2–5	2.1
	8.813	8771	19.2	10.8	6.0	4.1	2.7	2.3	1.7	0–2	1.1
	8.917	8871	12.0	5.7	2.7	1.6	1.0	0.9	0.6	5–10	14
	9.033	9026	6.7	5.2	4.0	3.0	1.9	1.4	0.8	5–10	31
	9.113	8942	9.9	5.9	3.3	2.0	1.1	1.0	0.7	5–10	20.8
	9.21	8831	16.2	11.0	6.4	3.6	2.0	1.6	1.1	2–5	1.8
	9.313	8898	9.9	4.2	1.3	0.6	0.3	0.2	0.1	5–10	40
	9.416	8966	7.6	4.2	2.6	1.9	1.2	1.1	0.8	5–10	40
	9.506	8700	21.1	10.1	4.0	2.2	1.2	1.0	0.6	0–2	2.1
	9.608	8859	16.0	11.2	6.9	4.5	2.9	2.4	1.6	2–5	2.4
	9.716	8906	10.3	6.8	4.1	2.6	1.5	1.2	0.8	5–10	16.1
	9.805	8799	17.2	10.6	5.5	3.4	2.1	1.8	1.3	2–5	1.6
	9.903	8608	28.7	16.5	6.9	4.2	2.6	2.3	1.6	0–2	0.2
	10.016	8450	32.7	14.3	6.1	3.8	2.5	2.4	1.7	0–2	0.2
	10.111	8751	16.0	9.6	5.1	3.4	2.3	2.1	1.6	2–5	2.3
	10.209	8477	25.3	12.8	5.5	3.6	2.4	2.3	1.7	0–2	0.4
	10.319	8406	21.7	14.0	6.6	4.0	2.5	2.2	1.6	0–2	0.5
	10.408	8557	27.5	14.1	6.6	4.4	2.8	2.4	1.6	0–2	0.2

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
SH 171	10.507	8696	17.9	11.4	7.2	4.4	2.8	2.5	1.9	0–2	1.3
	10.612	8847	13.3	7.7	4.6	3.0	1.9	1.6	1.1	5–10	5.8
	10.702	8942	9.1	7.0	5.0	3.6	2.4	2.1	1.4	5–10	12.3
	10.807	8982	6.2	4.8	3.9	3.2	2.3	2.1	1.5	5–10	40
	10.912	8902	13.3	10.6	8.6	7.0	5.2	5.0	3.7	0–2	1.8
	11.003	8775	14.2	8.5	4.6	3.2	2.1	1.9	1.2	2–5	4.1
	11.121	8573	26.5	13.8	6.8	4.3	2.8	2.4	1.6	0–2	0.3
	11.206	8871	10.5	7.3	5.2	3.6	2.3	2.0	1.4	5–10	12.2
	11.321	8624	18.2	10.5	5.3	3.6	2.2	1.9	1.3	0–2	1.3
	11.422	9085	7.7	5.8	4.4	3.4	2.2	2.0	1.3	5–10	17
	11.51	8863	11.2	6.9	4.5	3.0	1.9	1.6	1.1	5–10	13.1
	11.613	8795	12.6	7.8	5.1	3.4	2.3	2.0	1.4	5–10	7.8
	11.71	8660	16.1	8.9	4.9	3.4	2.5	2.2	1.7	2–5	2.4
	11.809	8708	15.2	9.2	5.2	3.5	2.2	2.1	1.5	2–5	2.8
	11.924	8767	13.5	9.3	5.0	3.1	1.8	1.5	1.1	5–10	3.9
	12.021	8744	14.4	10.1	5.1	3.1	1.9	1.7	1.2	2–5	2.9
FM 2257	0	9064	12.7	10.1	6.6	4.1	2.3	1.6	0.9	10+	11.4
	0.109	8703	29.1	12.7	4.7	2.6	1.6	1.5	1.1	0–2	0.2
	0.204	9056	7.8	6.1	4.1	2.9	1.9	1.7	1.2	10+	24.9
	0.311	9029	9.6	7.8	5.3	3.5	2.2	1.9	1.4	10+	15.9
	0.416	8989	12.6	9.7	6.1	3.7	2.1	1.7	1.1	10+	15
	0.504	9017	14.4	10.0	5.5	3.0	1.5	1.0	0.5	10+	16
	0.598	8981	18.1	12.4	7.1	4.3	2.6	2.2	1.6	5–10	0.8
	0.707	8993	14.5	9.4	5.3	3.0	1.8	1.5	1.1	10+	11.6
	0.801	8977	16.5	10.9	6.2	3.8	2.3	2.0	1.5	5–10	1.2
	0.901	9160	8.4	6.8	5.0	3.5	2.4	2.0	1.4	10+	14.5
	1	9076	9.5	8.2	6.1	4.4	3.0	2.7	1.9	10+	5.3
	1.108	9021	11.2	9.1	6.2	4.3	2.9	2.7	2.1	10+	13
	1.2	8961	17.8	11.5	5.9	3.3	2.0	1.9	1.4	5–10	5
	1.301	8949	16.0	11.4	6.6	4.1	2.6	2.2	1.5	5–10	5
	1.404	9128	7.7	5.9	3.7	2.3	1.3	0.9	0.5	10+	31.3
	1.519	9044	14.2	8.2	3.3	1.5	0.7	0.5	0.4	10+	13.8
	1.6	8997	11.6	6.3	2.8	1.3	0.6	0.5	0.4	10+	17.7
	1.7	9021	11.7	8.1	4.3	2.5	1.5	1.4	1.1	10+	13.7
	1.808	9072	12.2	8.9	5.4	3.4	2.0	1.5	1.0	10+	12
	1.926	8874	17.9	10.3	4.3	2.1	1.3	1.1	0.8	10+	14
	2.031	8941	11.8	9.5	6.4	4.0	2.4	1.7	1.1	10+	15
	2.108	8878	21.1	13.2	6.1	2.9	1.6	1.4	1.1	5–10	4.7
	2.208	8453	41.3	23.6	10.9	5.4	2.9	2.2	1.7	0–2	0
	2.309	8862	27.8	13.9	5.1	2.1	1.1	1.0	0.8	2–5	0.3
	2.416	9001	16.5	12.2	7.2	4.2	2.6	2.1	1.6	5–10	7.9
	2.505	8905	24.0	17.8	10.4	6.0	3.5	2.6	1.8	2–5	0.3
	2.602	8874	29.2	16.5	7.6	4.1	2.1	1.6	1.0	0–2	0.2
	2.716	9064	9.4	7.7	5.3	3.6	2.2	1.8	1.2	10+	6.2
	2.812	8929	24.3	14.6	6.8	3.5	2.0	1.7	1.2	2–5	0.4
	2.903	9068	12.0	9.4	6.4	4.2	2.7	2.2	1.6	10+	11.5
	3.008	9017	21.0	14.3	8.0	4.5	2.6	2.2	1.6	2–5	0.6

Table 58. Remaining Life Analysis Results (Fort Worth District) (continued).

Road	FWD Station	FWD Load	FWD Measured Deflection (mils)							Remaining Life (yrs)	
			R1	R2	R3	R4	R5	R6	R7	MODULUS	OTRA
FM 2257	3.116	8870	23.4	15.3	7.8	4.3	2.7	2.3	1.7	2–5	0.5
	3.225	8921	16.9	12.3	7.6	4.8	3.0	2.4	1.7	5–10	8.7
	3.304	8909	16.7	11.6	6.6	3.6	1.9	1.1	0.6	10+	11.1
	3.409	9013	14.8	10.0	5.9	3.7	2.2	1.8	1.2	10+	12.4
	3.524	9048	10.8	8.1	5.3	3.5	2.1	1.7	1.2	10+	13.9
	3.576	8989	18.2	12.2	6.7	3.9	2.3	1.7	1.2	5–10	10.9

APPENDIX B. TABULAR CRASH DATA

Table 59. Crash Rates on Sample Lubbock District Rural Collectors.

Year	Crashes per 100 Million VMT			
	Texas	District	Visited Corridors	Control Corridors
2003	91.8	63.5	60.5	49.3
2004	90.5	60.5	69.1	52.2
2005	93.2	60.1	33.1	62.6
2006	92.2	59.6	46.6	78.0
2007	93.8	69.3	54.3	45.8
2008	121.9	70.9	14.7	49.2
2009	117.4	70.5	73.4	36.9

Table 60. Crashes on Sample Lubbock District Rural Collectors (per 100 Miles).

Count type	Corridor type	2003	2004	2005	2006	2007	2008	2009
Total crashes	Visited corridors	8.7	10.8	5.4	6.7	8.1	2.0	10.1
	Control corridors	5.0	6.3	7.5	8.8	5.0	5.0	3.8
	District wide	11.3	11.5	11.6	10.9	11.5	10.8	10.8
Commercial vehicle crashes	Visited corridors	0.0	0.0	0.0	0.7	1.3	0.7	0.0
	Control corridors	0.0	0.0	0.0	0.0	0.0	1.3	0.0
	District wide	0.0	0.0	0.0	0.4	0.8	1.4	1.1
Severe crashes (fatal, injury)	Visited corridors	4.7	6.0	2.7	2.7	4.7	0.7	4.7
	Control corridors	0.0	1.3	3.8	7.5	2.5	5.0	2.5
	District wide	5.4	5.4	5.6	4.7	4.5	4.6	4.6
Intersection-related crashes	Visited corridors	1.3	4.0	0.7	1.3	1.3	1.3	1.3
	Control corridors	1.3	1.3	0.0	1.3	0.0	0.0	1.3
	District wide	4.3	4.0	4.0	3.2	3.5	3.1	3.0
Driveway-related crashes	Visited corridors	0.0	0.0	0.0	0.0	0.0	0.7	0.0
	Control corridors	0.0	2.5	0.0	1.3	0.0	1.3	1.3
	District wide	0.7	0.5	0.8	0.7	0.4	0.6	0.5

Table 61. Crash Rates on Sample Abilene District Rural Collectors.

Year	Crashes per 100 Million VMT			
	Texas	**District**	**Visited Corridors**	**Control Corridors**
2003	91.8	89.1	102.0	0.0
2004	90.5	78.2	205.1	100.4
2005	93.2	83.5	205.3	33.5
2006	92.2	79.5	134.0	0.0
2007	93.8	94.7	195.4	125.0
2008	121.9	91.6	144.3	36.8
2009	117.4	82.7	72.2	0.0

Table 62. Crashes on Sample Abilene District Rural Collectors (per 100 Miles).

Count type	Corridor type	2003	2004	2005	2006	2007	2008	2009
Total crashes	Visited corridors	12.4	26.9	26.9	18.6	26.9	20.7	10.4
	Control corridors	0.0	8.5	2.8	0.0	8.5	2.8	0.0
	District wide	13.3	12.5	13.5	11.8	14.7	13.8	12.4
Commercial vehicle crashes	Visited corridors	0.0	0.0	0.0	0.0	6.2	2.1	2.1
	Control corridors	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	District wide	0.0	0.0	0.0	0.5	1.1	1.8	0.8
Severe crashes (fatal, injury)	Visited corridors	6.2	14.5	14.5	4.1	10.4	4.1	6.2
	Control corridors	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	District wide	6.2	5.3	6.0	5.1	6.3	6.1	4.2
Intersection-related crashes	Visited corridors	0.0	4.1	8.3	8.3	8.3	6.2	0.0
	Control corridors	0.0	0.0	0.0	0.0	2.8	0.0	0.0
	District wide	3.1	3.6	3.7	3.3	3.7	2.9	2.9
Driveway-related crashes	Visited corridors	0.0	2.1	2.1	0.0	0.0	0.0	0.0
	Control corridors	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	District wide	0.6	0.4	0.9	0.4	0.5	0.7	0.5

Table 63. Crash Rates on Sample Fort Worth District Rural Collectors.

Year	Crashes per 100 Million VMT			
	Texas	District	Visited Corridors	Control Corridors
2003	91.8	101.3	164.2	104.4
2004	90.5	104.5	143.9	103.3
2005	93.2	102.3	147.7	96.8
2006	92.2	99.7	163.7	151.2
2007	93.8	100.6	129.5	106.5
2008	121.9	122.2	144.5	132.9
2009	117.4	107.4	102.4	151.9

Table 64. Crashes on Sample Fort Worth District Rural Collectors (per 100 Miles).

Count type	Corridor type	2003	2004	2005	2006	2007	2008	2009
Total crashes	Visited corridors	125.6	110.0	137.8	148.9	161.1	167.8	118.9
	Control corridors	43.4	43.4	43.4	69.1	51.4	56.3	64.3
	District wide	82.5	86.7	90.8	92.3	96.9	101.4	89.1
Commercial vehicle crashes	Visited corridors	0.0	0.0	0.0	14.4	26.7	50.0	21.1
	Control corridors	0.0	0.0	0.0	0.0	0.0	4.8	8.0
	District wide	0.0	0.0	0.0	4.8	6.1	16.6	8.0
Severe crashes (fatal, injury)	Visited corridors	57.8	43.3	54.4	58.9	65.6	54.4	53.3
	Control corridors	20.9	16.1	14.5	22.5	19.3	20.9	17.7
	District wide	34.0	33.9	35.2	35.0	33.3	38.4	33.0
Intersection-related crashes	Visited corridors	37.8	24.4	37.8	37.8	55.6	61.1	28.9
	Control corridors	8.0	11.3	6.4	11.3	11.3	11.3	12.9
	District wide	25.3	27.3	28.2	26.1	30.1	30.4	27.6
Driveway-related crashes	Visited corridors	11.1	10.0	11.1	18.9	6.7	12.2	4.4
	Control corridors	0.0	3.2	0.0	4.8	3.2	11.3	3.2
	District wide	7.0	5.9	6.5	7.7	7.1	8.3	6.5

Table 65. Crash Rates on Sample Fort Worth District Rural Minor Arterials.

Year	Crashes per 100 Million VMT			
	Texas	District	Visited Corridors	Control Corridors
2003	71.8	72.6	21.2	102.2
2004	71.0	72.1	94.2	92.1
2005	72.1	80.4	87.0	97.9
2006	69.0	74.7	30.6	96.2
2007	68.5	87.4	44.2	74.0
2008	82.7	81.3	62.9	71.4
2009	79.8	85.0	68.7	74.8

Table 66. Crashes on Sample Fort Worth District Rural Minor Arterials (per 100 Miles).

Count type	Corridor type	2003	2004	2005	2006	2007	2008	2009
Total crashes	Visited corridors	50.8	203.4	203.4	101.7	118.6	186.4	203.4
	Control corridors	190.2	173.8	186.9	183.6	147.5	134.4	141.0
	District wide	127.5	129.8	146.3	142.2	168.6	148.0	154.7
Commercial vehicle crashes	Visited corridors	0.0	0.0	0.0	0.0	16.9	33.9	16.9
	Control corridors	0.0	0.0	0.0	0.0	9.8	13.1	23.0
	District wide	0.0	0.0	0.0	4.7	9.4	23.1	18.8
Severe crashes (fatal, injury)	Visited corridors	0.0	101.7	67.8	33.9	67.8	84.7	84.7
	Control corridors	68.9	68.9	72.1	75.4	59.0	68.9	62.3
	District wide	55.8	54.0	61.7	54.6	62.3	60.1	55.2
Intersection-related crashes	Visited corridors	0.0	16.9	67.8	50.8	16.9	16.9	50.8
	Control corridors	39.3	16.4	49.2	29.5	36.1	16.4	13.1
	District wide	35.8	29.4	42.3	45.2	42.9	43.1	33.4
Driveway-related crashes	Visited corridors	33.9	84.7	16.9	16.9	16.9	118.6	33.9
	Control corridors	13.1	0.0	13.1	6.6	13.1	13.1	13.1
	District wide	7.6	8.2	7.0	7.0	11.7	9.7	11.5