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THE UNIVERSITY OF TEXAS AT AUSTIN

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IMPACTS OF ENERGY DEVELOPMENTS ON THE TEXAS TRANSPORTATION SYSTEM INFRASTRUCTURE

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16. Abstract

Texas's energy sector has a critical impact—historically and currently—on both the state economy and the Texas transportation system. The state's various transportation modes, including rail, highways, pipelines, and ports, form a system that supports the energy sector in a number of ways. Examples include the (a) movement of various components during the construction and implementation of the energy source (e.g., wind turbines and solar farms), (b) provision of enabling infrastructure (e.g., transmission lines), and (c) movement of the intermediate and final products in some energy supply chains (e.g., low sulfur mid-west coal by Class 1 unit trains to the major coal burning plants in Texas). It is thus critical that TxDOT develop a better understanding of the current and future impacts of the energy sector on Texas's transportation system, as well as quantify these impacts to ensure both adequate maintenance and its future sustainability.

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Chapter 1. Introduction

Texas has been known as an energy state ever since the Lucas Number 1 well blew mud, gas, and oil 200 feet into the air at Spindletop on January 10, 1901. Since then, the oil and gas industry has contributed greatly to the state's Gross Domestic Product (GDP). From the oil discoveries in North, East, and West Texas during the early 1900s to recent natural gas discoveries in the Barnett Shale region of Arlington and Fort Worth, the Haynesville Shale region of East Texas, and the Eagle Ford Shale of South Texas, the oil and natural gas industries have been a significant factor in Texas's economic success.

Today, Texas produces 30% of the natural gas consumed in the U.S. and accounts for 19% of total U.S. oil production (Governor's Competitiveness Council, 2008). At the same time, coal-generated power plants produce a significant share of the electricity in the state. More than half of the coal feedstock is low sulfur Wyoming coal that is brought to the state by Union Pacific (UP) and Burlington Northern Santa Fe (BNSF) on long, heavy unit trains. Increasing concerns over energy affordability, air quality, and carbon emissions have also resulted in the Texas legislature adopting policies that promote the generation of renewable energies. Texas is now the number one producer of wind energy in the U.S., with a rated capacity of approximately 10,000 megawatts (MW) installed in West Texas and the Texas Panhandle. Other renewable energy sources, such as biomass electricity generation, biofuel production, solar energy, and geothermal energy are also being promoted in different regions of the state.

The emphasis on renewable energy sources has changed the economic and demographic profile of the state in the last decade. Historically rural and agricultural regions, such as the Texas Panhandle, have become a locus for the development of wind farms and biofuel plants. Similarly, West Texas—from Abilene to El Paso—has seen an extraordinary amount of wind farm development. Finally, high oil prices resulted in a resurgence of oil production activity in the Permian Basin, while the Barnett Shale area is now producing over 3.75 billion cubic feet of natural gas per day and the Haynesville Shale area is expected to be one of the largest producers of natural gas in the U.S. by 2015 (Chesapeake Energy, ND).

The energy sector has placed significant demands on Texas's transportation system. The oil and gas industry, for example, requires the movement of equipment and water to the drilling sites, and brine water from the sites. This movement has raised concerns about the damage done by trucks and has resulted in many cities requiring payment bonds from energy companies drilling in, for example, the Barnett Shale area to maintain the integrity of the roadway infrastructure. Similarly, rural roads in West Texas and the Texas Panhandle are experiencing an increased number of oversized and overweight (OS/OW) truck traffic generated by the development of wind farms. Both the provision/construction of the enabling infrastructure and the daily operations of the different energy industries impact Texas's transportation infrastructure. It is thus imperative to understand how Texas's transportation system serves the energy sector, how the sector impacts the transportation system, and the future transportation needs of the energy sector.

The objective of this research study were to (a) illustrate and quantify the impacts imposed by the energy sector on Texas's transportation system and (b) identify key energy demand indicators by energy source that TxDOT can track in an effort to anticipate the associated future transportation impacts on Texas's transportation system. To accomplish these objectives, the Texas energy sector must first be understood. The next section of this report provides a detailed overview of Texas's energy sector. Subsequent chapters describe how Texas's energy sector uses the transportation system and quantifies the impact imposed by the energy sector on Texas's road infrastructure. However, also important is understanding what the future holds: which industries within the energy sector are expected to grow, which industries are expected to decline, and how Texas's transportation system could be impacted in the future. TxDOT Technical Report 0-6513-1B, the companion to this report, develops four energy scenarios for Texas that reflect different assumptions and outcomes for Texas's future energy sector and the associated impacts on Texas's transportation system.

1.1 Texas's Energy Sector: An Overview

Texas's energy sector consists of the following industries:

- oil,
- natural gas,
- coal,
- wind,
- bioenergy (bio-fuels and biomass),
- solar, and
- geothermal.

As mentioned earlier, the energy sector is a significant contributor to the Texas economy. In 2005, mining (which is mostly oil and gas extraction) accounted for $40.13 billion (in constant year 2000 dollars) of the state's GDP and in 2006 it was estimated that Texas's energy sector employed nearly 375,000 people who earned more than $35 billion in wages (Texas Comptroller of Public Accounts, 2008). The energy sector is currently dominated by fossil fuels. However, state and federal concern over air quality, carbon emissions, energy independence, and affordability have resulted in various legislative initiatives to support renewable energies. Some of this legislation includes passage of the following:

- Texas Senate Bill 20 in 2005. The state legislature increased the goal of Texas's Renewable Portfolio Standard to 5,880 MW by 2015 and to 10,000 MW in renewable energy capacity by 2025. The Texas legislature also mandated that 500 MW of the 2015 goal has to come from non-wind resources (State Energy Conservation Office, ND).
- Texas House Bill 1090 in 2007, which established incentives for the development of biomass energy in Texas.
- The Federal Energy Independence and Security Act in 2007, which mandated higher levels of ethanol and biodiesel blending—increasing production of ethanol to 9 billion gallons in 2008.
- Various state and federal tax incentives for blenders of ethanol and biodiesel (State Energy Conservation Office, ND).

These legislative initiatives have acted as an impetus for the accelerated development of many renewable energy industries.

Although the Texas economy has diversified over the past two to three decades, energy remains an important contributor to the Texas economy today. Furthermore, the energy sector is also anticipated to continue to be an important contributor to the Texas economy due to three significant factors:

(1) drilling for oil in the Permian Basin spurred by high oil prices,

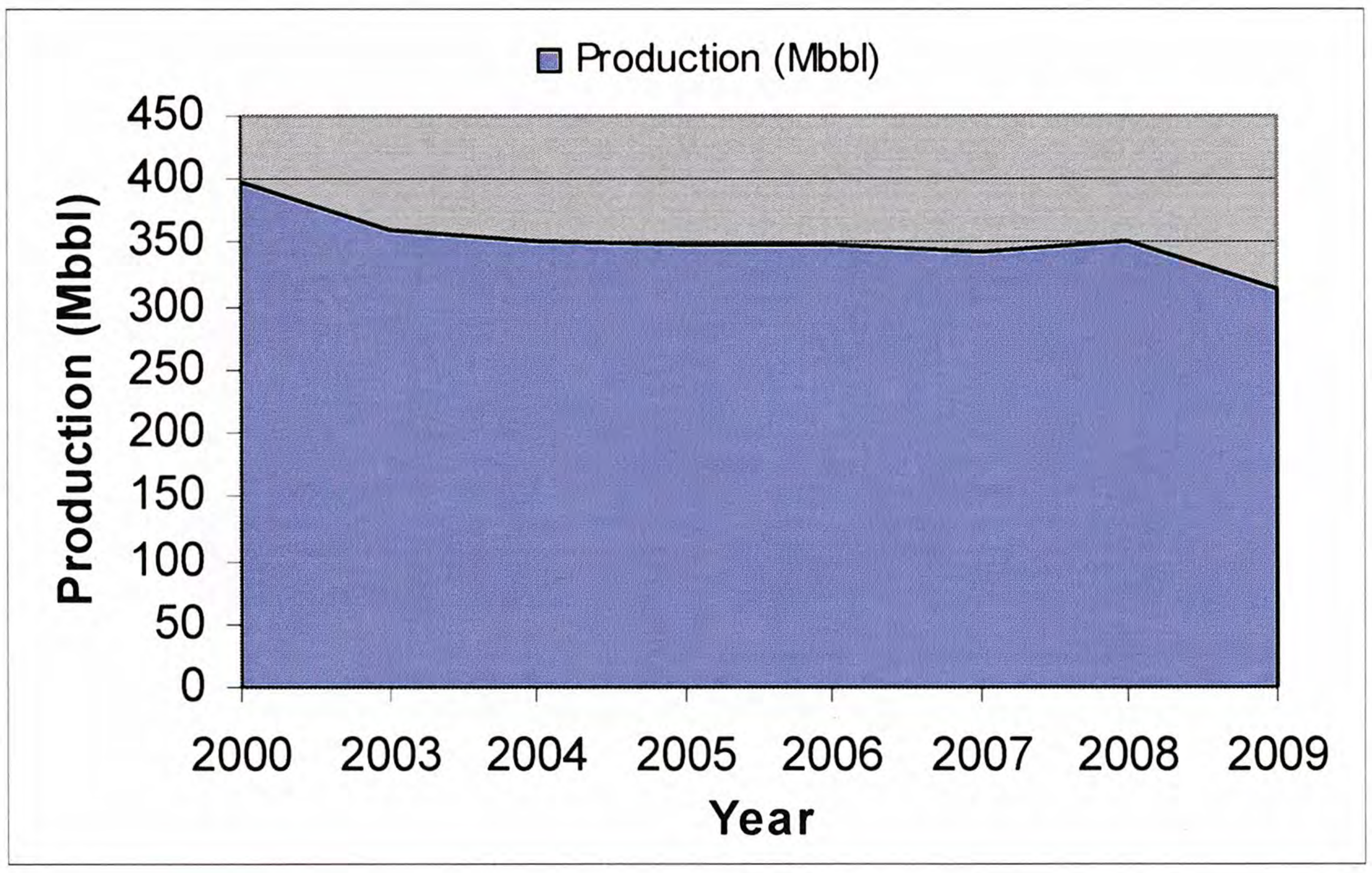
(2) drilling for natural gas to meet the state's growing energy demands, and

(3) the emergence of a diverse renewable energy sector, which will stimulate growth of the energy market.

The remainder of this chapter highlights key elements of Texas's energy industries.

1.1.1 Oil Production in Texas

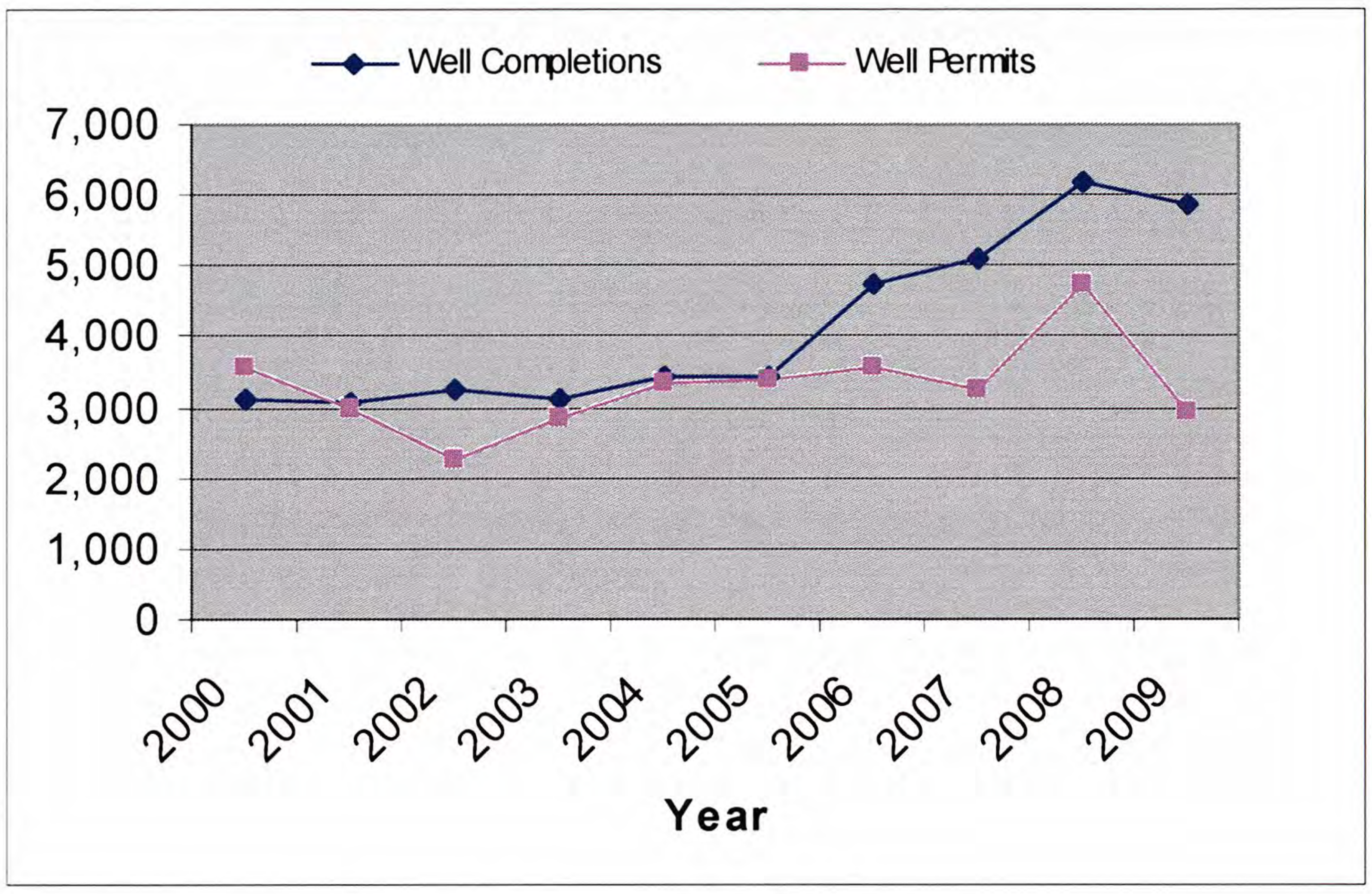
Oil production has been a significant contributor to Texas's economy for over 100 years. Although Texas is no longer the largest producer of oil in the U.S., it still accounts for 19% of total U.S. oil production. A review of the Texas Railroad Commission (RRC) records indicated that overall oil production in the state has been steady at around 350 Mbbl per year for the last decade (RRC, 2010).



Source: RRC, 2010

Figure 1.1: Oil Production in Texas

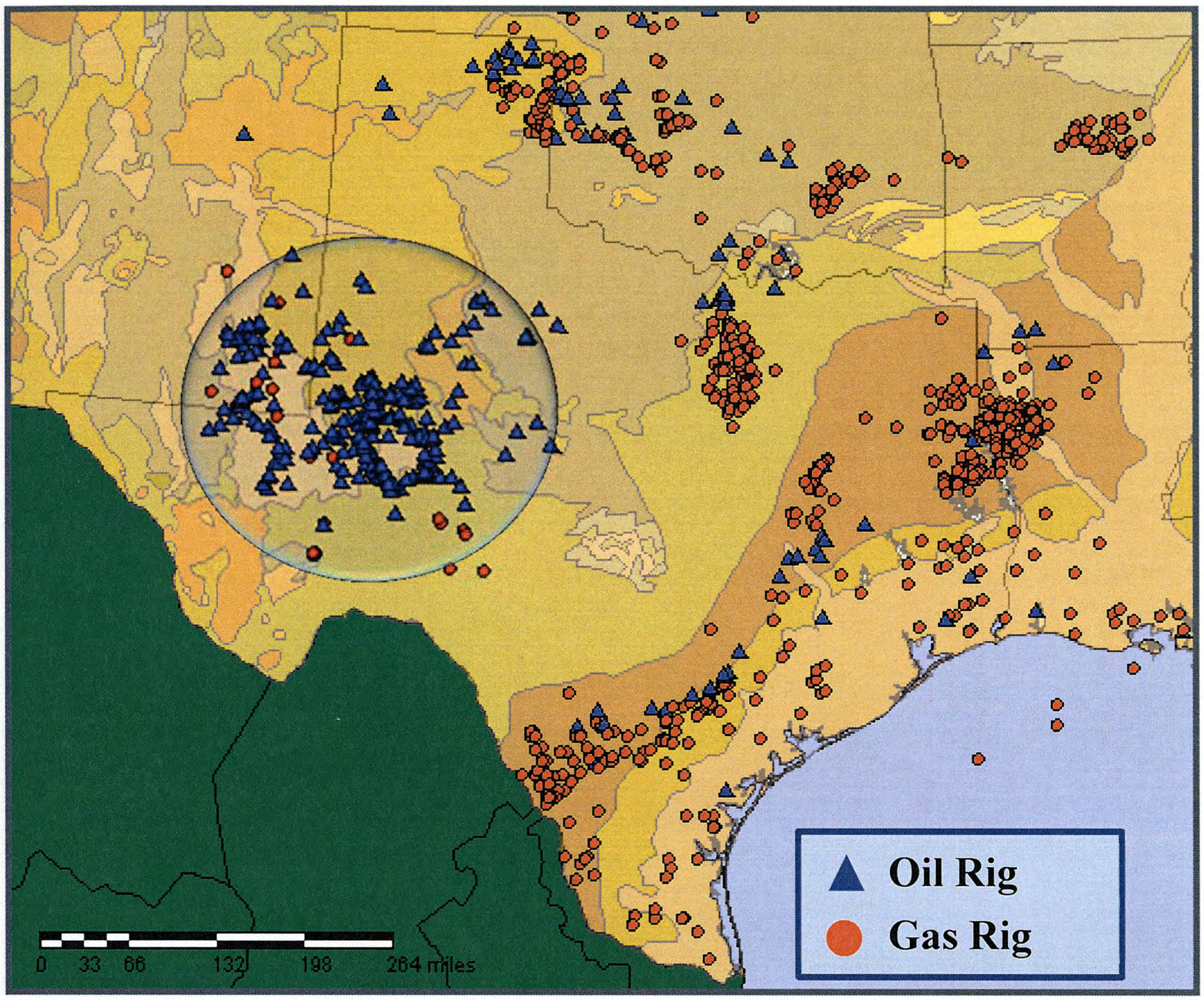
A review of well data summary logs also indicated that exploration for oil in Texas continues as new permits are issued every year and new wells are completed (see Figure 1.2).



Source: RRC, 2010

Figure 1.2: Oil Well Completions and Permits in Texas

To develop a better understanding of where in Texas most of the exploration occurs, Baker Hughes Investor Relations offers a comprehensive map of rotary rig counts in the U.S. A rotary rig is a derrick equipped with rotary drilling equipment used for drilling new wells or sidetracking existing ones. Rotary rigs are important for the exploration, development, and production of oil and natural gas. They can therefore serve as an indicator of oil and natural gas activity within a specific area. Figure 1.3 presents a map of active rotary rigs in Texas. The blue triangles represent rotary rigs actively drilling for oil and red circles represent rotary rigs actively drilling for natural gas.

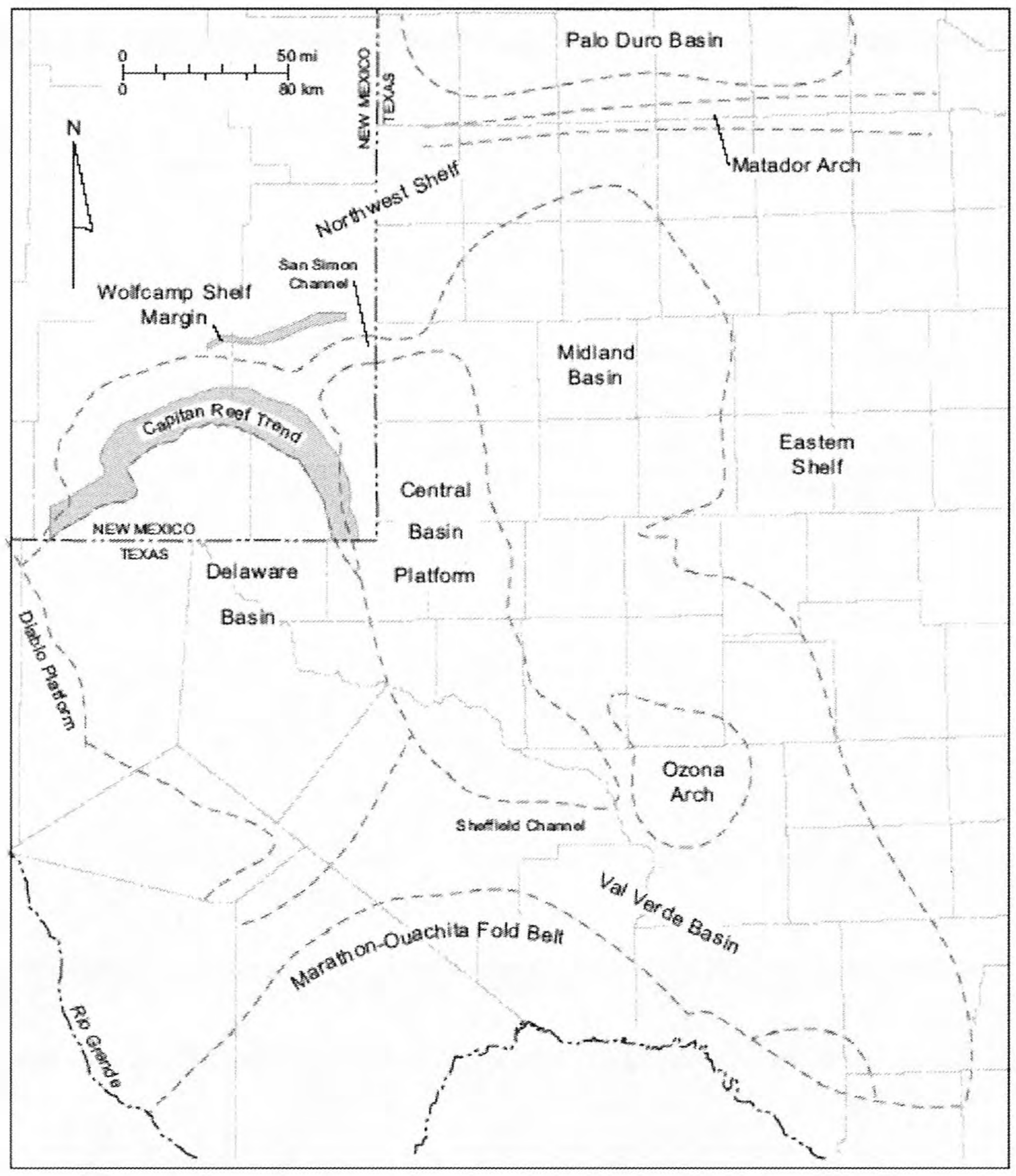


Source: Baker Hughes Investor Relations—Accessed June 2010

Figure 1.3: Oil Activity in Texas

Figure 1.3 makes evident that most of the oil activity in the state in June 2010 was concentrated in the Permian Basin—more specifically in Andrews, Hamlin, Howard, Ector, Midland, Upton, and Reagan counties.

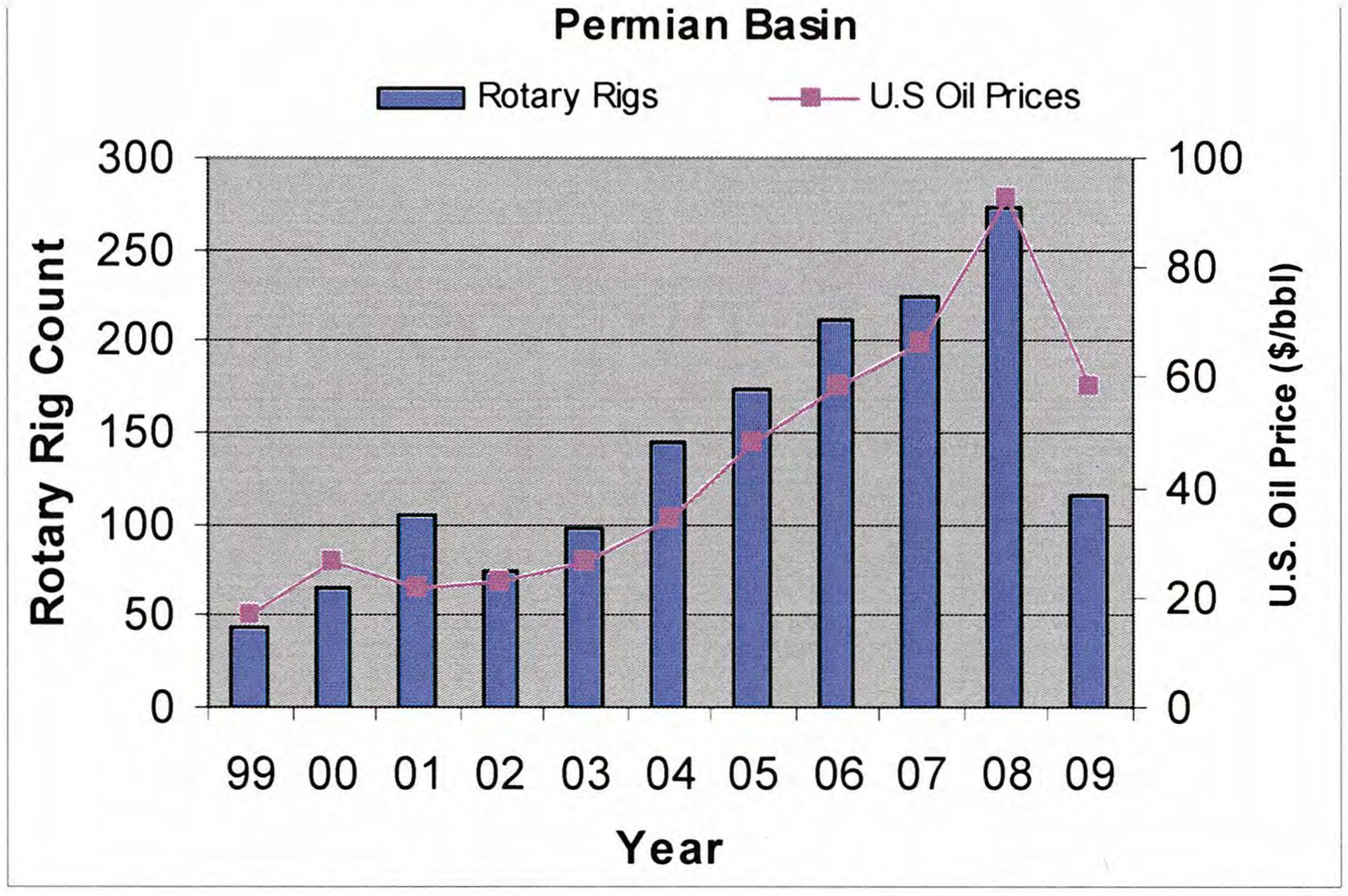
The Permian Basin is one of the largest oil reserves in the U.S. It covers a significant area of West Texas and comprises several plays. Figure 1.4 illustrates the extent of the area and the various oil producing regions within.



Source: Bureau of Economic Geology, 2002

Figure 1.4: Permian Basin

The Permian Basin is estimated to still hold about 30 billion barrels (Bbbl) (4.77 x 10^9 m^3) of mobile oil and 45 Bbbl (7.15 x 10^9 m^3) of residual oil—about 22% of the proved U.S. oil reserves (Dutton, S.P, 2002). However, because most of the oil requires advanced extraction techniques for procurement, drilling for oil becomes expensive in the Permian Basin and oil activity is largely a function of the oil price. For example, when the oil market collapsed in 1997–98 and oil prices fell below $10 per barrel, only 43 rigs were active in the Permian Basin. In 2008, when oil prices reached a record high of $145 per barrel, 272 rotary rigs were in operation (PBPA, March 2009). Figure 1.5 illustrates how the activity in the Permian Basin has changed over the years with the price of oil per barrel.

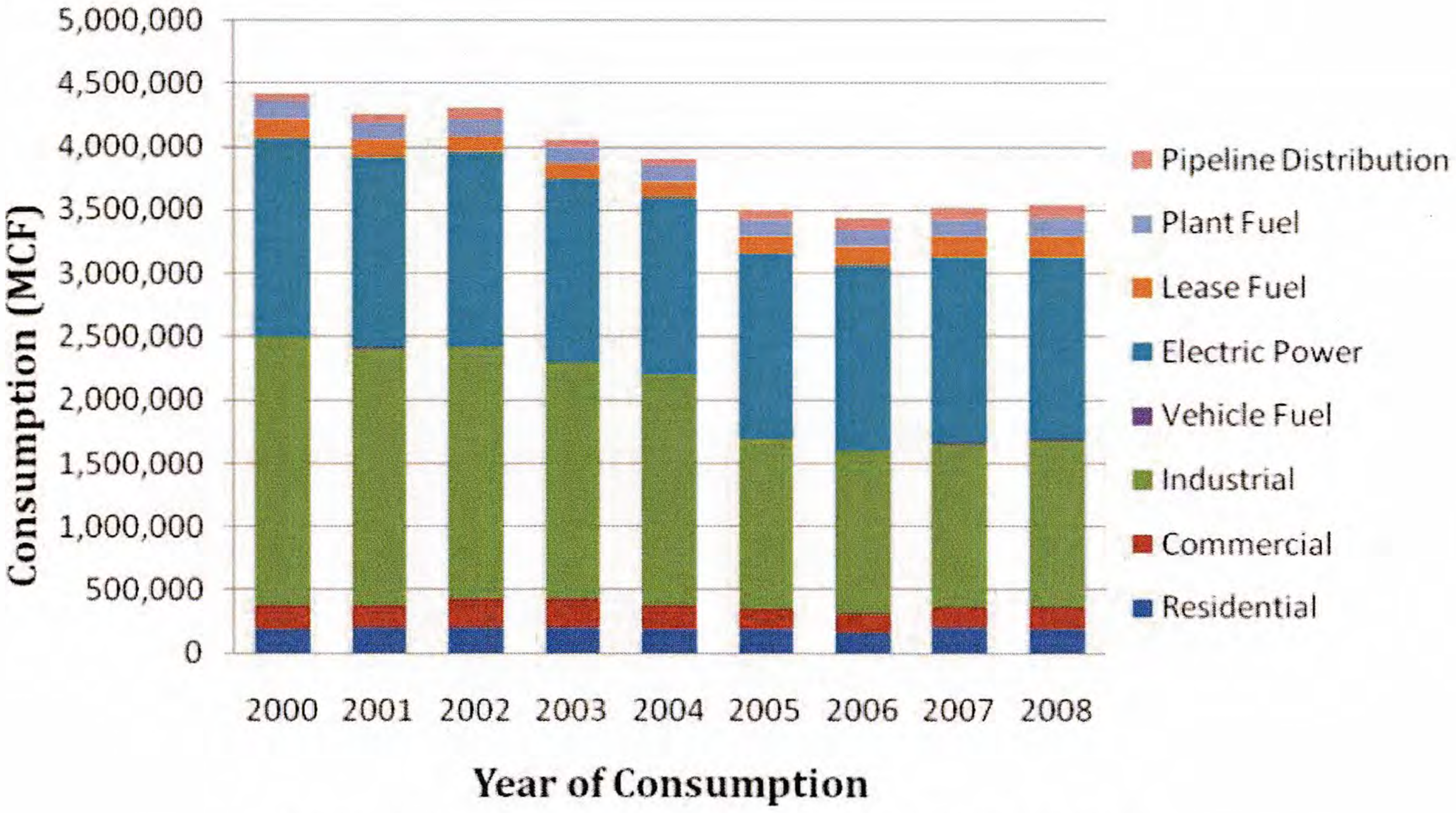


Source: Baker Hughes, PBPA, U.S. Energy Information Administration

Figure 1.5: Activity in the Permian Basin Based on Rotary Rig Counts

1.1.2 Natural Gas Development in Texas

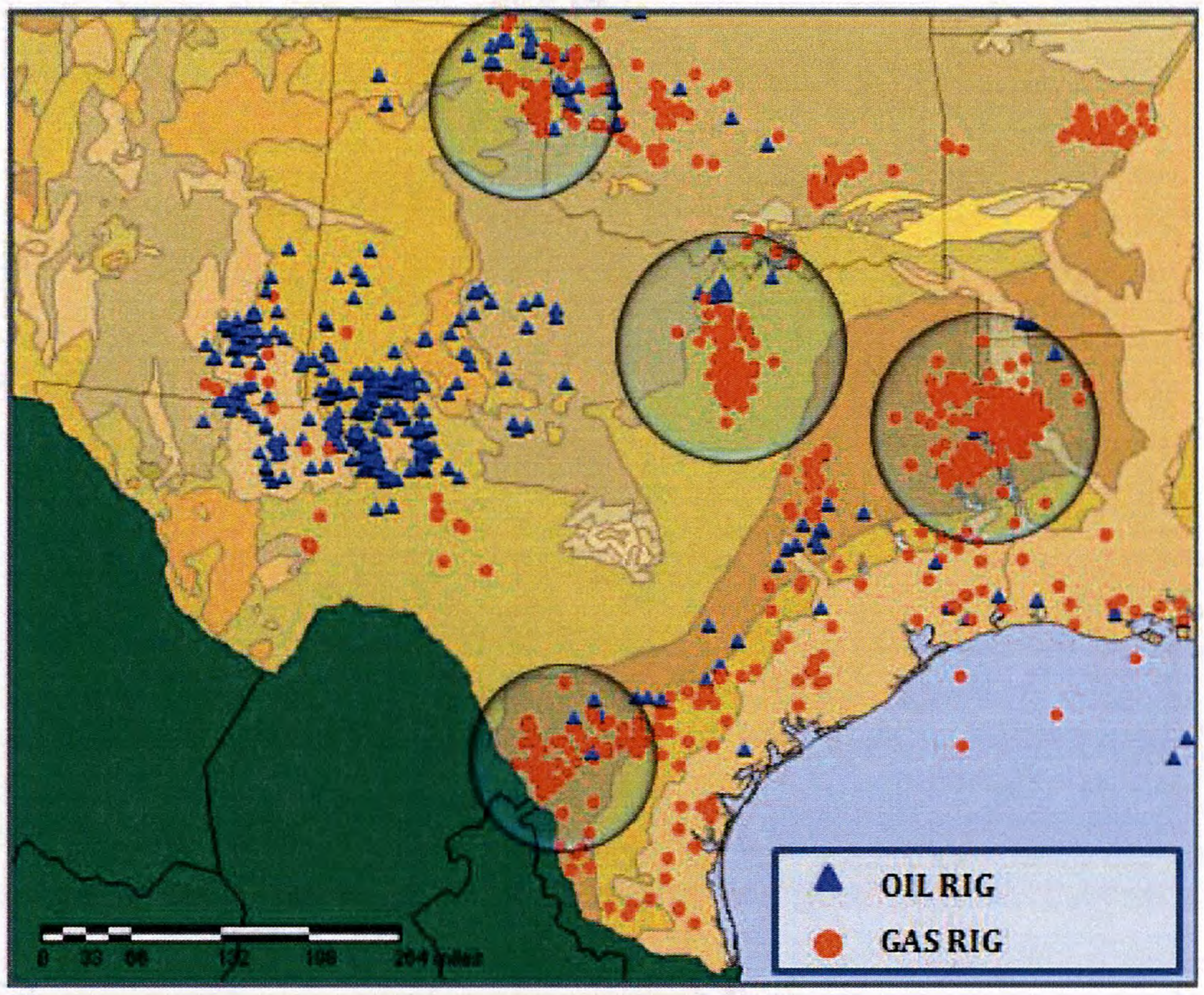
Texas is one of the leading producers of natural gas in the U.S., responsible for approximately 25% of total domestic natural gas production. Currently, Texas has over 75,000 active natural gas wells (Combs, 2008). Natural gas is used for many different purposes: 1) electric power generation, 2) commercial and residential consumption for heating, air-conditioning, cooking, and other appliances, and 3) industrial consumption for manufacturing processes and mining operations. A small percentage of natural gas is also used as a CNG/LNG vehicle fuel, and for power generation at well sites, compressor stations, and natural gas processing plants. Figure 1.6 illustrates Texas natural gas uses over the past decade, and indicates that the industrial sector consumes most natural gas for electric power generation.



Source: U.S. Energy Information Administration

Figure 1.6: Natural Gas Consumption by Sector in Texas

Although natural gas is mined throughout the state, there are certain areas that have significantly higher concentrations of hydrocarbons and hence are the major focus points for natural gas activity. Figure 1.7 presents information on rotary rig counts in June 2010 from Baker Hughes. This is a good indicator of natural gas activity in the state. The blue triangles represent rotary rigs actively drilling for oil and the red circles represent rotary rigs actively drilling for natural gas.



Source: Baker Hughes Investor Relations- Accessed June 2010

Figure 1.7: Oil and Natural Gas Activity in Texas

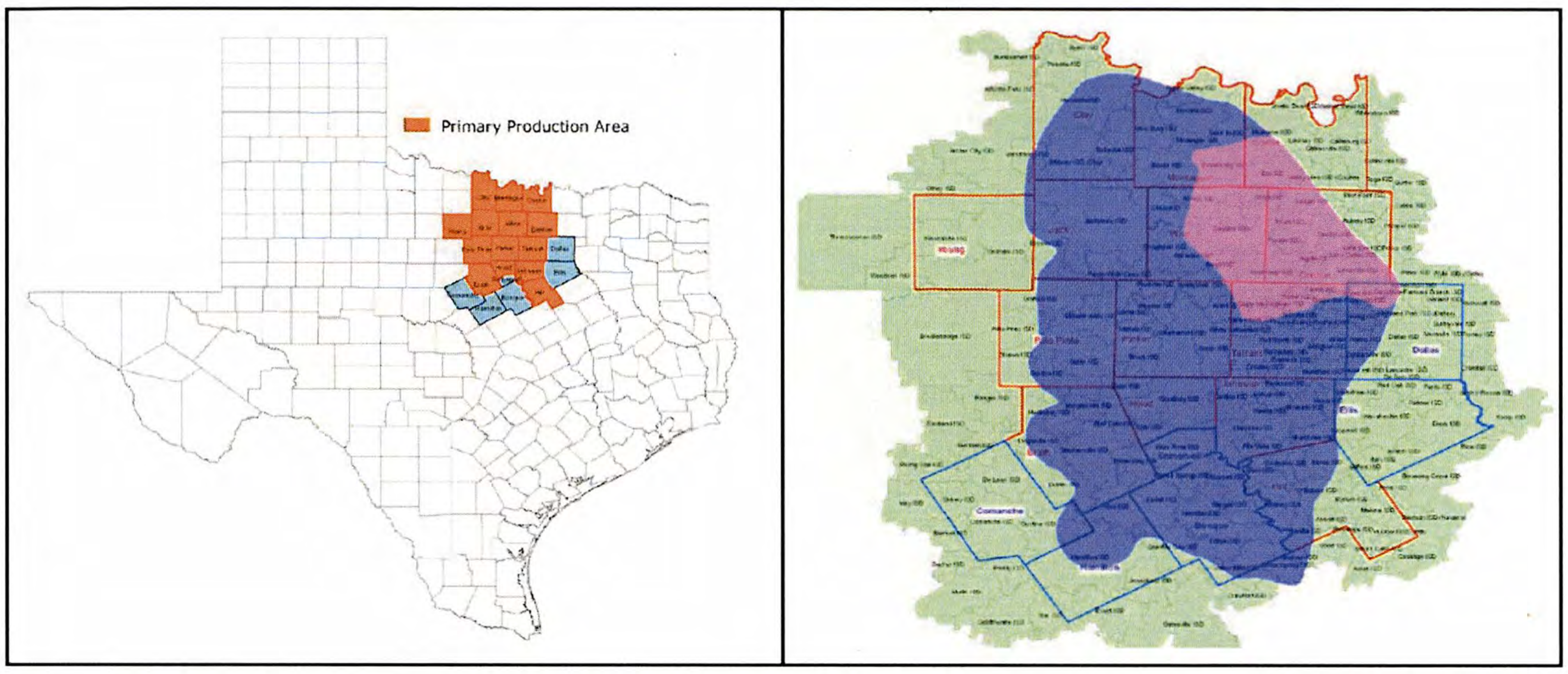
As shown in Figure 1.7, Texas has four main areas of natural gas:

- Anadarko Basin in the Texas Panhandle stretching into Oklahoma,
- the Barnett Shale in the Dallas-Fort Worth-Arlington region,
- Bossier/Haynesville Shale of East Texas stretching into Louisiana, and
- the geo-pressured Gulf Coast region stretching from Webb to Anderson County.

The following sections provide an overview of the Barnett Shale, Bossier/Haynesville Shale, and Eagle Ford Shale natural gas fields.

1.1.2.1 The Barnett Shale

The Barnett Shale area is a 19-county region of rapidly increasing natural gas production. It covers Clay, Cooke, Denton, Erath, Hill, Hood, Jack, Johnson, Montague, Palo Pinto, Parker, Tarrant, Wise, Young, Bosque, Comanche, Dallas, Somervell, and Hamilton counties (Barnett Shale Energy Education Council, ND). These counties are illustrated in Figure 1.8.

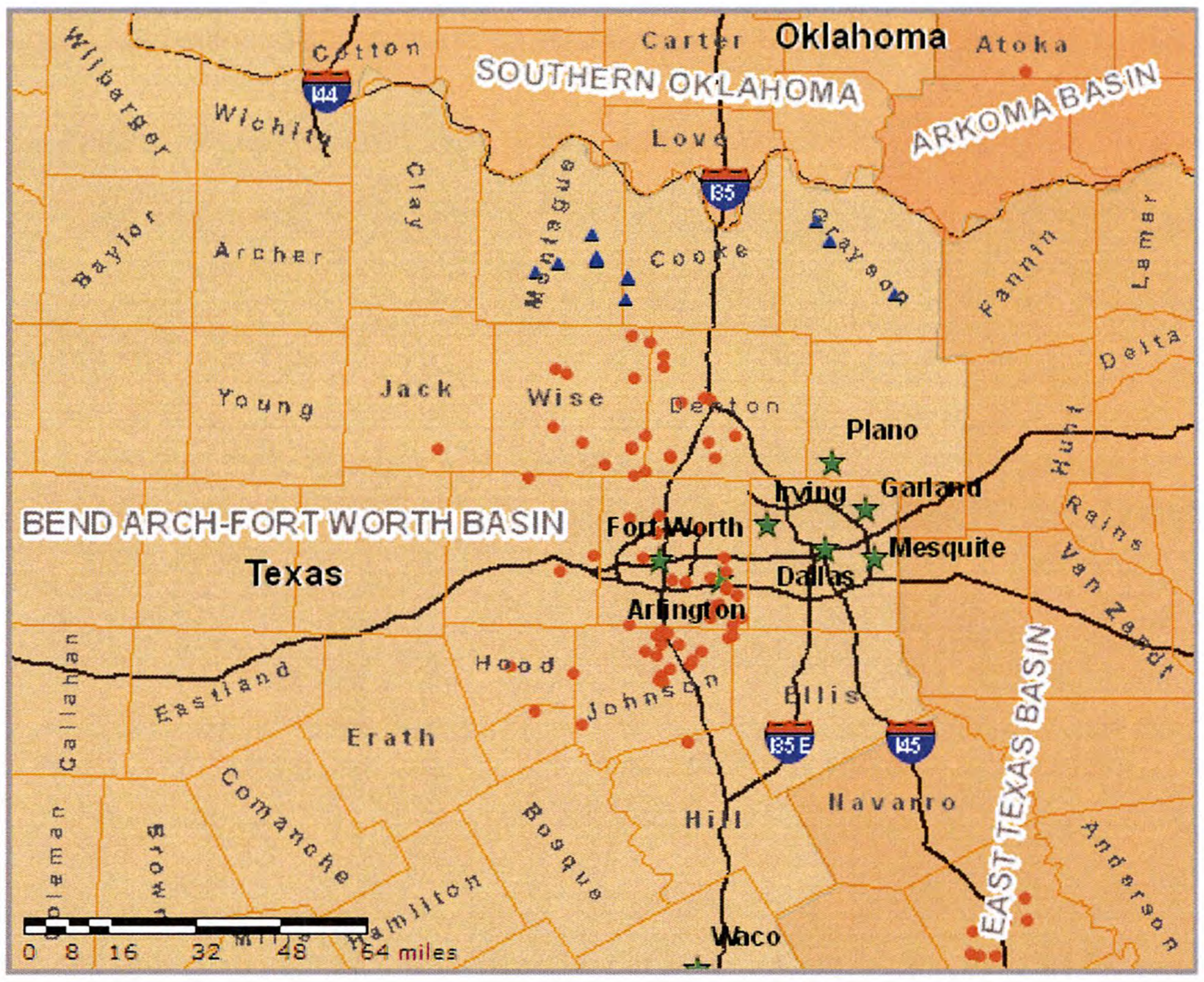


Note: Most of the natural gas production (and highest concentration of well development) occurs in the areas shaded in pink.

Source: Perryman Group, 2007

Figure 1.8: Barnett Shale Area

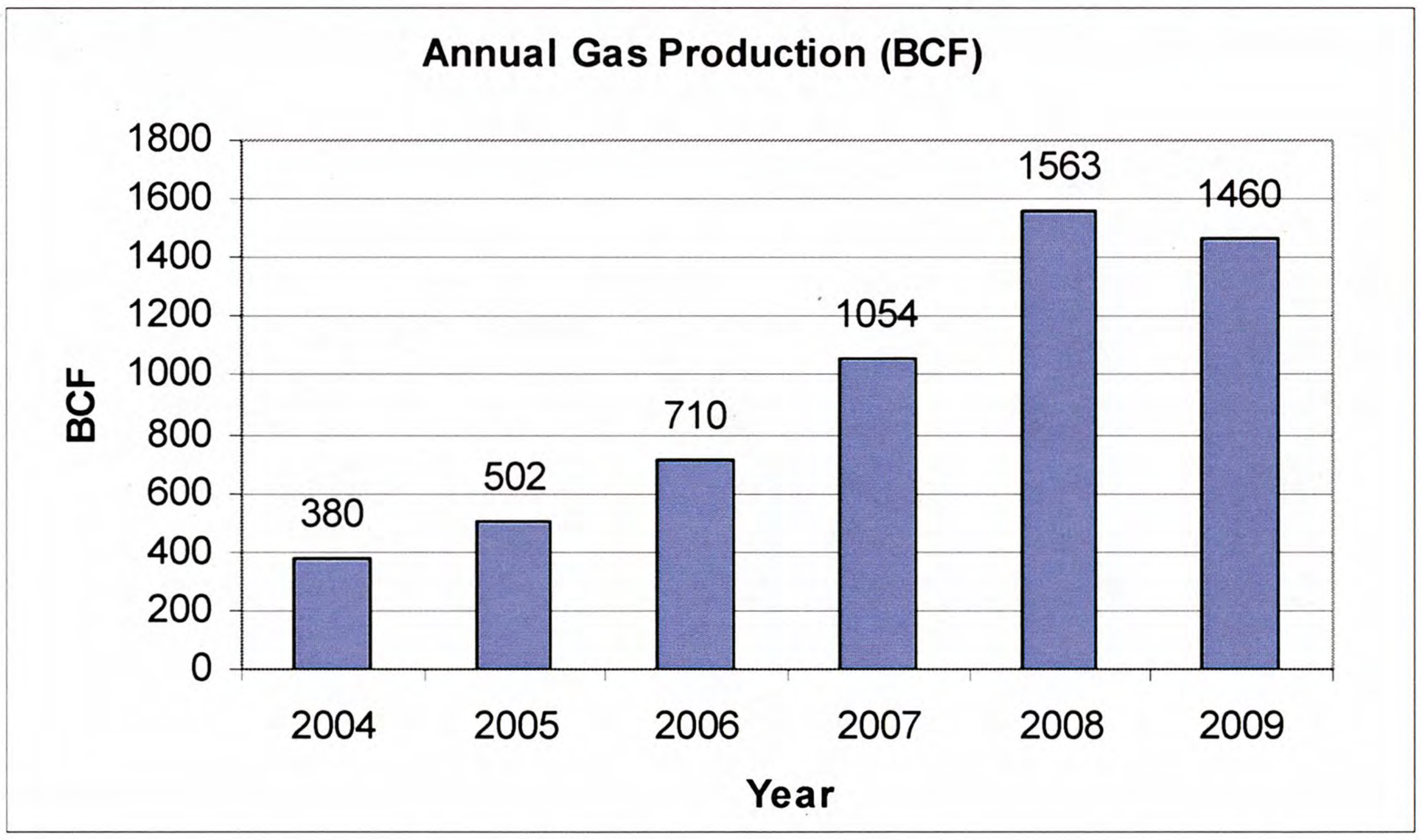
The Barnett Shale area was first discovered by Mitchell Energy in 1981. However, due to restrictions in horizontal drilling technology, it did not become a significant producer of natural gas until 2000. Today, the Barnett Shale is one of the largest producing natural gas fields in North America. Since 2000, approximately 5.7 trillion cubic feet of natural gas have been extracted from the reserve, while another 30 trillion cubic feet of estimated resources remain. In 2007, the Barnett Shale region produced approximately 3.75 billion cubic feet of natural gas per day (The Perryman Group, 2007) and in 2009 production had increased to about 5 billion cubic feet per day (Fuquay, 2009). Most of the production in the Barnett Shale area (approximately 80%) occurs within the Fort Worth-Arlington metropolitan area, specifically Denton and Wise counties. However, major metropolitan areas in Tarrant, Johnson, and Parker counties have also seen a significant increase in well development over the past several years. The Baker Hughes Investor Relations comprehensive map indicates where most of the current activity in the Barnett Shale is taking place (see Figure 1.9).



Source: Baker Hughes Investor Relations RIG COUNTS on 11-12-2009

Figure 1.9: Current Natural Gas Activity in the Barnett Shale

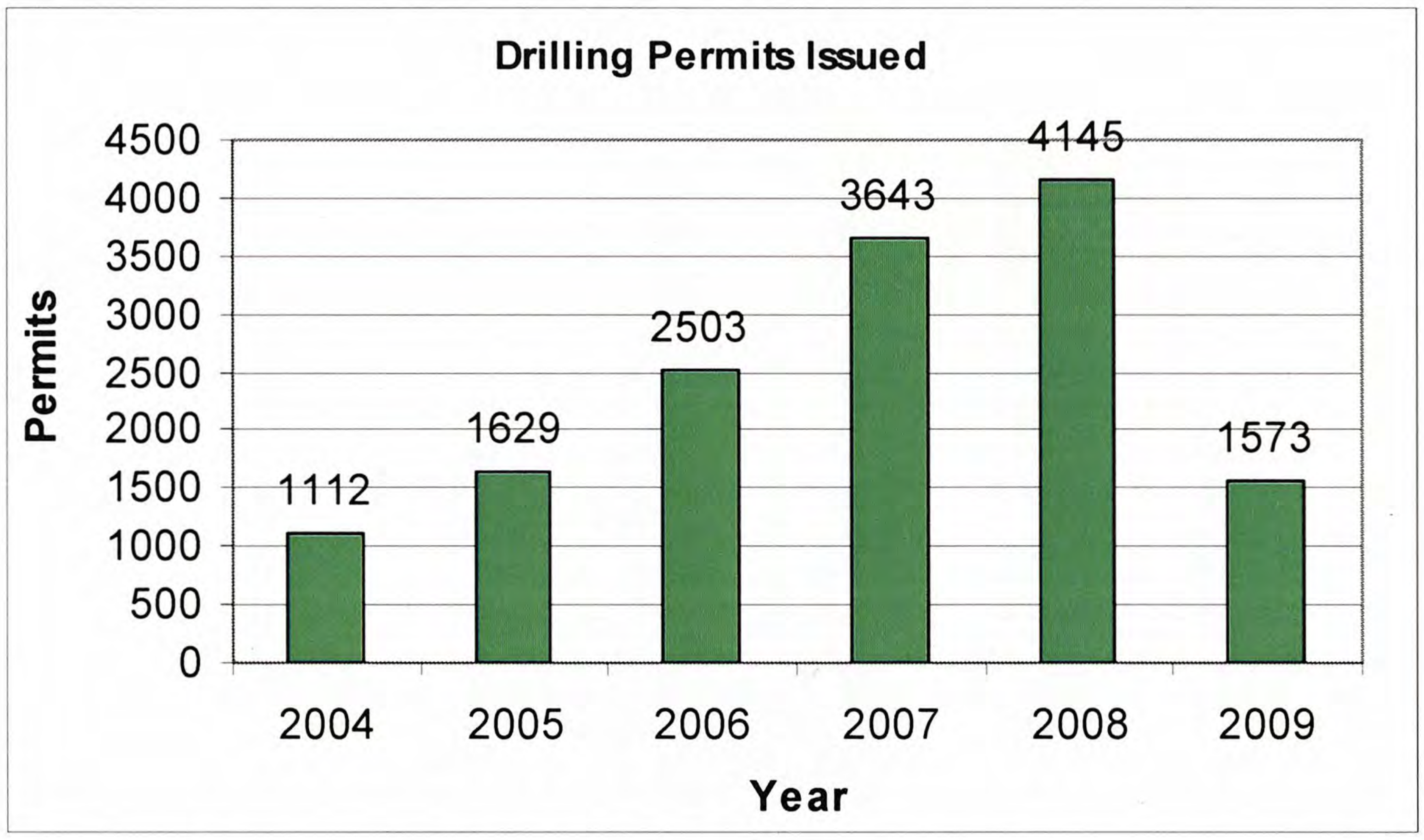
As mentioned earlier, the Barnett Shale area became a significant producer of natural gas after advances in drilling technology in the mid-nineties (Petroleum Extension Service, 2001) allowed oil and gas producers to drill horizontally through the thick shale and after significant increases in the price of natural gas. Over the past 5 years, annual gas production increased from 380 billion cubic feet per year in 2004 to 1,460 billion cubic feet per year in 2009. Figure 1.10 illustrates this dramatic increase in natural gas production.



Source: RRC Records, 2009

Figure 1.10: Barnett Shale Natural Gas Production (Billion Cubic Feet per Year)

These production levels are also reflected by the number of drilling permits issued by the RRC and the number of wells drilled in the Barnett Shale area. As of January 2009, 10,146 gas wells were entered into the RRC records (RRC, ND).



Source: RRC Records, 2009

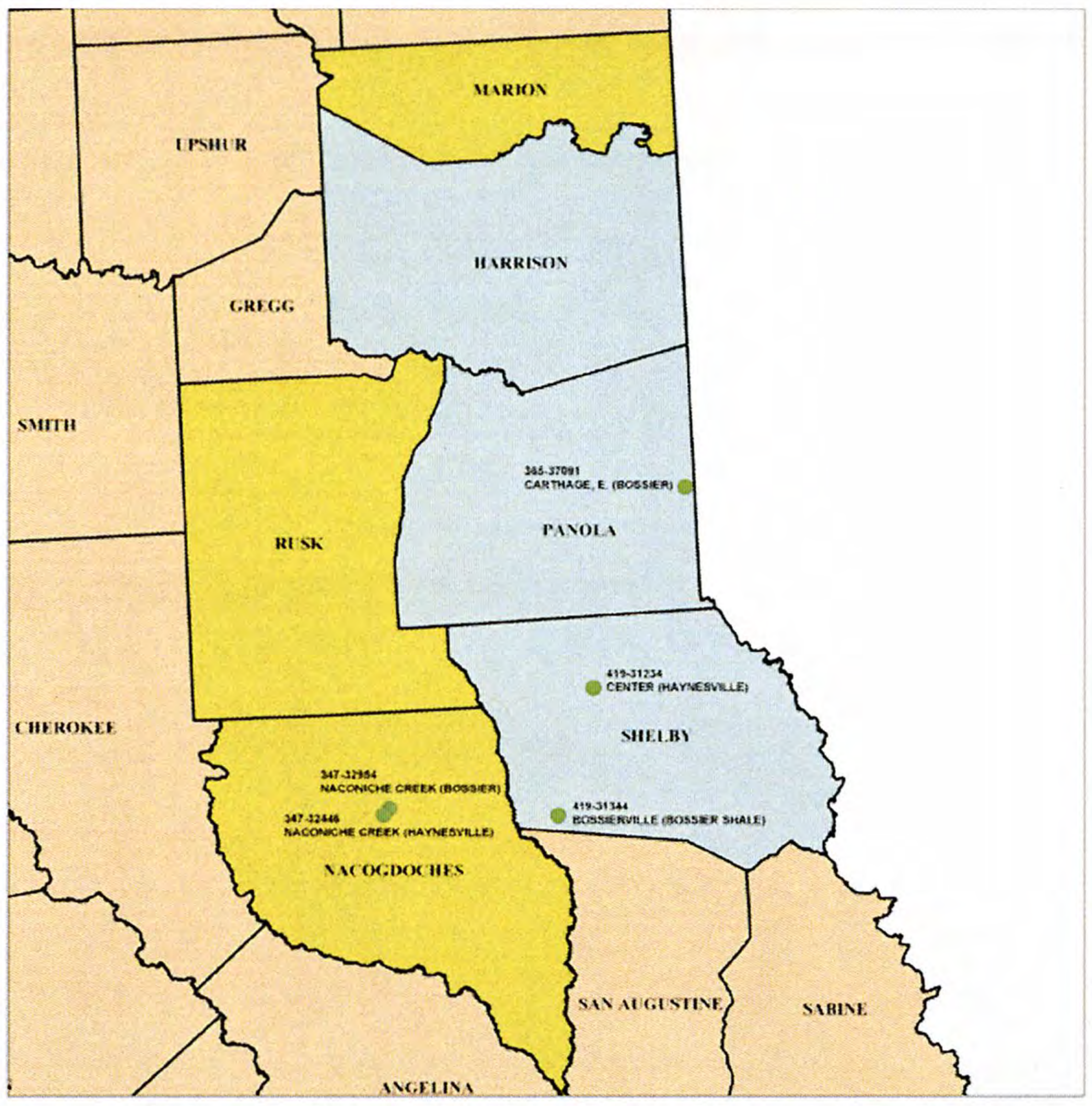
Figure 1.11: Annual Natural Drilling Permits in Barnett Shale

Natural gas production in the Barnett Shale area has resulted in tremendous economic benefits to the region. According to The Perryman Group (2007), the Barnett Shale area has generated 55,385 permanent jobs in 2006. By 2015, The Perryman Group predicts that the Barnett Shale will generate approximately 108,116 permanent jobs within the region.

Increased truck activity in the Barnett Shale area, together with an increase in the population of the area, has resulted in increased pressure on the road infrastructure. This pressure is evident from the traffic data compiled by TxDOT. According to TxDOT's Transportation Planning and Programming Division, average daily traffic (ADT) in some areas, such as Benbrook and near Lake Worth has increased by 16 and 23%, respectively, since 2000 (TxDOT, 2009). Truck traffic associated with drilling and the day-to-day operations of a natural gas well could accelerate pavement deterioration and reduce the service life of roads in the area.

1.1.2.2 Haynesville/Bossier Shale

The Haynesville/Bossier Shale is a hydrocarbon rich formation stretching over Shelby, Panola, Harrison, Marion, Rusk, and Nacogdoches counties in East Texas. Figure 1.12 presents a map of the Haynesville/Bossier Shale region.

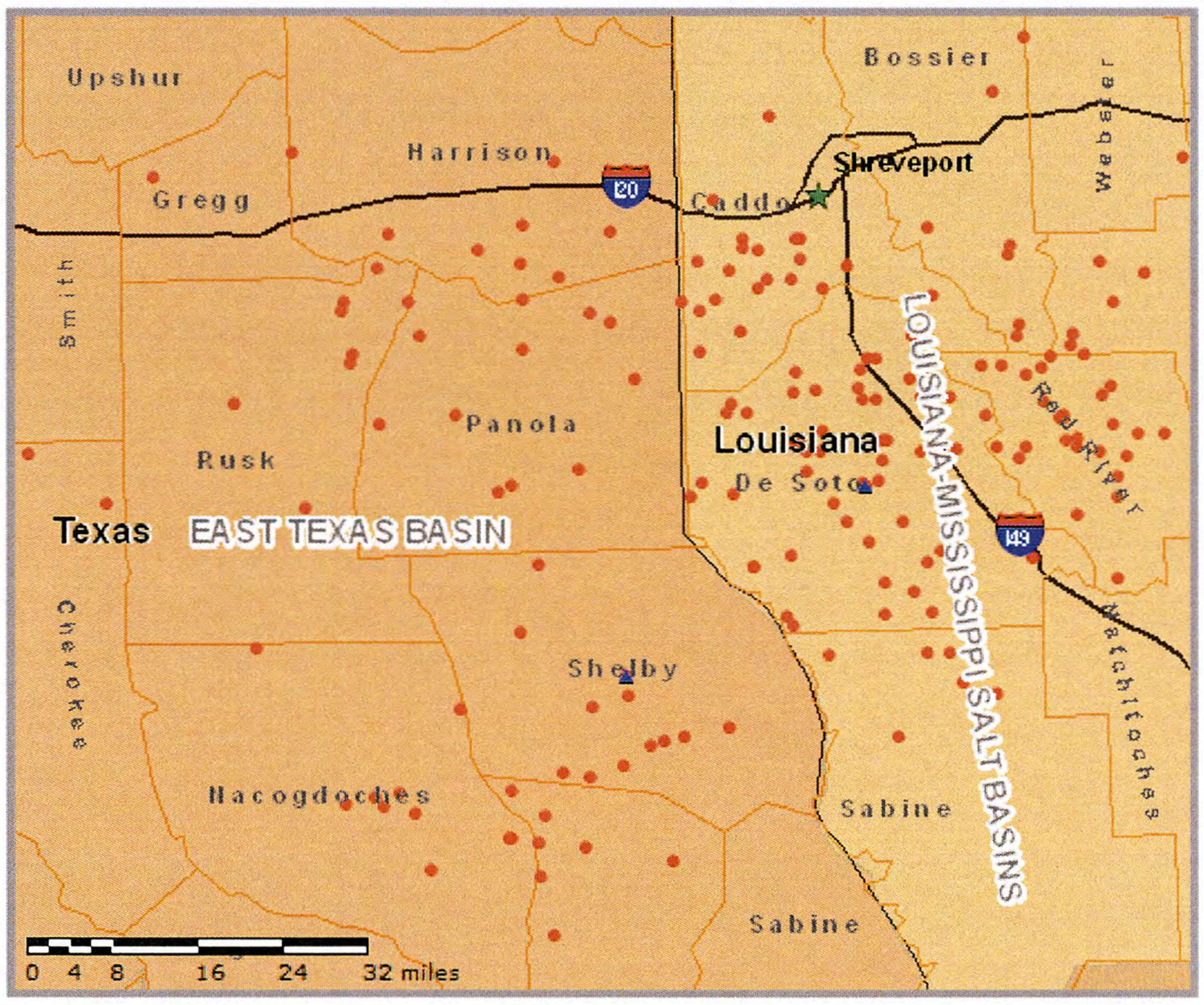


Note: Most discoveries have been made in Harrison, Panola, and Shelby counties.

Source: RRC, 2010

Figure 1.12: Haynesville/Bossier Shale

In early 2008, the Haynesville/Bossier Shale formation became commercially viable. As of August 13, 2009, 205 permitted well locations and 142 completed wells were operating in East Texas (RRC, ND). To understand the current activity in the area, see the Baker Hughes Investor Relations' comprehensive rig count map (Figure 1.13).



Source: Baker Hughes Investor Relations RIG COUNTS on 1-21-2009

Figure 1.13: Haynesville/Bossier Shale Current Rotary Rig Activity

Figure 1.13 shows 56 active rotary rigs operating in the region in January 2009. One of the biggest operators in the Haynesville/Bossier Shale area is Chesapeake Energy. Currently, they have 35 rotary rigs operating in the area and they anticipate having an average of 40 rigs operating in 2010. Current production levels for Chesapeake Energy are 370 million cubic-feet (mmcf) per day. Production is expected to increase to 690 mmcf per day by 2011 (Chesapeake Energy, ND).

Currently, not enough information is available to assess the impacts of the Haynesville/Bossier Shale formation on the Texas transportation system with any accuracy. Although similar truck traffic activity as seen in the Barnett Shale area can be expected, the haul trip lengths for moving equipment to the site during the construction phases, and for moving saltwater to injection wells during production, will likely be longer than in the Barnett Shale region. Therefore, the impacts on the Texas transportation system are expected to be spread over a larger network of roads.

1.1.2.3 Eagle Ford Shale

The Eagle Ford Shale is a hydrocarbon-producing formation of significant importance to Texas's economy due to its potential for producing both gas and more oil than other traditional shale plays. The shale play area starts at the Texas–Mexico border in Webb and Maverick counties and extends 400 miles toward East Texas. The play is 50 miles wide and an average of 250 feet thick at a depth between 4,000 and 12,000 feet. The shale contains a high amount of carbonate, which makes it brittle and thus easier to use hydraulic fracturing to produce the oil or gas (RRC, ND).

The oil reserves in the Eagle Ford Shale are estimated at 3 billion barrels with a potential output of 420,000 barrels a day (Gebrekidan, 2011). To put it in perspective, total production in the Permian Basin region up to the beginning of 1993 was about 14.9 billion barrels, but production has significantly declined over the years. Current production of crude oil in the Permian Basin is estimated at 350 million barrels per year (The Permian Basin Petroleum Association Magazine, 2009). Figure 1.14 provides the oil production levels in the Eagle Ford Shale, which illustrates the substantial increase in production levels between 2009 and 2010.

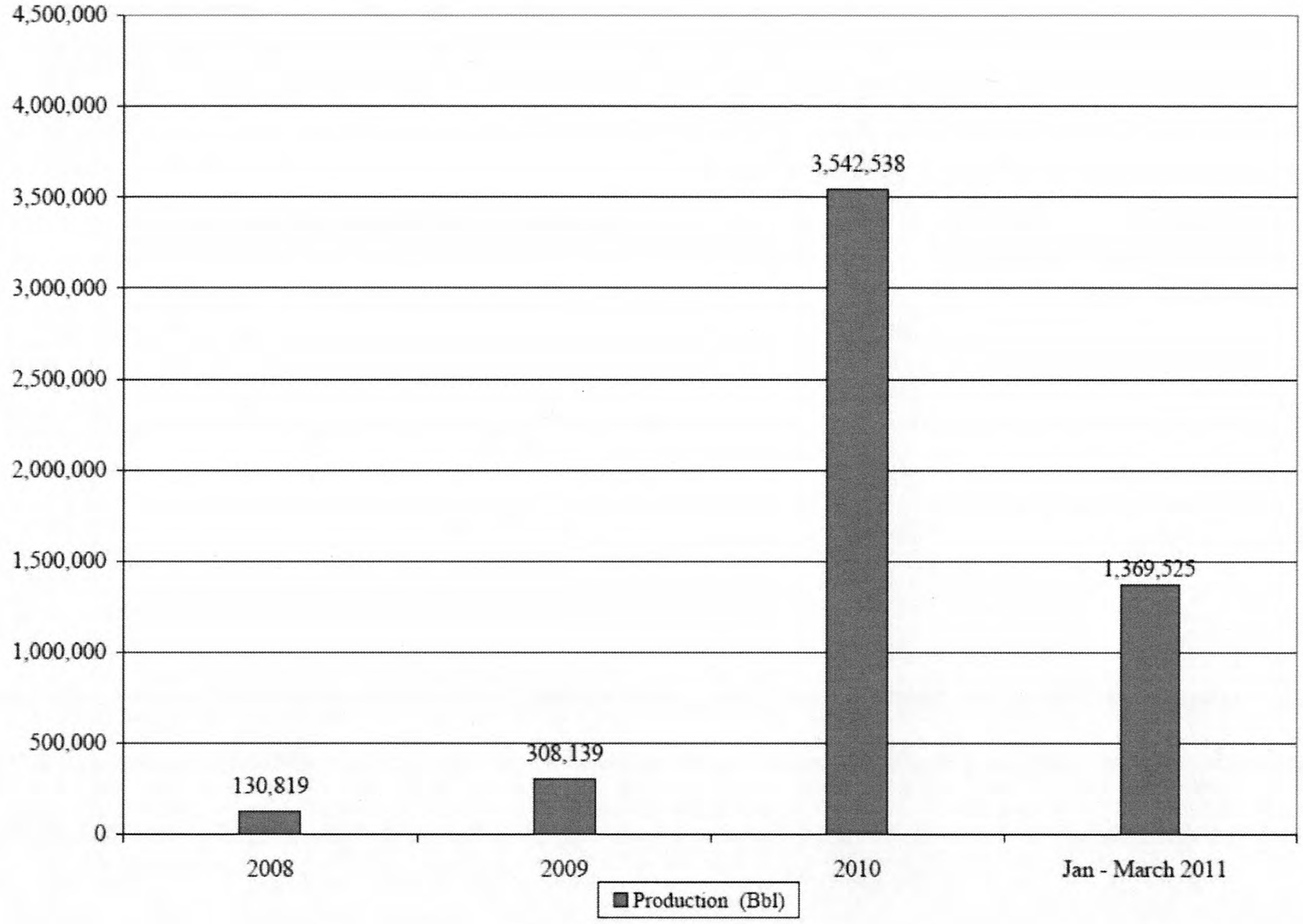


Figure 1.14: Eagle Ford Shale Oil Production

In addition, the Eagle Ford Shale is also rich in natural gas, which may have an even bigger economic impact than the Barnett Shale geological formation in North Texas. Figure 1.15 provides the current oil production levels mined in the Eagle Ford Shale area.

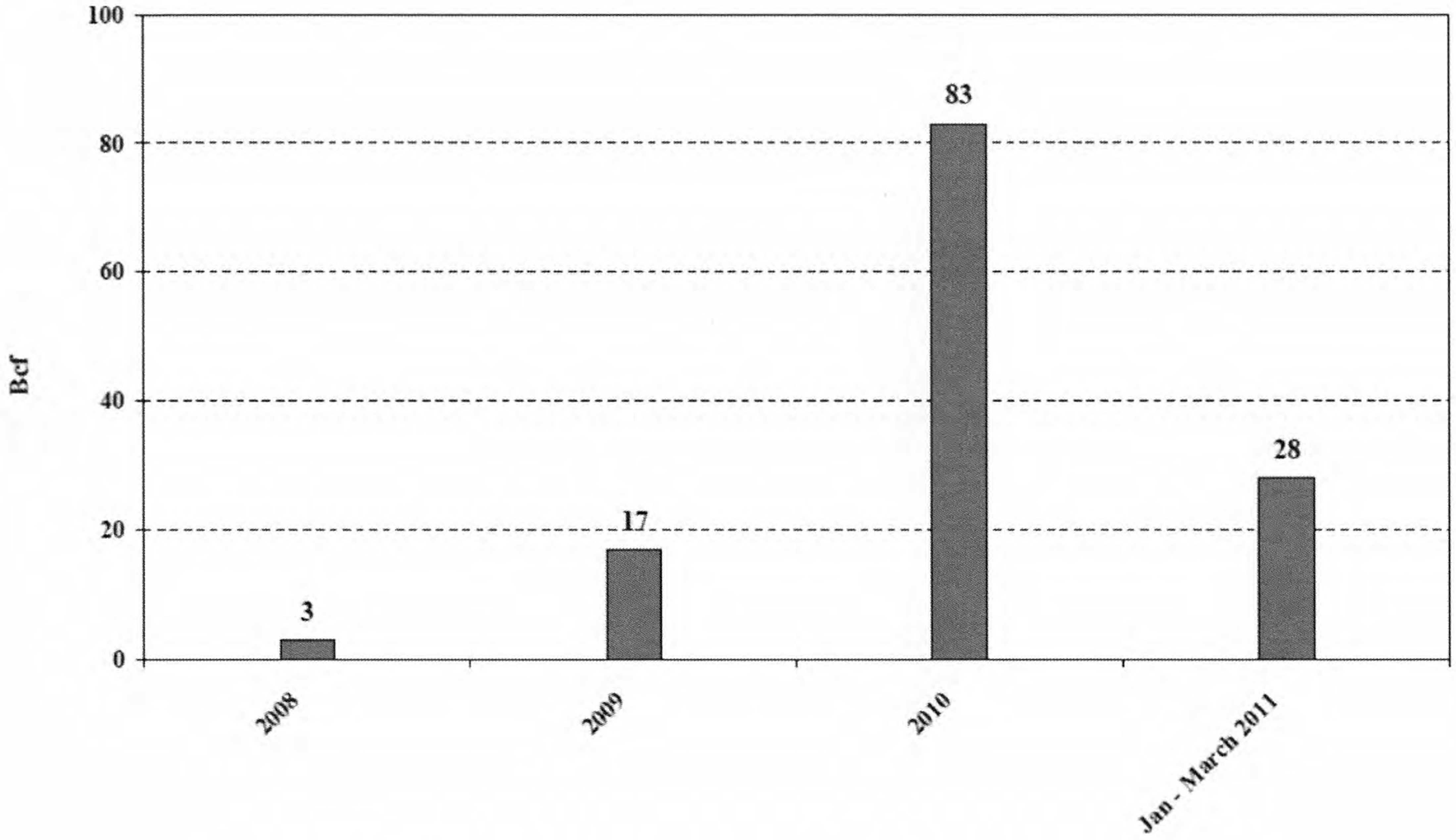
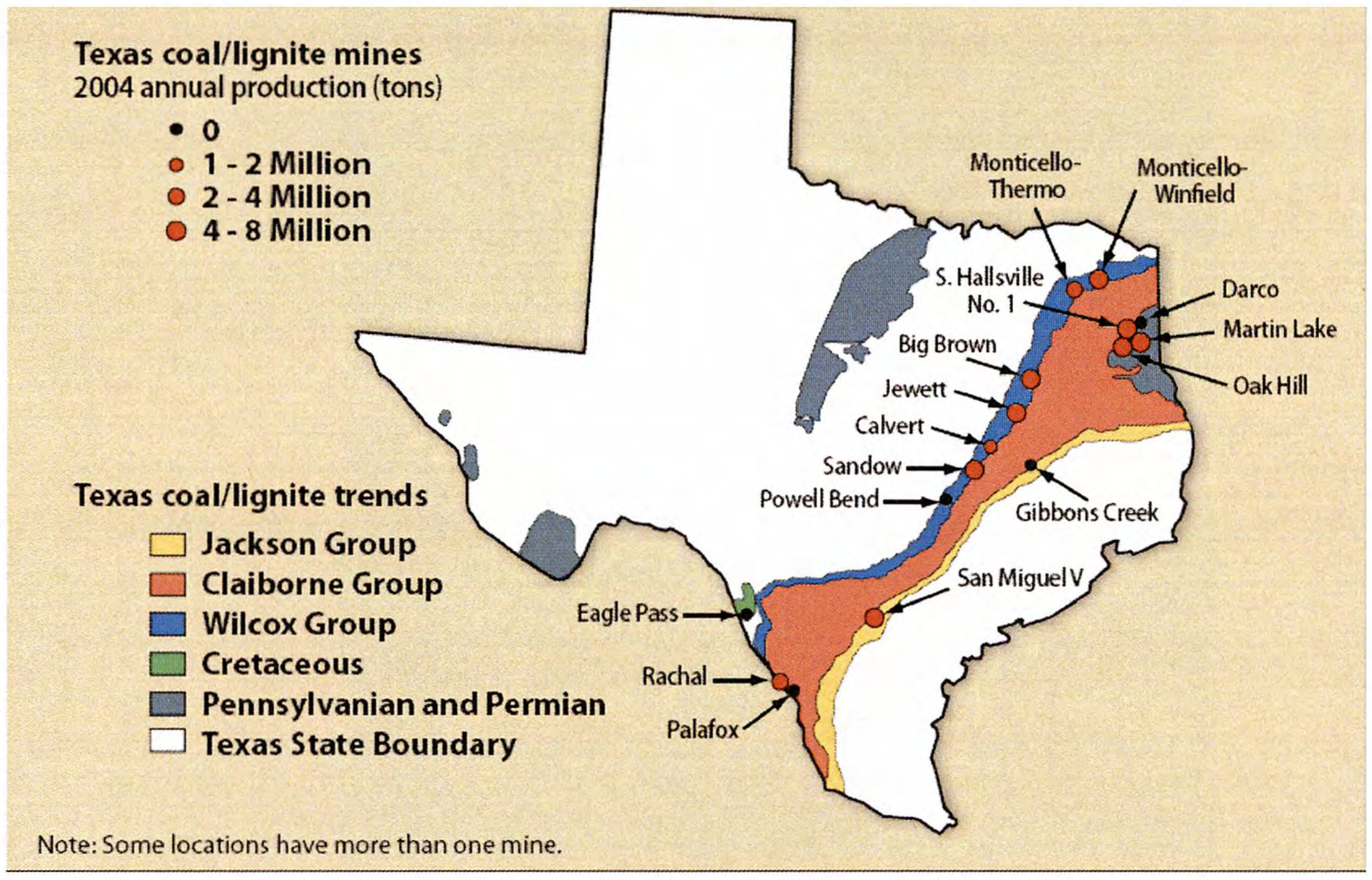


Figure 1.15: Eagle Ford Shale Natural Gas Production

In addition to the oil and natural gas resources, the Eagle Ford Shale is also rich in wet-gas reserves and condensates. With crude oil prices hovering around $110/barrel, the Eagle Ford Shale is a profitable destination for the oil producing companies. Currently, natural gas production is experiencing a modest growth due to the decline in natural gas prices. However, if natural gas prices rebound to 2008 levels, the region is anticipated to experience unprecedented growth in economic activity.

1.1.3 Coal Energy in Texas

In Texas, coal is mined in the lignite belt, which starts on the southern tip near the Gulf Coast and stretches into areas of Arkansas and Oklahoma. Figure 1.16 illustrates this area and the active coal mines operating along the belt.

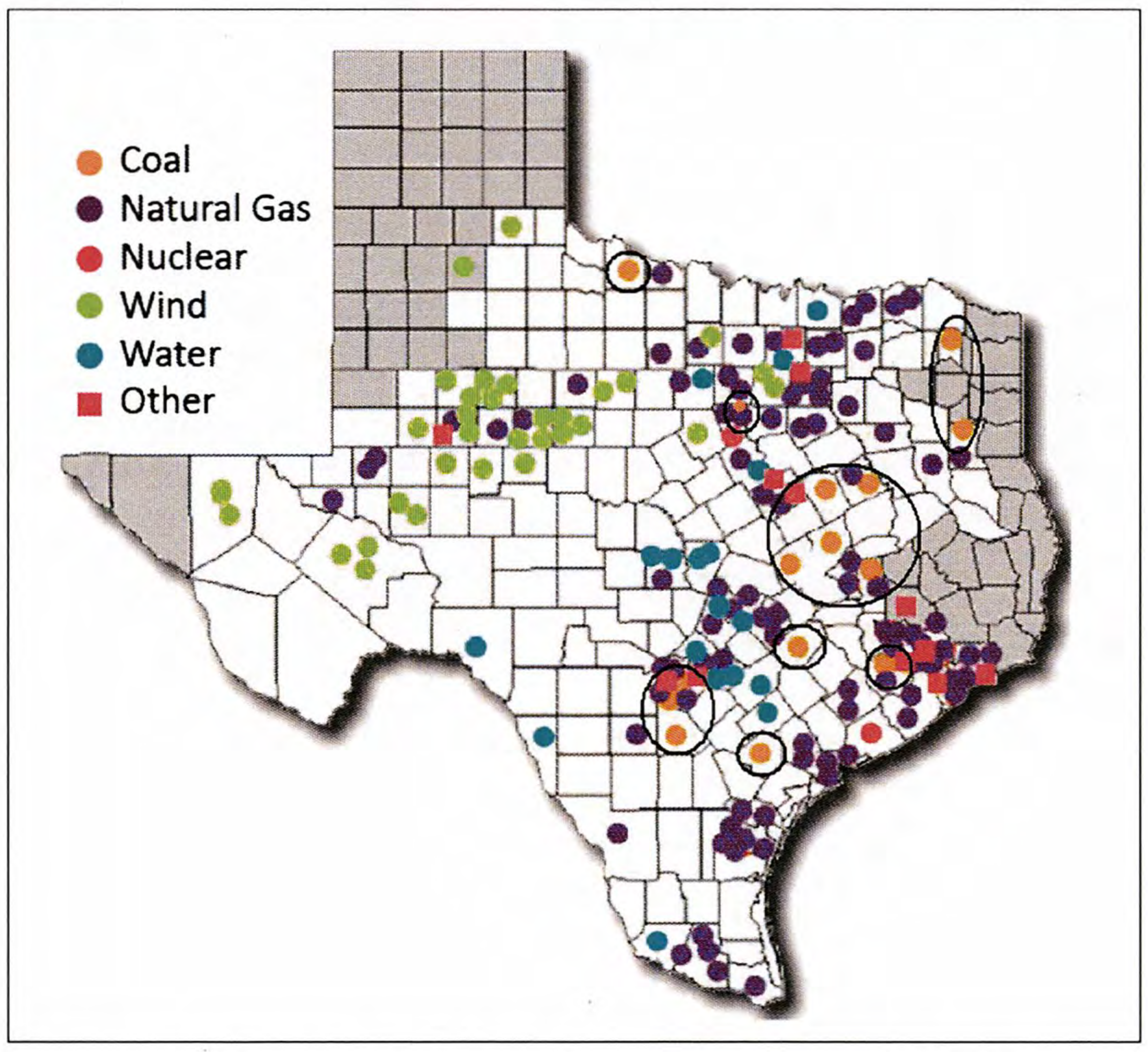


Source: Governor's Competitiveness Council, 2008

Figure 1.16: Coal Mines in Texas

As of 2008, 13 active lignite mines were on record with the RRC. Most of the coal mined in Texas is procured through surface mining or "strip" mining (Texas Mining and Reclamation Association, ND), which requires the removal of the top soil to reach the coal bed that is typically 40 to 120 feet below the surface. Once mining of an area is completed, the land is "reclaimed." In other words, the earth is restored and the area is replanted with vegetation.

Over 96% of the coal mined in Texas is used for electricity generation (Texas Comptroller of Public Accounts, 2008). The coal-powered electricity generation plants are usually located near coal mines to reduce transportation costs. These types of facilities are known as *"mine to mouth"* operations. As of 2008, Texas had 11 coal-powered electricity generation plants. Figure 1.17 illustrates their location.



Source: ERCOT Annual Report, 2007

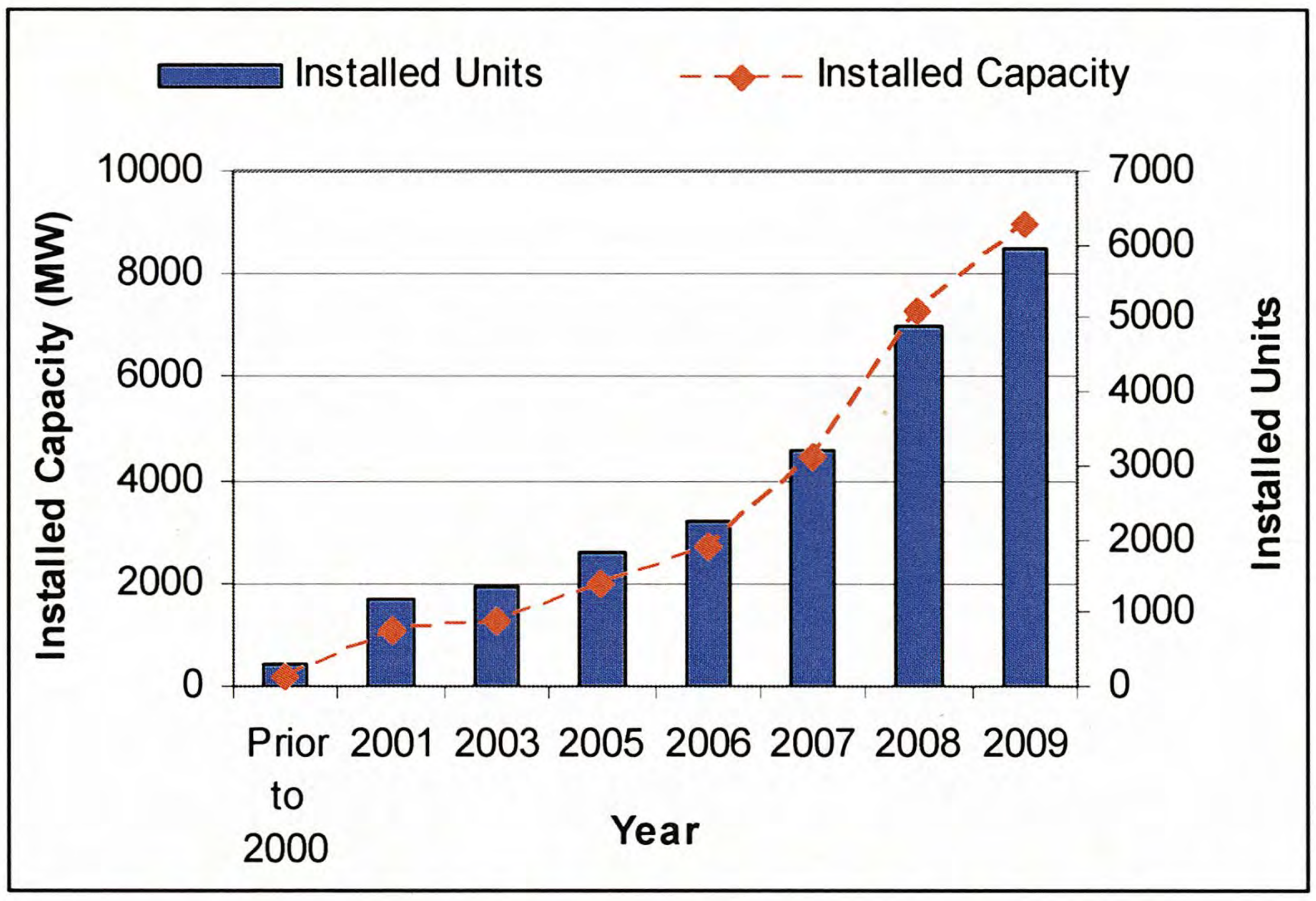
Figure 1.17: Coal-Powered Electricity Generation Plants

With respect to the coal mines presented in Figure 1.16, most of the power plants are in close proximity to their "sister" mines along the lignite belt. Coal is usually transported between the mines and the generation plants by rail over longer hauls, and conveyor or tramway over shorter hauls. The coal produced in Texas is, however, insufficient to meet demand. Texas consumes about twice as much coal as it produces and thus about 56.6% of its total coal needs is imported from other states (RRC, ND). Almost all of the imported coal (i.e., 99.6%) is transported by rail.

In recent years, given increased concerns about global warming and various attempts to urge the U.S. Environmental Protection Agency to regulate greenhouse gas emissions from mobile and stationary sources under the Clean Air Act, efforts began to reduce the number of coal-powered electricity generation plants or at least to use cleaner burning coal and technologies. Since 1995, 82% of all new power generation added to the Electric Reliability Council of Texas (ERCOT) grid thus came from natural gas-fired power plants. However, the price of natural gas, similar to the price of oil, is susceptible to severe price fluctuations. ERCOT thus proposed the construction of approximately 6,000 MW of coal power generation capacity by 2015 (Governor's Competitiveness Council, 2008). Additional coal-powered electricity generation capacity will increase the demand for coal imports via rail, as well as in-state coal production necessitating short haul coal movements from mining sites.

1.1.4 Wind Development in Texas

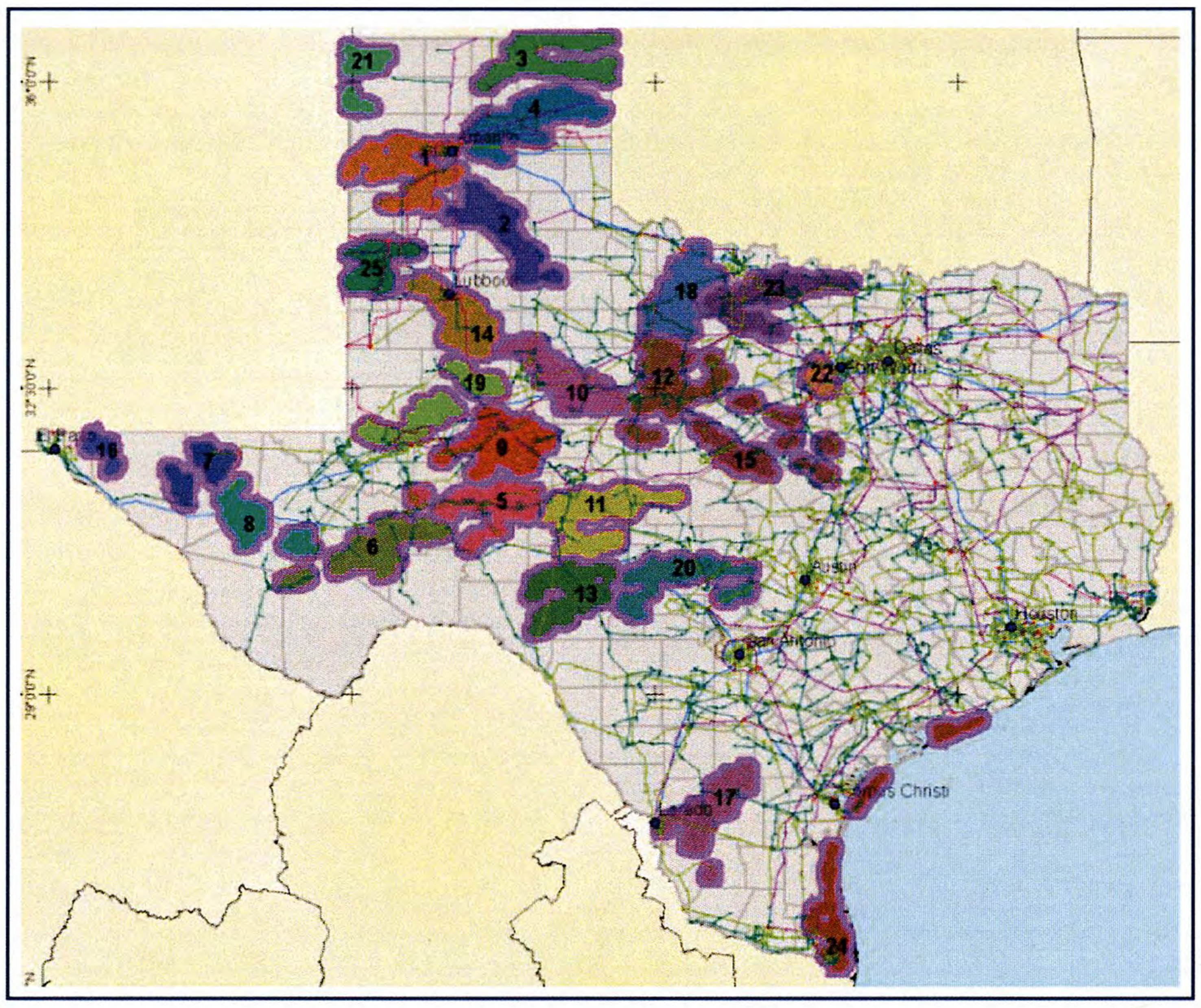
The passing of Senate Bill 20 provided an impetus for the accelerated development of wind energy capacity in Texas. Texas's production of wind energy increased from 180 MW in 1999 to 8,948 MW in June of 2009, considerably exceeding the bill's original goal of 5,880 MW of installed capacity by 2015. Figure 1.18 illustrates how drastically the wind energy sector has grown in the state within the last decade.



Source: American Wind Energy Association, 2009

Figure 1.18: Wind Capacity Growth in Texas

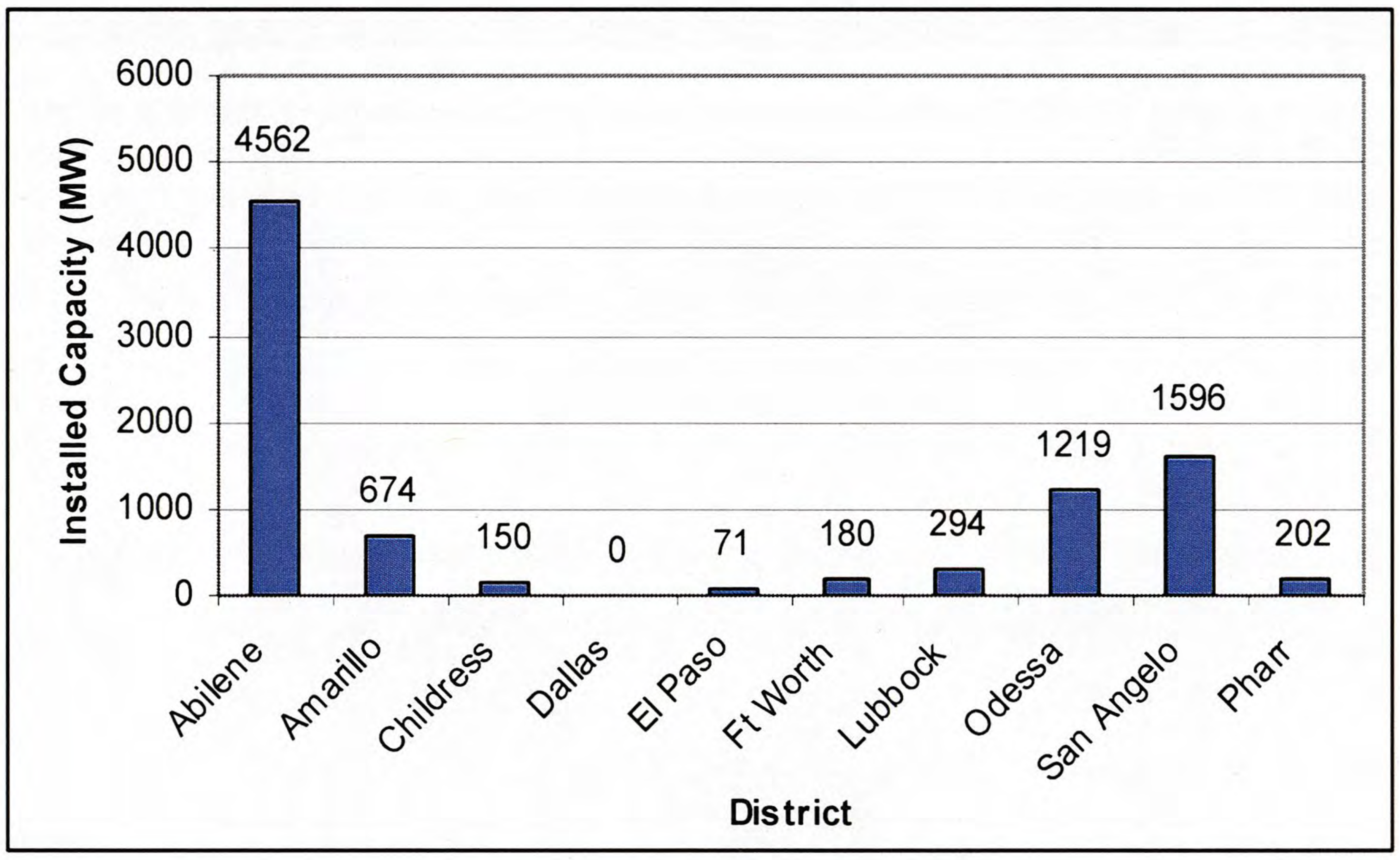
Most of the development has occurred within the Competitive Renewable Energy Zones (CREZ) set in place by the Texas legislature. These zones are highlighted in Figure 1.19.



Source: ERCOT, 2006

Figure 1.19: Texas's Competitive Renewable Energy Zones

Figure 1.20 illustrates the districts affected the most by the wind energy sector.



Source: American Wind Energy Association, 2009

Figure 1.20: Installed Wind Capacity by District

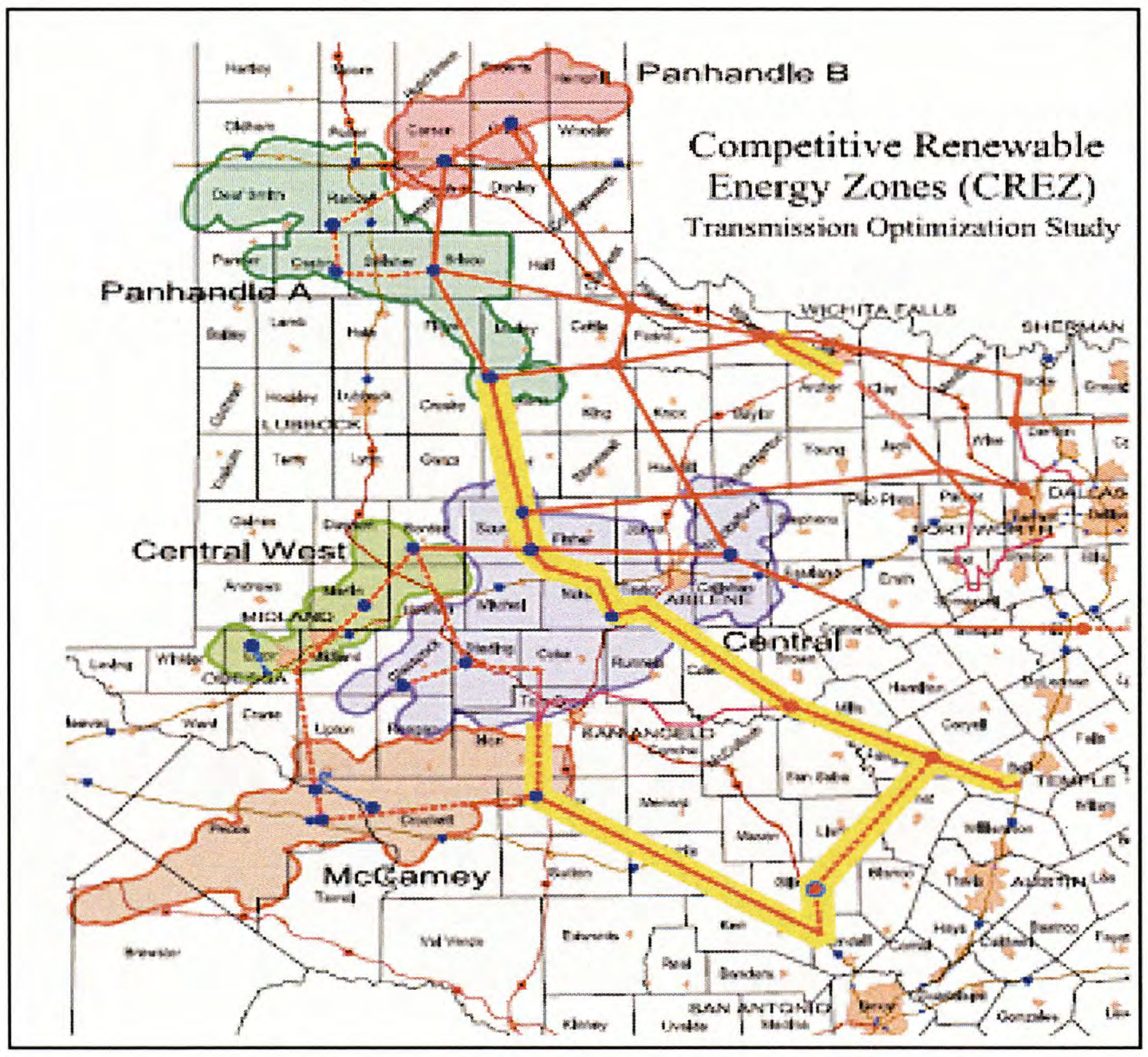
Figure 1.20 makes clear that most of the development is concentrated in the Central and the Central West CREZs near Abilene, Midland, and Sweetwater. Significant capacity also exists in the McCamey region near San Angelo and regions of the Texas Panhandle. The current volatility of the financial market has resulted in many developers stepping back, waiting for the market to rebound before construction can once again be under way.

Long-term plans for Texas include expansion of the wind energy industry into the Gulf Coast and up into the Great Plains corridor through the Texas Panhandle (U.S. DOE, 2008). According to the American Wind Energy Association, Texas has enough wind capacity to produce up to 136,000 MW of wind energy. This estimate is more than twice the current peak hour demand of the state's entire energy grid. To make use of this abundant resource, ERCOT has been studying the feasibility of adding another 45,000 MW of wind energy capacity to its grid. However, the growth of the wind industry will depend on the various incentives provided by the federal and state government that make wind energy competitive with conventional fossil fuels (Governor's Competitiveness Council, 2008).

1.1.4.1 Future Challenges for the Wind Industry

A key challenge in the development of wind energy in the state of Texas is inadequate transmission infrastructure. Most of the energy generated from wind is located in rural regions of West Texas and the Texas Panhandle. However, the major load centers in the state are within the Houston–San Antonio/Austin–Dallas/Fort Worth region (known as the Texas Triangle). Currently, the transmission lines are inadequate for transporting the electricity from areas of production to areas of consumption. For example, in 2007, wind energy contributed approximately 2,981 MW to the ERCOT grid system at a time when potential production was 4,296 MW. The bottom line is that far more wind energy capacity has been installed than what can be utilized, resulting in wastage.

As a result of this, in 2006 ERCOT conducted an optimization study of its transmission lines, and in September 2008, the council proposed a plan to the Public Utility Commission of Texas (PUCT) to construct approximately 2,400 miles of new 345-kV transmission lines to connect the CREZs of West Texas and the Texas Panhandle to the major load centers of the Texas Triangle. Figure 1.21 illustrates the proposed plan for the high priority transmission lines.



Source: ERCOT, 2006

Figure 1.21: High Priority Transmission Lines

In January 2009, PUCT allocated approximately $5 billion to implement this plan (Energy Future Holdings, 2009). The construction of nearly 2,400 miles of new transmission lines could impact Texas's transportation system. Specifically, farm-to-market (FM) and ranch-to-market roads in rural areas of West Texas and the Texas Panhandle will be further impacted by the construction of the enabling infrastructure.

1.1.4.2 Economic Benefits of Wind Energy

In general, a wind farm development will generate a significant number of *temporary* construction jobs, which will last for the duration of the project. However, it is doubtful that the number of permanent jobs associated with the wind energy sector will revitalize whole regions of rural America. Personal communication with NextEra Energy revealed that their 735.5 MW (421 unit) Horse Hollow Wind Energy Center employs only 36 people (i.e., 4 site leads, 1 production manager, 4 plant technicians, and 27 wind technicians). Also, a visit to the newly constructed 179.85 MW (109 Unit) Papalote Creek Wind Farm revealed that their operations and maintenance office employs 15 technicians. Based on the data provided by NextEra Energy, Table 1.1 provides an estimate of the direct employment benefits of wind energy development to a region.

Table 1.1: Direct Permanent Employment Associated with Wind Energy Development

Power (MW)	Units	Employees	Technicians
735.5	421	36	27
MW/Employee	20.4	Units/Employee	11.7
MW/Technician	27.2	Units/Technician	15.6

Source: NextEra Energy, 2009

Table 1.1 indicates that on average one employee is required for about 20 MW of installed capacity, or approximately 11 units. If 8,948 MW of capacity are installed in Texas, then approximately 450 direct permanent jobs—associated with the maintenance and operation of the wind energy units—will be generated. Although these jobs may be a significant contribution to the rural economy, this figure is far less optimistic than what has been stated[1].

1.1.5 Bio-Fuel Production in Texas

To understand the bio-fuel production potential in the state of Texas, and its potential impacts on the Texas transportation system, it is important to understand the current and future bio-fuel market in the United States. Also important is understanding the type of agricultural resources necessary for the production of bio-fuels, along with the co-products and byproducts of the industry.

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[1] During a congressional hearing—"T. Boone Pickens: Energy Security Plan" (2008)—it was stated that a 4,000 MW wind farm can generate up to 1,500 permanent jobs in a region.

1.1.5.1 The Bio-Fuel Market

Bio-fuels are liquid fuels derived from plant production. Bio-fuels can be split into two categories: ethanol fuels and bio-diesel. About 95% of all domestic ethanol production comes from corn fermentation, while about 90% of all domestic bio-diesel production comes from oil extraction from soybeans (Aventine, 2007). Ethanol fuels are marketed across the U.S. as a gasoline blend component that serves the following purposes:

(1) oxygenation to help meet fuel emission standards,

(2) octane enhancer to improve gasoline performance, and

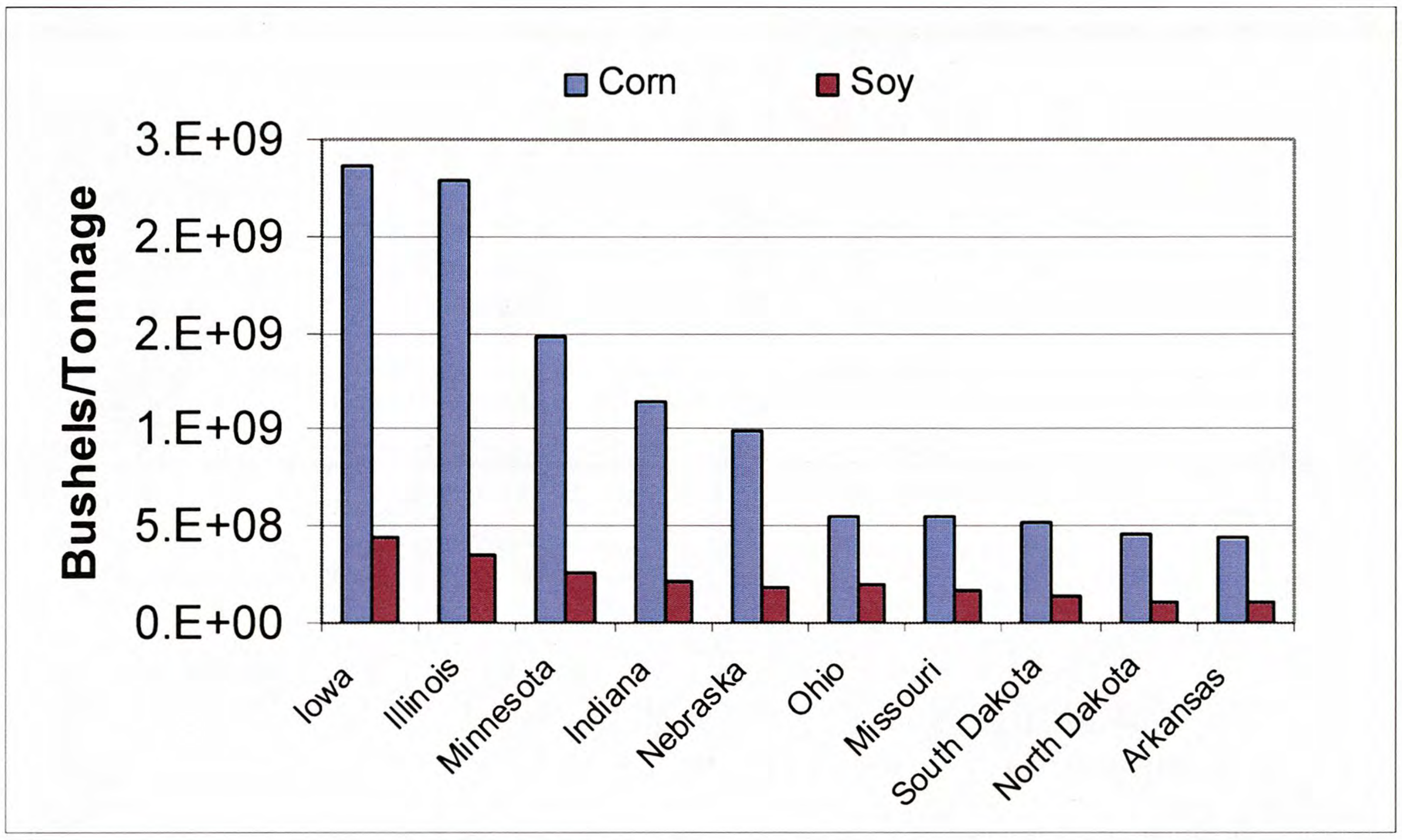
(3) extender of diminishing fuel supplies (Aventine, 2007).

Bio-diesels find similar uses in the petroleum industry. Mainly, they are used as a blend component with petroleum diesel to power both the auto and rail industries. Ethanol products compose the bulk of the bio-fuel industry, with bio-diesel production making up about 6.0–8.0% of the entire production market.

In recent years, the bio-fuel industry has experienced rapid growth. The U.S. production of ethanol has increased from 1.3 billion gallons in 1997 to approximately 6.5 billion gallons in 2007. With the passing of the 2007 U.S. Energy Bill, which requires significantly higher levels of blending, demand has increased to 9 billion gallons in 2008 and is projected to further increase to 13.2 billion gallons by 2012 and 15 billion gallons by 2015 (Texas Renewable Energy Resource Assessment, 2008). Demand for bio-diesel in the U.S. has also increased from 2 million gallons in 2000 to 700 million gallons in 2008. The future demand for bio-diesel is, however, uncertain. In 2009, international sales were greatly reduced as a result of anti-dumping and anti-subsidy tariffs imposed by the European Commission on all bio-diesel produced in the U.S. The tariffs went into effect in March 2009 and are expected to last through 2014 (Iowa Renewable Energy, 2009). This action took a heavy toll on the U.S bio-diesel industry, with most plants operating at 15% capacity in the last quarter of 2009. However, with energy independence becoming a national concern, government legislation that seeks to encourage the use of renewable fuels could lead to a revitalization and perhaps even expansion of the current market.

The mandated usage of renewable fuels along with tax incentives provided by the federal government have made bio-fuel production a profitable venture. An economic study conducted by Frontier Associates, LLC—for the Texas Renewable Energy Resource Assessment—found that ethanol fuels can compete with petroleum-based fuels when crude oil prices are in excess of $100 per barrel. A review of one of the bio-fuel industry's top producing company's annual report for the 2007 fiscal year revealed that the company sold their ethanol to gasoline blenders at an average fixed market price of $1.78 per gallon, or about $74.76 per barrel (Aventine, 2008).

Currently 91 producers are operating 136 ethanol plants in the U.S. Most of these companies operate within the Midwest, specifically Illinois, Indiana, Iowa, Minnesota, and Nebraska (First United Ethanol, 2009). The Midwest provides close proximity to the corn and soybean feedstock necessary for bio-fuel production. Figure 1.22 presents the Top 10 corn and soybean producing states in the U.S. The Midwest is also in the middle of the country, which is ideal for distribution purposes.



Source: NASS/USDA

Figure 1.22: Top 10 Producing States of Corn and Soybean in the U.S.

1.1.5.2 Texas Potential

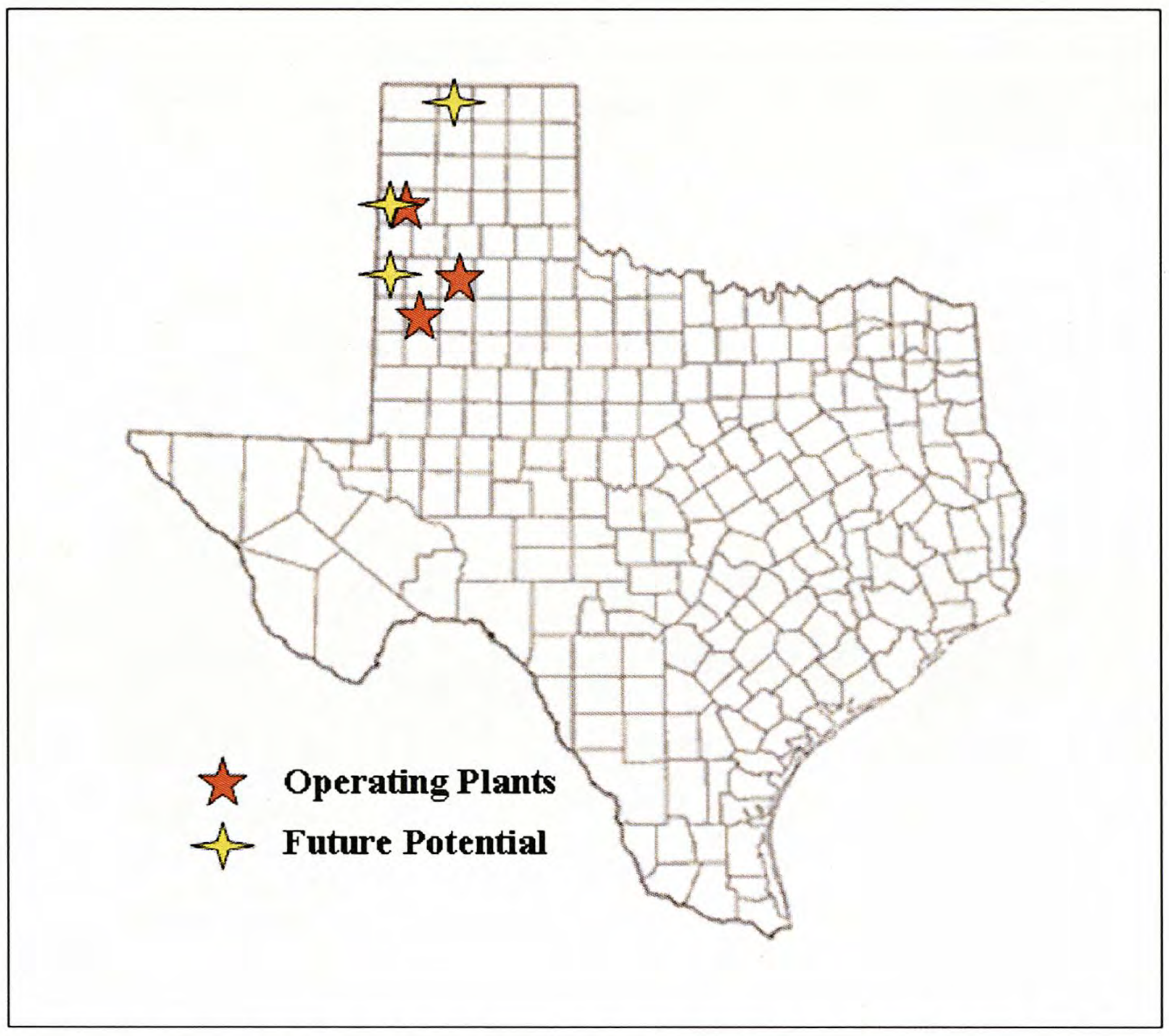
Currently, three ethanol production plants are operating in the state of Texas. However, some areas of the Texas Panhandle have been identified by the bio-fuel industry as having a high potential for future development sites. Panda Ethanol, Inc., in their assessment of Texas, has identified three suitable locations for ethanol production:

- Hereford in Deaf Smith County,
- Sherman County, and
- Muleshoe in Bailey County.

These locations hold several strategic advantages over other areas in Texas because of the following reasons:

- Proximity to BNSF main railway line to facilitate
  - delivery of corn stock from the Midwest for ethanol production and
  - shipment of the final product across the country.
- Access to local cattle feedlots, resulting in
  - 4.2 billion tons of local cow manure available for purchase and use as a cheap and reliable fuel source for powering the plant, and
  - a market for wet and dry distiller grain co-products.
- Physical proximity to significant ethanol markets in Texas, Colorado, and California that would result in
  - lower transportation costs to blenders.

These advantages can play a significant role, especially for those companies that are willing to rely on the cattle market for meeting their fuel demands by powering their production plants on bio-gas. Currently, all ethanol production facilities in Texas are powered by natural gas or coal. However, bio-gas provides a competitive advantage in that minimal expenditures have to be made for powering the facility. The BNSF main railway line that runs through the Texas Panhandle provides the other major competitive advantage that other regions in Texas do not share. Figure 1.23 presents the location of current operating ethanol plants in the state of Texas and locations with future potential.



Source: Panda Ethanol, Inc., and First United Ethanol, LLC

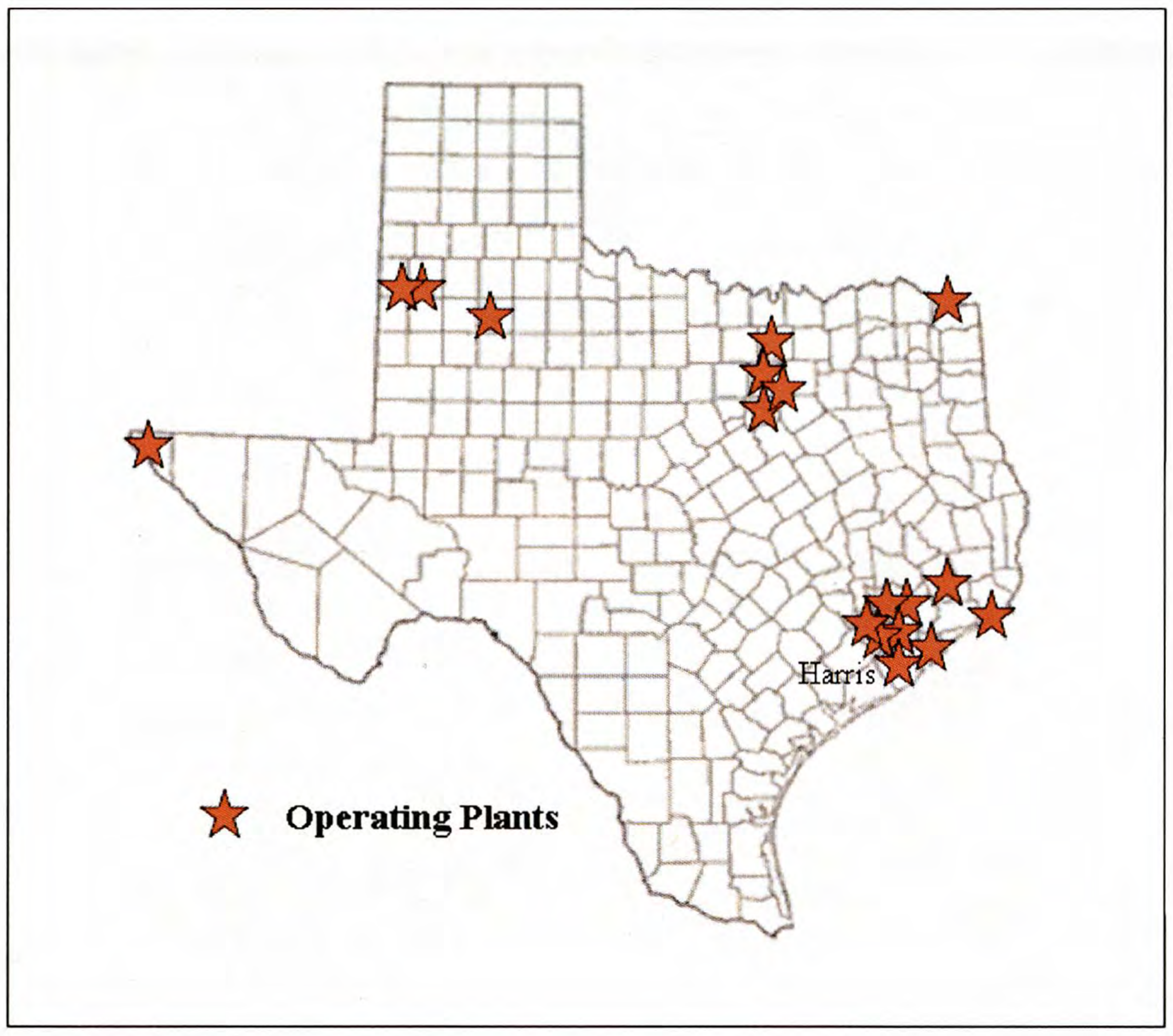
Figure 1.23: Current Ethanol Plants and Future Potential Sites

Table 1.2 also presents information about the three plants currently in operation.

Table 1.2: Operating Ethanol Plants in Texas

Producer	Feedstock	Location	Capacity (MGY)
Levelland/Hockley County Ethanol, LLC	Corn/Milo	Levelland, TX	40
White Energy	Corn/Milo	Hereford, TX	100
White Energy	Corn/Milo	Plainview, TX	110

Bio-diesel production in the state has evolved in different regions. Figure 1.24 presents a map of bio-diesel plants in Texas. Eighteen bio-diesel plants were operating in the state of Texas in 2009, with a significant portion located near the ports of Houston and Galveston.



Source: Iowa Renewable Energy, 2009

Figure 1.24: Bio-diesel Producers in Texas

The development of bio-diesel plants near the Gulf Coast can be attributed to two primary reasons:

- close proximity to oil refineries and blenders on the Gulf Coast that results in reduced transportation costs, and
- close proximity to a network of ports that allows for the shipment of product overseas (mainly Europe).

Currently, the bio-diesel industry is well established in the state of Texas. GreenHunter Energy, Inc., for example, has one of the largest bio-diesel plants in the U.S. The plant operates in the Houston Ship Channel and has a production capacity of 105 million (MMY) gallons.

As mentioned earlier, with the imposed tariffs on U.S. subsidized bio-diesel, the future of the industry is uncertain. Currently the industry is operating at 15% of its capacity. Unless the bio-diesel industry finds a new market for their product, expansion of the industry in the state of Texas remains uncertain.

1.1.6 Biomass Energy Generation

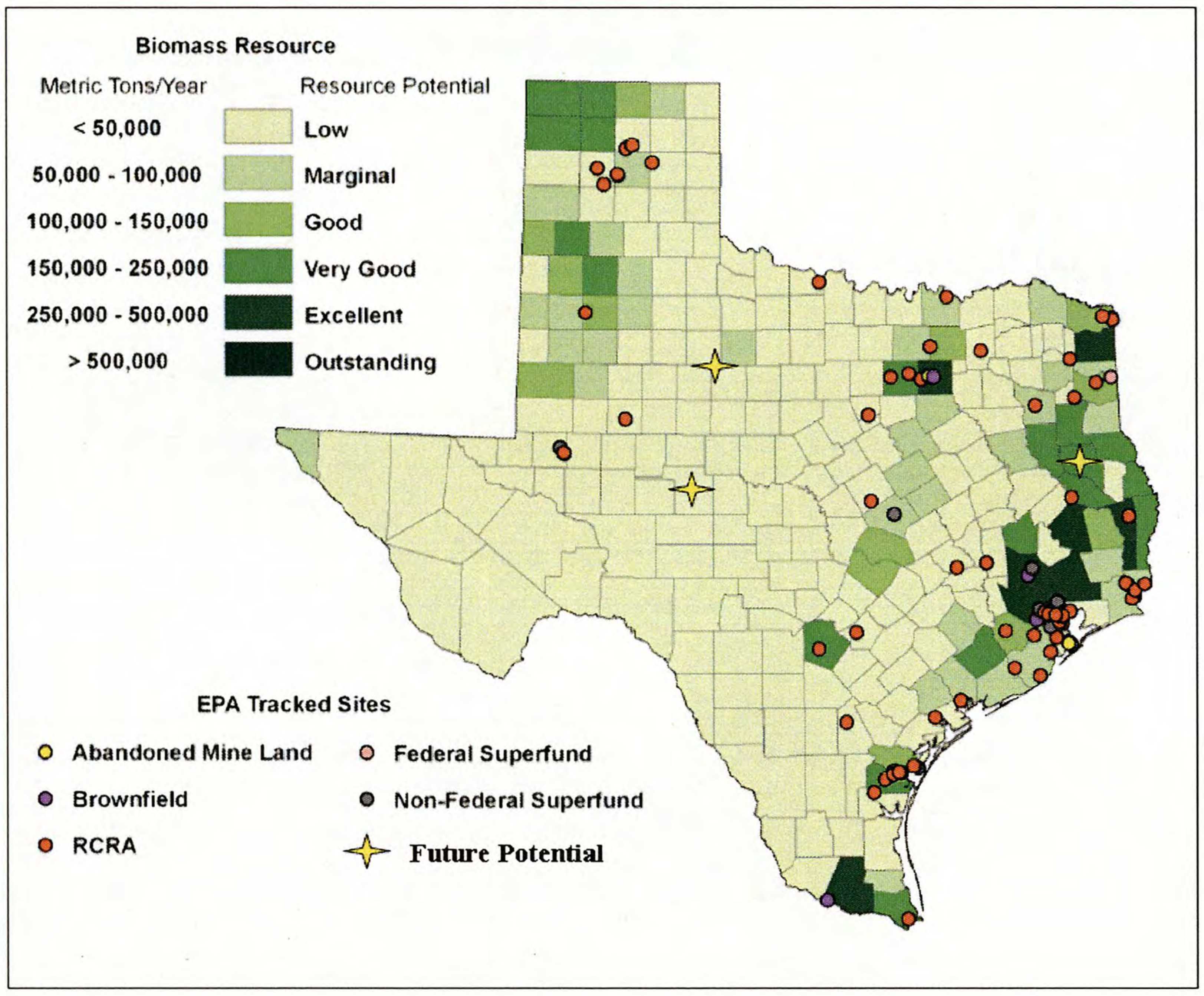
Texas has significant amounts of biomass resources that can be used for bioenergy production. The typical feedstock for biomass in Texas can include

- animal waste,
- crop and mill residue,
- wood chips/sawdust,
- forest products/mesquite/cedar,
- municipal solid waste,

- sorghum,
- switchgrass, and
- oil seed crops/husks/grain.

1.1.6.1 Texas Potential

Given these feedstocks, the Environmental Protection Agency conducted an analysis that identified areas of Texas with the highest potential for biomass resources.



Source: EPA

Figure 1.25: Texas Biomass Resource Potential

Figure 1.25 shows that the highest potential for bioenergy production occurs in East Texas due to the developed lumber industry and in the Texas Panhandle due to an abundance of animal waste from the cattle ranching industry. Currently, about 20 MW of biomass and 67 MW of landfill gas capacity have been developed in East Texas (Governor's Competitive Council, 2008). However, three more sites, which would add over 100 MW of biomass capacity, are being considered for future development:

- Sacul in Nacogdoches County,
- Hamlin in Fisher County, and
- San Angelo in Tom Green County.

In November of 2009, Southern Power broke ground on a 100-MW biorefinery in Sacul, TX. Construction of the facility is expected to last 32 months and the facility is expected to go into operation by 2012. According to company reports, one million tons of biomass will be required annually as fuel for the facility. The bio-resource is planned to be procured within a 75-mile radius of the project site. The biomass resource within the area is estimated to be abundant enough to support the refinery for 20 years. Southern Power has also signed a 20-year agreement with Austin Energy to purchase electricity from the generation plant (Southern Power News Releases, 2009).

Another two sites proposed by Mesquite Fuels & Agriculture, Inc. are located in Hamlin and San Angelo, TX. The proposed plant in Hamlin (East Texas) seems to have more potential because of the established lumber industry. For example, in 2005, logging companies produced 9.5 million tons of logging and mill residues. These residues will have to be moved by truck over relatively short distances (usually less than 50 miles) to the power plant. The San Angelo facility, on the other hand, plans to rely on mesquite as a fuel source, which would be harvested from more than 300,000 acres in and around the San Angelo area (Mesquite Fuels & Agriculture, ND).

1.1.7 Geothermal Energy in Texas

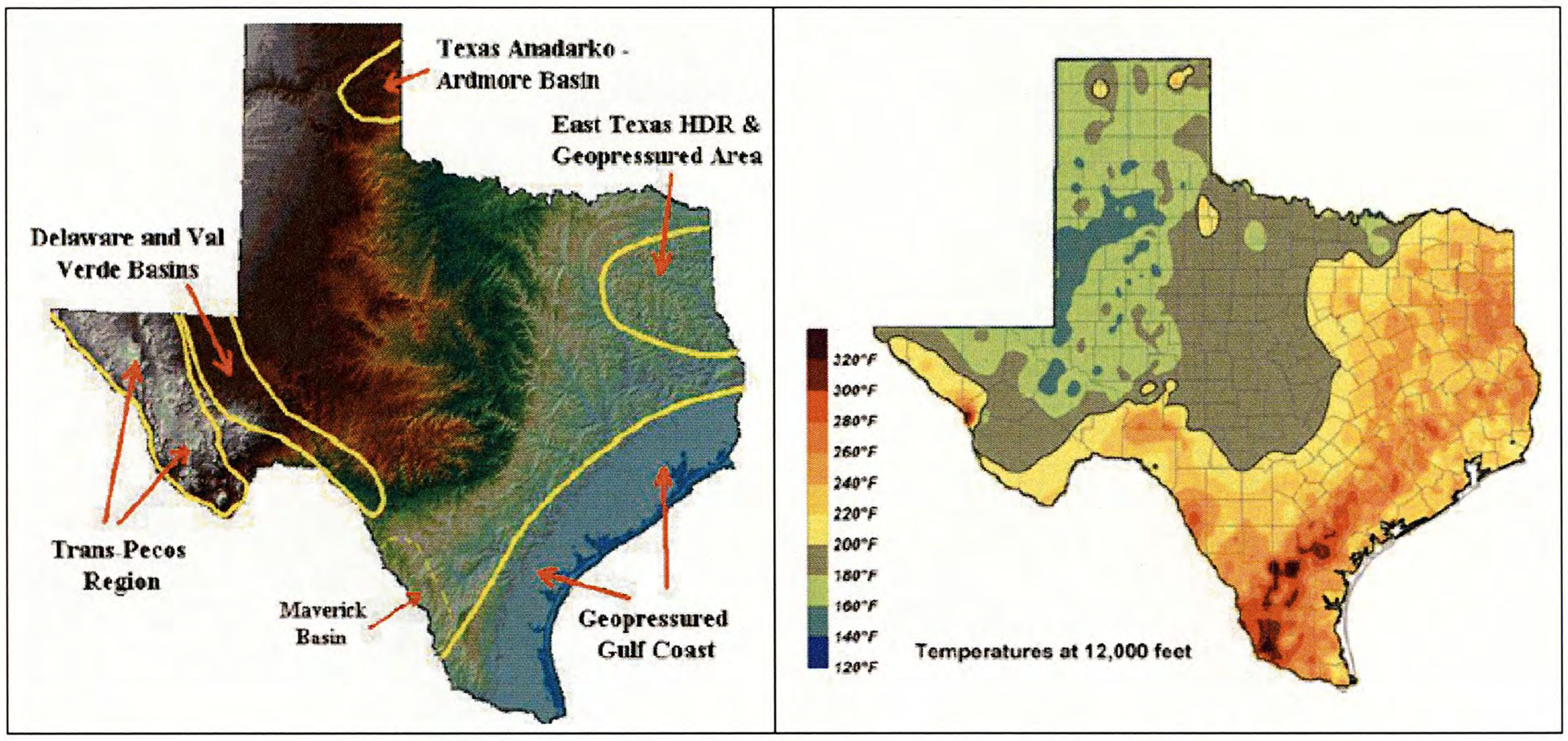
Geothermal energy can be defined as "heat" energy produced from inside the earth, while "geothermal resource" can be thought of as the energy resource accessible for human use. Depending on the temperature of the geothermal resource, heat from the earth can be used for various applications (see Table 1.3).

Table 1.3: Applications for Geothermal Energy

Resource Temperature	Best Application for Geothermal Heat
Surface Temperature (40°F to 80°F)	Geothermal HVAC systems for homes and buildings
Low Temperature (70°F to 165°F)	Direct Use: agriculture and greenhouses, aquaculture (fish farming), spas and bath facilities, district water heating, soil warming, food processing
Moderate Temperature (165°F to 300°F)	Binary fluid generators for electrical production. Direct Use: absorption chillers, fabric dyeing, pulp and paper processing, lumber and cement drying, sugar evaporation
High Temperature (>300°F)	Electricity production, mineral recovery, hydrogen production, ethanol and biofuel production

Source: Texas Renewable Energy Assessment

Texas has an abundant geothermal resource, which can be used for various applications. Most areas of the state, for example, can make use of the moderately high surface temperatures for heating-ventilation and air-conditioning (HVAC) systems for home and building applications. Meanwhile the low to moderate temperature zones of central Texas have supported the bath and spa industry since the late 1800s. Large-scale electricity production from geothermal resources is limited mainly to areas of east, west, and south Texas. Figure 1.26 indicates that, at depths of 12,000 feet, several areas in the state attain temperatures that are high enough to sustain geothermal energy production.



Source: Texas Renewable Energy Assessment

Figure 1.26: Texas Geothermal Potential

An assessment of Texas's geothermal energy potential conducted by the University of Texas of the Permian Basin identified several areas where geothermal electricity production is viable:

- geo-pressurized wells along the Texas Gulf Coast line,
- East Texas Hot Dry Rock (HDR),
- Delaware and Val Verde Basins,
- Trans-Pecos Region, and
- Anadarko Basin.

The basement rock of East Texas was identified as having the greatest potential for geothermal electricity generation and the region in general is considered to be the area with the highest heat flow in the state. Temperatures at well bore holes were calculated to reach 400 °F at depths of 20,000 feet. The high temperature of the basement rock makes the area ideal for electricity production through Enhanced Geothermal Systems (EGS). These systems rely on the injection of fluid into the dry hot rock to act as a carrier of heat for electricity production. Overall, the potential of East Texas was estimated to be approximately 90,000 EJ (exajoules) of available geothermal resource—over 100 times more energy than the annual energy consumption of the entire state (Erdlac, 2007).

Although Texas has an abundant geothermal resource, it has not been developed. The only known case of geothermal energy production in Texas was a one-MW geo-pressured/geothermal demonstration facility in Pleasant Bayou that was sponsored by the U.S. Department of Energy (DOE). The facility was in operation for 121 days from 1989–1990 and it produced 3,445 MWh of energy during the period of operation. It was eventually shut down due to economic reasons. Conventional wisdom holds that the price of electricity needs to stay above $0.08 per kWh for geothermal electricity to be financially viable in Texas. Also, geothermal projects are high in upfront investment costs and have long payback periods of 10–30 years (Texas Renewable Energy Resource Assessment, 2008). These factors along with a lack of economic incentives and legislative support have hindered the development of Texas's abundant geothermal resource.

The most promising use of geothermal energy today lies in modular small-scale geothermal power units offered by energy companies to oil and natural gas well developers. Powering an oil or natural gas pad site can require a significant amount of electricity. Therefore, energy companies such as KGRA Energy specialize in providing modular geothermal power units to well developers. These units use the heat waste from the oil and gas wells to produce electricity for the pad site, while excess electricity is sold back to the grid. These units have the potential to produce up to 3–5 MW of electricity. According to KGRA Energy's Chief Executive Officer, the units provide several benefits to the user:

- carbon credits for the operator,
- long-term stable power source at a cheaper price,
- extended economic life of a reservoir, and
- lowered production costs.

The impacts of geothermal energy production on the Texas transportation system are thus minimal. Although the industry has potential for growth, at this time the most promising use of geothermal power lies in modular small-scale units that, according to KGRA Energy's representative, fit comfortably on a single flatbed truck (Permian Basin Petroleum Association Magazine, 2009). Figure 1.27 illustrates one of these units being installed on site.

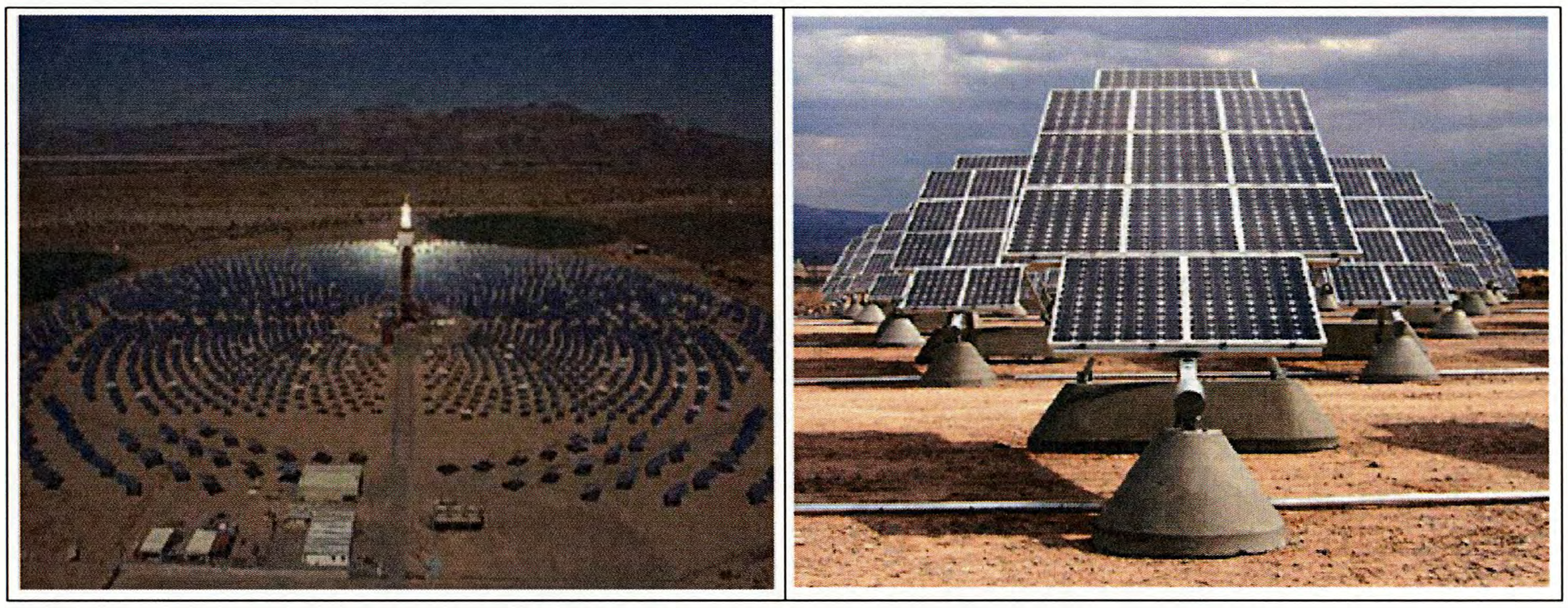
Source: PBPA, 2009

Figure 1.27: Modular Geothermal Power Unit

1.1.8 Solar Energy Development in Texas

The solar energy industry in Texas is currently dominated by rooftop panels. However, legislation, such as Senate Bill 20, and incentive programs, such as the Southwest Concentrating Solar Power 1000-MW Initiative[2], can stimulate the growth of commercial solar panel farms in Texas. If a commercial solar power industry were to emerge in the state, then potentially adverse impacts on the Texas transportation system could occur. This section of the report provides information about those regions that have the highest potential for solar farm development in Texas. However, to understand Texas's potential for harnessing the power of the sun, it is first important to understand the solar energy market.

The solar energy market is dominated by two types of technologies: (1) solar thermal and (2) solar photovoltaic. Thermal technologies typically rely on parabolic concentrators to reflect direct solar radiation onto a fluid that then flows to a steam turbine that drives an electric generator. Photovoltaic (PV) technologies rely on cells constructed from semiconductor materials that directly convert sunlight into electricity (Texas Renewable Energy Resource Assessment, 2008). These two types of technologies are presented in Figure 1.28.



Source: Texas Renewable Energy Resource Assessment, 2008

Figure 1.28: Solar Thermal Power System (left), Photovoltaic Cell System (right)

The future of the solar industry is anticipated to lie in PV technologies. PV technologies are expected to surpass solar thermal and even wind technology in terms of cost effectiveness in the near future. However, the success of the industry will depend upon its ability to produce a cost-effective and reliable product. Currently, most companies involved with PV technologies are in their development stages. The two biggest challenges that these companies face are 1) development of PV cells with high conversion efficiencies, and 2) a cost-effective manufacturing process. The most promising process *"uses monolithic integration to deposit multiple layers of material, including a thin film copper-indium-gallium-diselenide (CIGS) semiconductor on a flexible, lightweight, plastic substrate*" (Ascend Solar, 2007). If this process is ever refined, it will likely revolutionize the solar energy market, allowing PV technologies to become more affordable and competitive for both commercial and residential applications.

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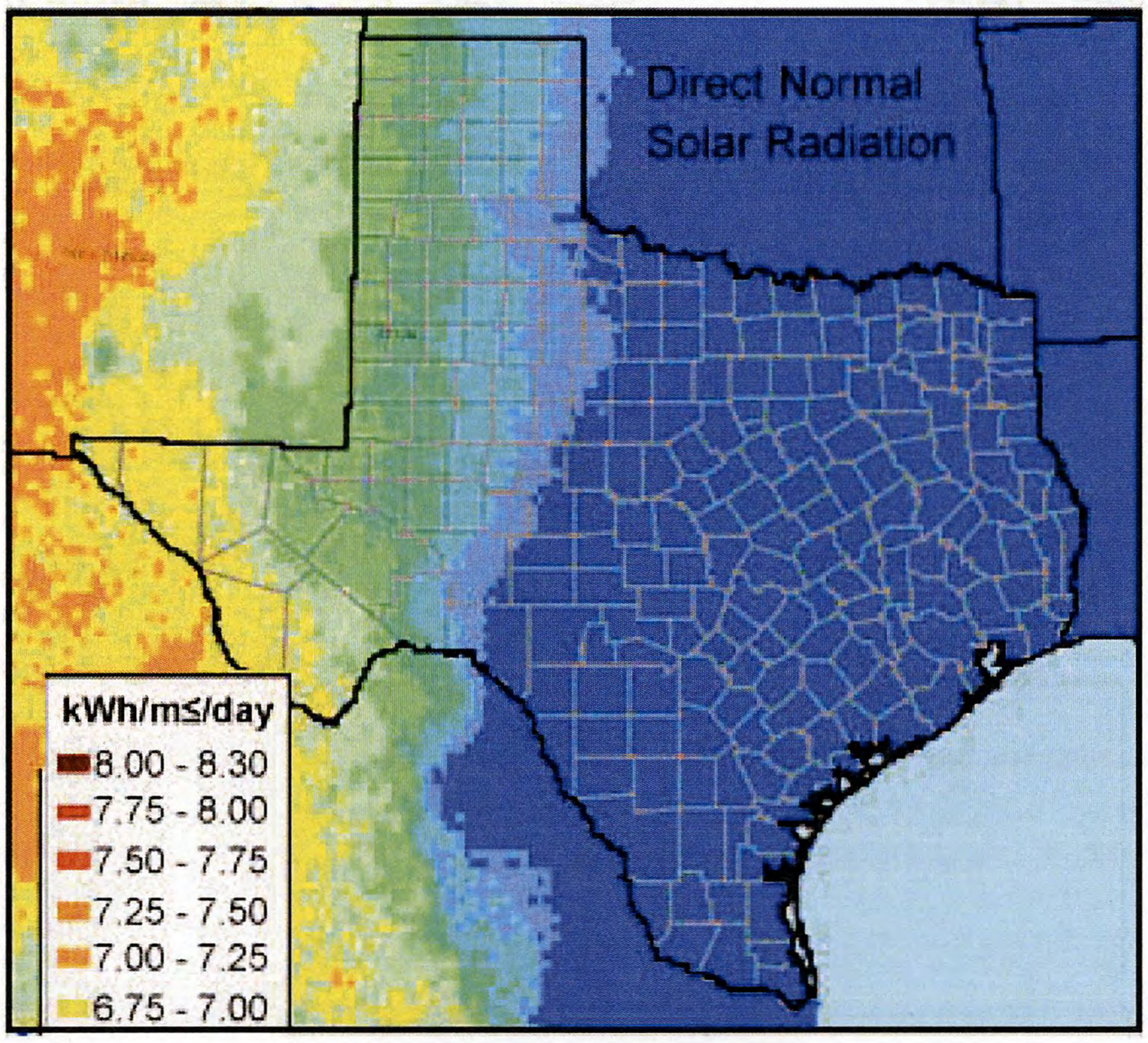
[2] The Southwest Concentrating Solar Power 1000-MW Initiative is a U.S. DOE-sponsored program whose goal is to install 1,000 MW of new concentrating solar power systems in the southwestern United States by 2010.

1.1.8.1 Texas Potential

Texas, due to its large size and abundance of sunshine, has one of the largest solar energy resources in the U.S. Figure 1.29 illustrates the areas with the highest potential for solar energy production.

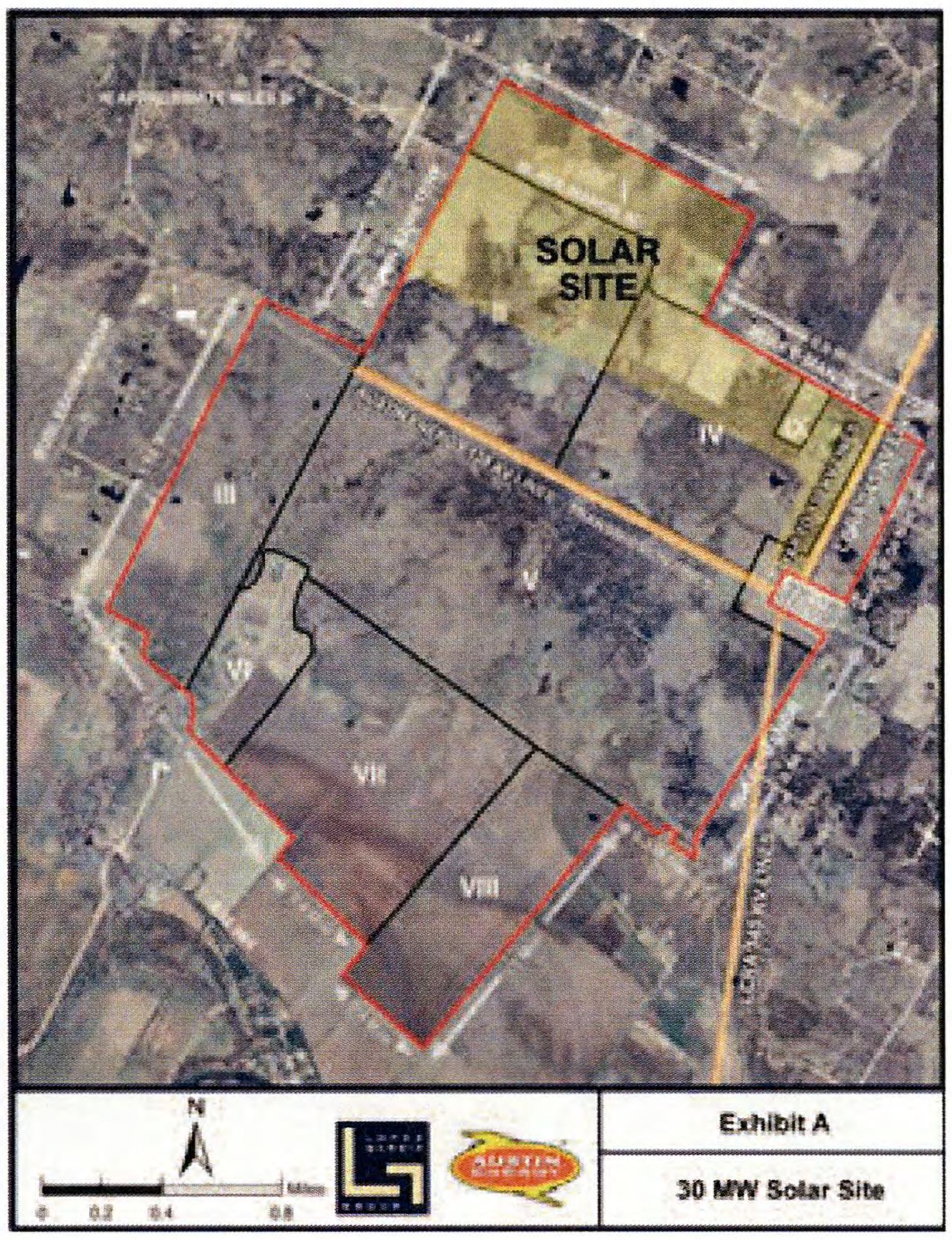


Source: National Renewable Energy Laboratory

Figure 1.29: High Potential Solar Energy Generation Areas

As Figure 1.29 indicates, based on current technology, some areas in Pecos County, near El Paso, have the potential to produce 6.75 kWh/meter/day of solar energy from direct normal solar radiation. To put this number in perspective, an average home typically consumes 10,650 kWh per year or 29 kWh per day.

Although West Texas is considered to have the highest potential for large-scale solar energy generation, no solar power plants are operating in Texas today. Austin Energy is currently developing a 300-acre solar facility outside Webberville, TX (Figure 1.30) that is expected to have a generating capacity of 30 MW during the peak hours of the day (Austin Energy, 2009).



Source: Gemini Solar Development Company, ND

Figure 1.30: Austin Energy Solar Facility, Weberville, TX

An estimated 170,000 photovoltaic cells will be installed on the development site (Gemini Solar Development Company, ND). This project represents the first step towards the Austin City Council's goal to develop 100 MW of solar capacity for the city by 2020 (Austin Energy, 2009). More solar farm projects are thus expected to emerge around the Austin area.

However, in general solar energy generated by rooftop panels is believed to have more potential than large-scale solar farms (Grady, 2006). However, incentives to reduce the cost[3] of solar energy generation could result in the development of solar farms in West Texas and around the Austin area.

1.2 Concluding Remarks

This chapter of the report attempted to familiarize the reader with the diverse industries that comprise Texas's energy sector. Specifically, this chapter aimed to identify those industries that have and will continue to have an impact on Texas's transportation system. Chapter 2 details the energy supply chains that were developed for Texas and Chapter 3 documents the calculated impacts of the wind energy, natural gas, and crude oil industries on Texas's transportation system. Chapter 4 summarizes the work completed and provides major conclusions from this study. Finally, three appendices are included in this report: Appendix A, Appendix B, and an attached CD. Appendix A has been broken into four sections as follows: A1 is titled *GPS*

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[3] Solar electricity is still more expensive compared to wind and grid prices (Grady, 2006). Austin Energy estimated the cost of power produced by their solar plant at 16.5 cents per kilowatt-hour, while the power generated through the development of a new natural gas or coal plant would cost around 9 to 16 cents per kilowatt hour (Austin Energy.)

Coordinates of Pavement Sections; A2 is titled *Pavement Damage Estimates due to Wind, Natural Gas, and Crude Oil Energy Developments*; A3 is titled *Reduction in Service Lives of Pavements due to Wind, Natural Gas, and Crude Oil Energy Developments*; and A4 is titled *The Mechanistic Empirical Pavement Design Guide*. Appendix B contains information on major gas well developers and operators. This report also contains a CD, found at the back of this book, with ARCGIS files that were developed as part of this research study.

Chapter 2. Energy Supply Chains for Texas

This chapter details the energy supply chains that were developed for Texas. Supply chains were developed for (a) the construction/development of enabling infrastructure that allowed for the exploitation of the energy source, and (b) the movement of the energy between production centers in Texas and consumption centers in the state, U.S., and beyond. These supply chains were developed from information collected through reviewing the literature, attending conferences, conducting telephone interviews, and initiating personal communication with industry representatives and relevant government agencies. The development of these supply chains enabled the research team to measure the transportation impacts imposed by Texas's energy sector on the Texas transportation system (see Chapter 3).

> Supply chains can be defined as *"network(s) of autonomous or semi-autonomous business entities collectively responsible for procurement, manufacturing, and distribution activities associated with one or more families of related products"* (Janyashankar et al. 1996).

2.1 Energy Supply Chain for Natural Gas

The Barnett Shale is currently the largest natural gas play in the state. In 2009, it accounted for 25% of total Texas natural gas production (RRC, 2010). Its location in the heart of the Dallas-Fort Worth-Arlington metropolitan region makes it unique. Therefore, the Barnett Shale was used as the case study for developing detailed supply chains for the natural gas sector. The following sections will provide an overview of drilling activity in the Barnett Shale along with the steps that were taken to develop supply chains for the natural gas sector. The information presented includes data regarding various construction and production activities found to have an impact on Texas's transportation system.

2.1.1 Developing a Supply Chain for Natural Gas

Natural gas production is a complex multi-stage operation that involves the collaboration of many parties. First, seismic exploration is conducted to determine the most economically suitable locations for drilling natural gas. Then a pad site and a site access road are prepared to receive construction traffic and drilling traffic. Afterwards, the rotary rig is delivered in several sections and assembled on site. Once the rig is assembled, drilling begins and the well site is continuously visited by various service companies, for example cement and mud services, over a span of several weeks. If the well is determined profitable, a well head is installed and the well is connected to the main pipeline (Chesapeake Energy, ND).

Typically, several wells are drilled on the same pad site and are connected to one main gathering line, which then connects to a compressor station. Compressor stations function similarly to electrical substations in that they act as central distribution points for natural gas. Natural gas flows through the well head to the pipe and into compressor stations where water vapor and other condensate is removed to ensure a higher quality product. Then higher pressure is applied to move the gas to local and distant markets through transmission pipelines. In the U.S., almost all natural gas (approximately 95%) is distributed from the well to its final destination through a network of pipelines. Truck, rail, or barge transportation of natural gas requires converting the gas into liquid form—which occurs at approximately -260° F—and hauling it in specially outfitted tanker units (American Petroleum Institute, ND). Therefore, it is rarely transported via those means.

Natural gas production consists of several major operations that use and impact the Texas transportation system. In this context, well construction traffic plays a significant role. Also, in the Barnett Shale—as with other "unconventional" natural gas shale plays, where hydraulic fracturing is used to stimulate the flow of hydrocarbons—the disposal of "production" or salt water is a major concern as it generates a significant amount of truck traffic. Figure 2.1 illustrates the natural gas supply chain and the major construction/production activities that comprise the mining and distribution of natural gas.

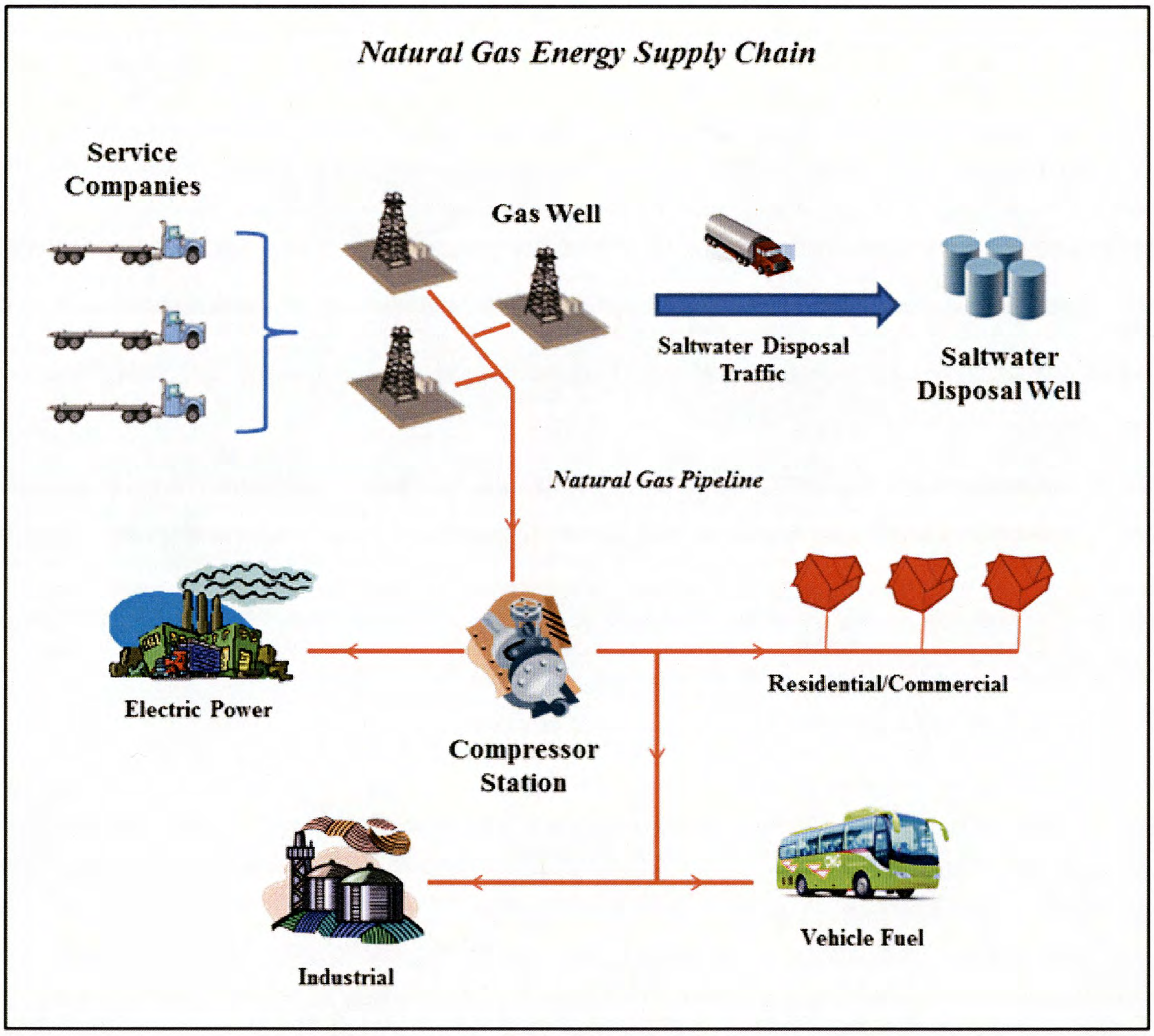


Figure 2.1: Natural Gas Energy Supply Chain

Truck traffic associated with natural gas well development in the Barnett Shale can thus be attributed to three operations:

(1) seismic exploration,

(2) construction traffic, and

(3) production traffic.

The following sections discuss these traffic generating activities.

2.1.1.1 Seismic Exploration

Seismic exploration is conducted to determine where to drill for natural gas. Typically, seismic exploration involves the creation of artificial vibrations, called *seismic waves*, which travel through the earth and are reflected back to the surface. The earth's crust is composed of different layers that reflect the waves in different ways, depending on the geology. This reflection allows seismologists to determine where the natural gas formations are underneath the earth's crust.

Seismic exploration requires the use of seismic trucks to create vibrations. Seismic trucks are typically 40,000–65,000 lbs all-terrain four-wheel drive vehicles analogous to a large rubber-tired log skidder or a very heavy farm tractor. Seismic trucks can be split into two types—"thumper" trucks and "vibe buggies"—depending on the mechanics of the artificial vibration. *Thumper trucks* rely on a heavy ground impact plate that is hoisted 9–10 ft off the ground and then released to create a seismic wave (Moore, 2008). *Vibe buggies,* on the other hand, rely on a mounted plate that is placed on the ground, and then the truck is raised, so most of its weight is on the plate. The plate then vibrates, generating a seismic wave. A vibe buggie operating in the Barnett Shale is illustrated in Figure 2.2.

Source: askchesapeake.com, 2009

Figure 2.2: Vibe Buggie Operating in the Barnett Shale

Seismic trucks can result in profound damage to the pavement network. In fact, different states have written various regulations prohibiting the use of seismic trucks next to buildings or on the pavement infrastructure (Moore, 2008). In Texas, regulations have been introduced that dictate that thumper trucks ***cannot*** be used on paved surfaces, because of the force of the impact. However, the regulations on vibe buggies are unclear.

Seismic exploration in the Barnett Shale will continue as more wells are drilled to meet the state's growing energy demand. Because the Barnett Shale is located in an urban area, seismic exploration needs to be closely monitored as old underground pipes, building foundations, and the roadway infrastructure *may* be significantly damaged.

2.1.1.2 Construction Traffic

Construction traffic is generated during the five-step well development process: site preparation, rigging up, drilling, hydraulic fracturing, and rigging down. Initial site preparation requires heavy bulldozers for grading and building a road to serve the pad site. Subsequently, the rotary rig must be moved to the pad site and assembled on site. Typically, a rig that can drill a 10,000 foot well will require 35 to 45 semi-trucks to move and 50 to 75 people to assemble the rig (Barnett Shale Energy Education Council, ND). Once the drilling of the well hole begins, steel piping and cement are delivered on site by truck for casing and cementing the well hole to prevent groundwater contamination. Mud used for lubricating the drill is also delivered on site by truck. Drilling of the well hole takes about 2 to 3 weeks. If the well hole is determined to be economically viable, the well is perforated and hydraulic fracturing begins. Hydraulic fracturing or "fraccing" is the process of pumping air, water, and sand under high pressure into the well hole to fracture through the thick shale and stimulate the flow of natural gas. According to a study conducted by Texerra (2007), a typical well in the Barnett Shale area requires approximately 3.05 million gallons of water for drilling and hydraulic fracturing. If water from the local area is unavailable, it must be delivered to the well site by truck. Appendix B provides information about the major gas well developers and operators in the Barnet Shale Region.

A Marcellus Shale field study, conducted by the New York State Department of Conservation, showed that the volume of truck traffic generated by the development of a single gas well can range from 295 to 455 truck visits (one way). The average distribution of one-way truck trips by construction activity is presented in Table 2.1.

Table 2.1: Truck Traffic Associated with the Construction of a Single Gas Well

Well Pad Traffic (1 Well)	Min	Max
Drill Pad and Road Construction Equipment	10	45
Drilling Rig	35	45
Drilling Fluid and Materials	25	50
Drilling Equipment (casing, drill pipe, etc.)	25	50
Completion Rig	15	15
Completion Fluid and Materials	10	20
Completion Equipment (pipe wellhead)	5	5
Hydraulic Fracturing Equipment (pump truck, tanks)	150	200
Hydraulic Fracture Sand Trucks	20	25
Total	**295**	**455**
Hydraulic Fracture Water	400	600
Total	**695**	**1055**

Source: New York State Department of Environmental Conservation, 1998

Typically, a single well is not drilled on a pad site. If a site is determined to be economically productive, then several wells may be drilled on the same site, followed by several more a couple of years later. Therefore, Table 2.2 presents construction traffic for a typical pad site where eight wells are drilled using two rigs.

Table 2.2: Truck Traffic Associated with the Construction of a Pad Site

Well Pad Traffic (8 Wells, 2 Rigs)	**Min**	**Max**
Drill Pad and Road Construction Equipment	10	45
Drilling Rig	60	60
Drilling Fluid and Materials	200	400
Drilling Equipment (casing, drill pipe, etc.)	200	400
Completion Rig	30	30
Completion Fluid and Materials	80	160
Completion Equipment (pipe wellhead)	10	10
Hydraulic Fracturing Equipment (pump truck, tanks)	300	400
Hydraulic Fracture Sand	160	200
Total	**1050**	**1705**
Hydraulic Fracture Water**	3200	4800
Total	**4250**	**6505**

Source: New York State Department of Environmental Conservation, 1998

From these statistics, a general number of construction-generated truck trips in the Barnett Shale area can be estimated using well count data from the RRC's records. Using the minimum (i.e., 695) and maximum (i.e., loss) values for the construction of a single well on a pad site and applying it to the number of wells in the Barnett Shale, it can be estimated that construction traffic has generated ***9.7 to 14.7 million truck trips*** in the Barnett Shale region (13,902) area since commercial production of natural gas began in 2000.

To determine road usage and the average length of haul associated with construction traffic, a route analysis was conducted using the TxDOT OS/OW permit database. The OS/OW permit database captures specific information on routing and the truck dimensions involved in hauling equipment that does not meet legal length, height, width, and weight limitations. The OS/OW data collected for years 2007 to 2009 was analyzed and permit information associated with the natural gas industry was extracted. Specifically, the dataset was queried to identify vehicles reported to move loads, such as rig equipment, drilling equipment, and salt water storage tank equipment in the Barnett Shale area. In total, approximately 1.5 million permits were included in the OS/OW database over the span of 3 years. Naturally querying for information pertaining to a single industry sector within such a large database presents challenges and potentially introduces some margin of error. Furthermore, it should be pointed out that the database only captures the OS/OW traffic. Therefore, the majority of well construction traffic that meets legal limits goes unrecorded. That being said, the information obtained from the OS/OW database pertaining to the natural gas industry in the Barnett Shale did provide a sizable sample and it provided a method for quantifying road usage of construction traffic associated with the natural gas industry.

From the OS/OW dataset, the researchers identified 4,750 route permits that started in the Barnett Shale area and 5,494 route permits that ended in Barnett Shale area over the 3-year period (i.e., 2007 to 2009). Therefore, it is implied that approximately 86.5% of all construction-related traffic included in the OS/OW dataset was local. Figure 2.3 presents a density distribution map of trips that originated in the Barnett Shale. The map indicates that most of the trips began in Denton, Johnson, Wise, and Tarrant counties.

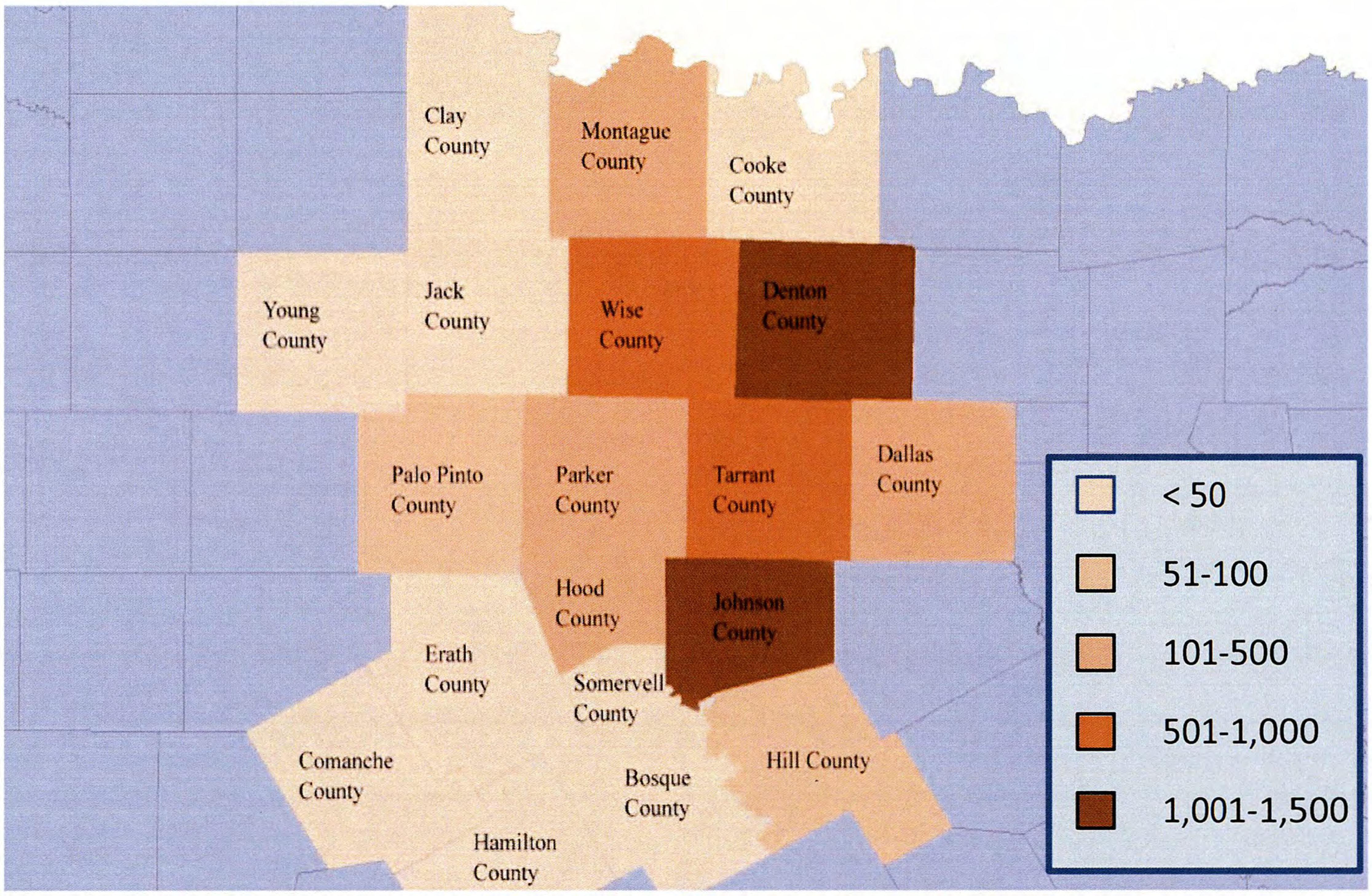


Figure 2.3: Permit "Route Starts" in the Barnett Shale Region (2007–2009)

To understand the types of roads used for moving construction equipment between sites and the average distance of haul, a sample of 50 permit routes was randomly selected from the population and the route data was further analyzed. The OS/OW dataset includes information on the start location and end location of each route, along with a detailed route description to get from the point of origin to the point of destination. This allowed the research team to plot each route, in accordance with the route description, using Google Maps. The length of each trip was subsequently determined using the Google Maps Directions application. Finally, given the mileage traveled on each roadway segment and the total vehicle-miles traveled (VMT) for the entire sample, road usage was determined as a percentage of VMT. Figure 2.4 maps (i.e., the blue lines) the sample of 50 permit routes analyzed. Darker lines represent higher numbers of trips on those roadway sections.

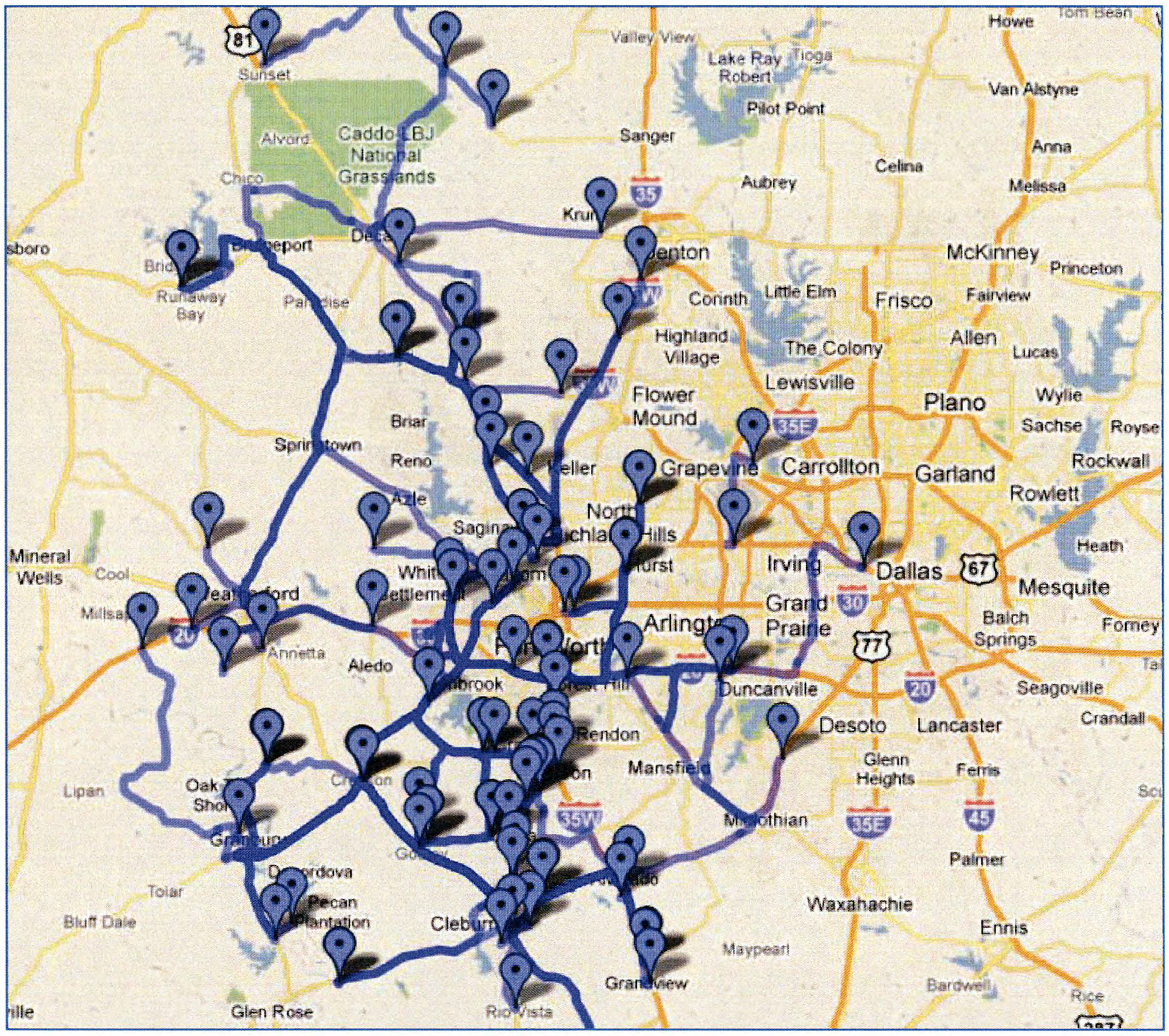


Figure 2.4: Construction Traffic Routes in the Barnett Shale Region

From Figure 2.4, it is evident that very few major roads in the Fort Worth-Arlington area are *not* used for the movement of gas well equipment. Analyzing the trip lengths for the sample of 50 permit routes also showed that the average trip length for hauling gas well equipment is 32.88 miles (standard deviation: 24.95 miles). A histogram distribution for the entire sample size is presented in Figure 2.5.

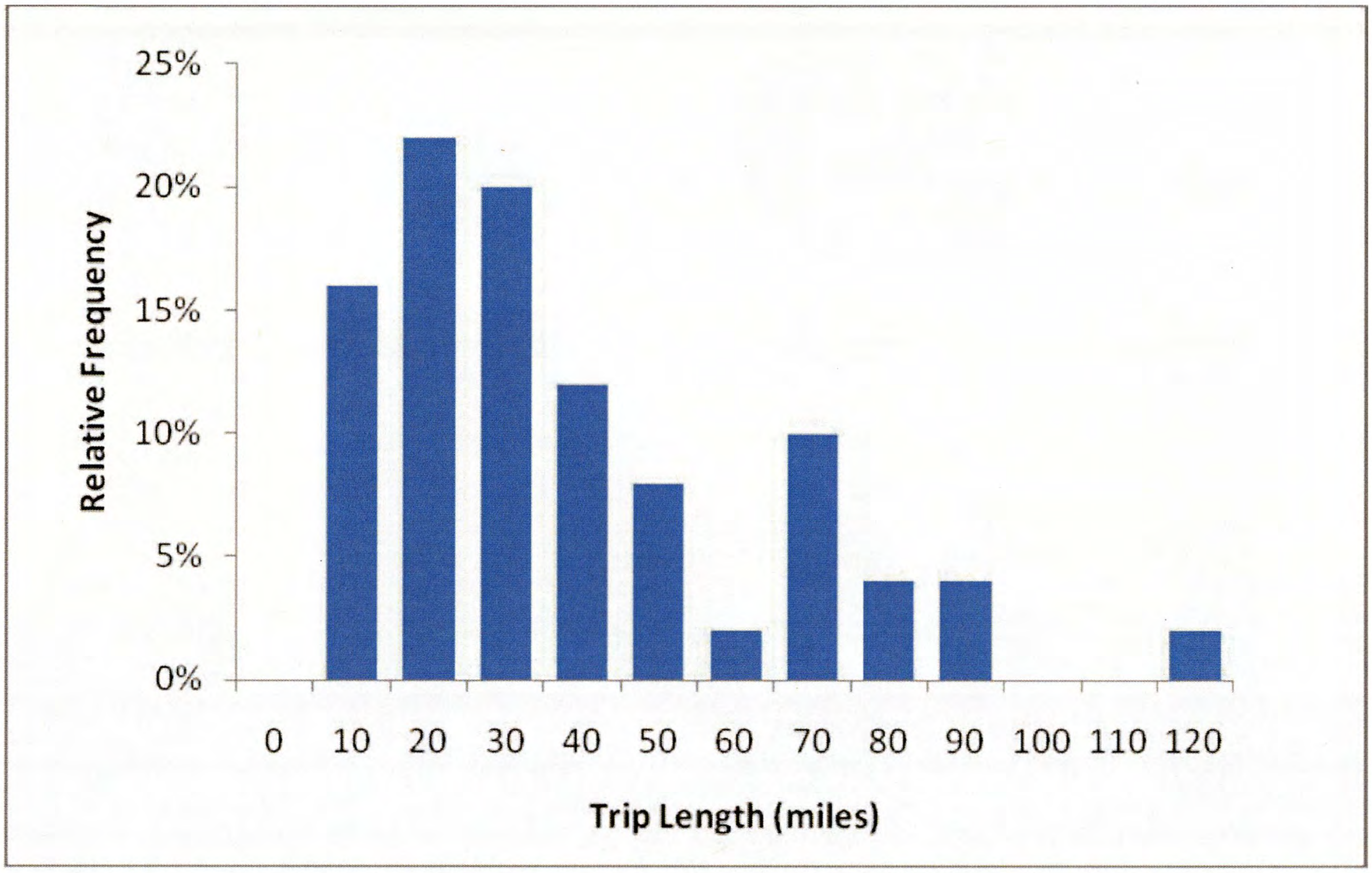


Figure 2.5: Haul Length for Construction Equipment in the Barnett Shale Region

The mileage traveled on each roadway segment was categorized by different road types as follows:

- Interstate Highway,
- US Highway,
- Texas State Highway,
- FM Road,
- Beltways, Spurs, Loops, and Business Roads, and
- Other roads, such as local and county roads.

This categorization allowed for a clear picture as to which types of roads are used in the movement of construction traffic. Based on the sample of 50 permit routes, the total VMT for the entire sample was determined to be 1,643.9 miles. Road usage as a percentage of total VMT is presented in Figure 2.6, which indicates that State Highways (28%) and FM roads (27%) are used more in the Barnett Shale region than Interstates (19%) and US Highways (23%) for the movement of construction traffic.

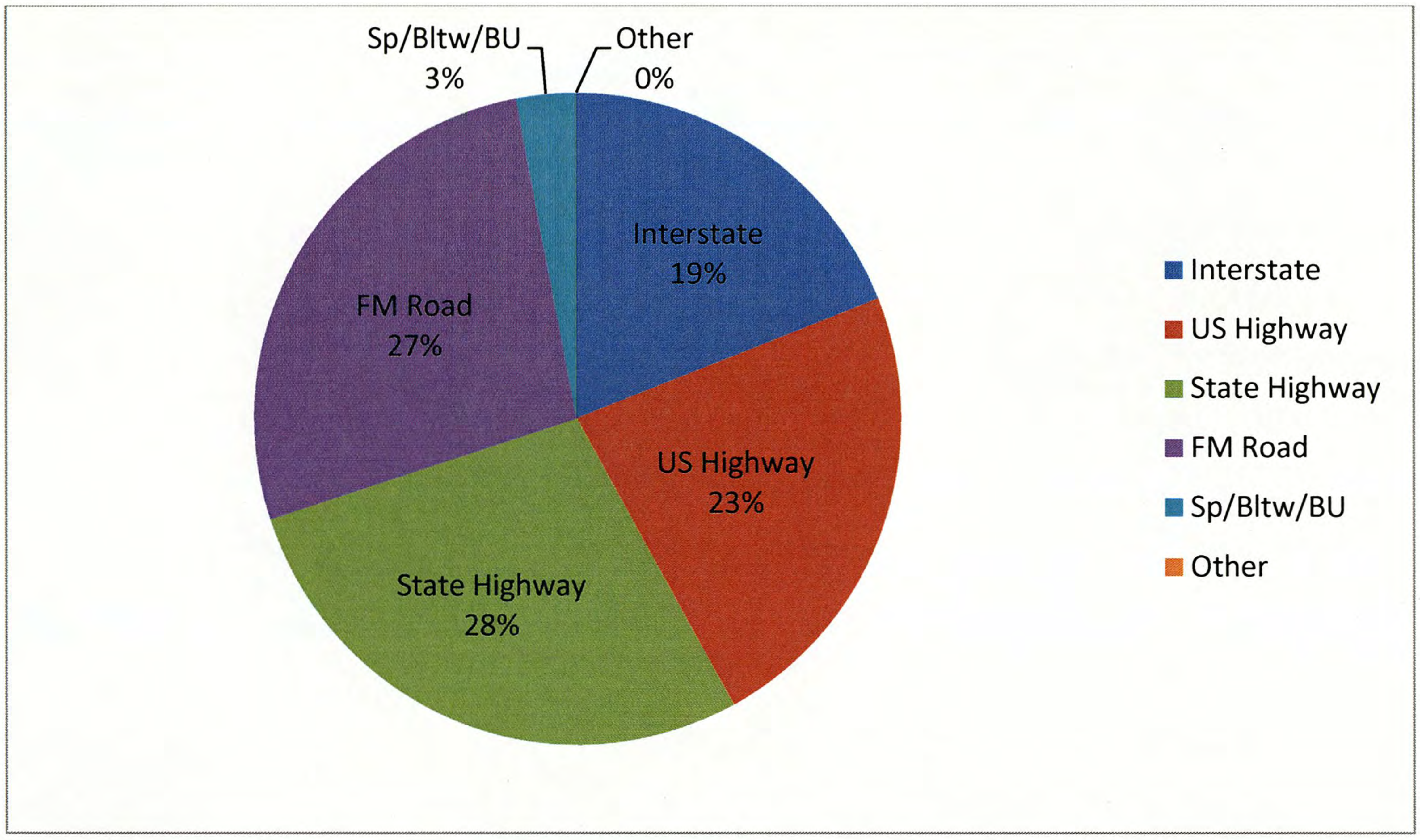
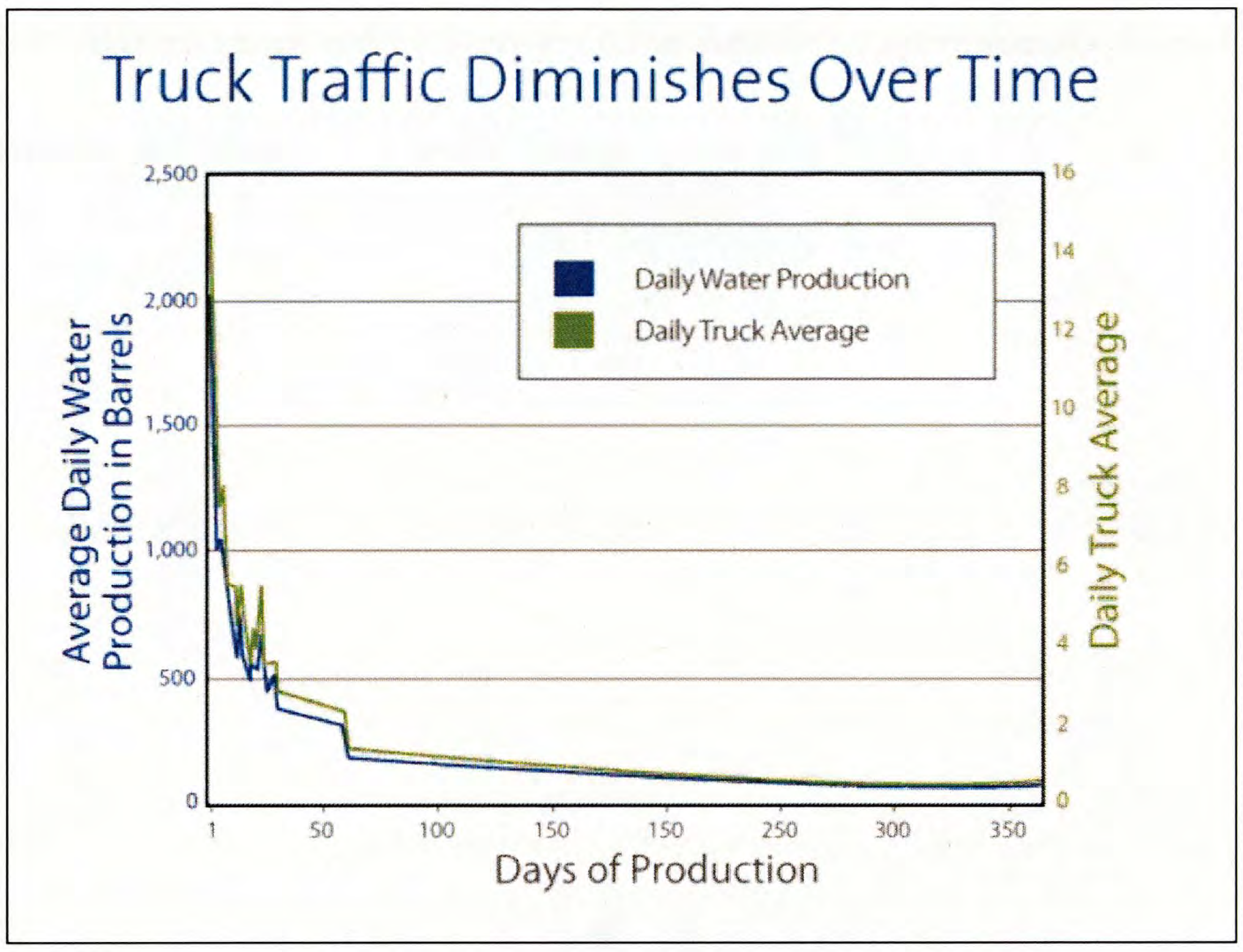


Figure 2.6: Road Usage by Construction Traffic in the Barnett Shale Region

2.1.1.3 Salt Water Disposal Traffic

The second major traffic generating activity in the natural gas energy supply chain is the disposal of salt water. A natural gas well produces water throughout its life, referred to as *backflow*, which is typically trucked from natural gas well sites to Class II salt water disposal wells. A study conducted by Texerra, Inc. found that a natural gas well in the Barnett Shale area requires on average 3.08 million gallons of water for hydraulic fracturing. However, 95% of the latter water emerges above ground again as "production" water, which is then too saturated with salts and other minerals (70,000 ppm) to be recycled and must be properly disposed of in Class II salt water disposal wells (Texerra, 2007). Furthermore, after the initial fracturing, a natural gas well continues to produce salt water throughout the well's life.

Underground disposal of saltwater is regulated by the RRC, which requires proper disposal in Class II saltwater disposal wells. Typically, the saltwater is pumped from the well into storage tanks on the site. From there, it is hauled by truck or moved by pipeline to the saltwater disposal well site, where it is injected into porous rock deep underneath the earth's surface (Chesapeake Energy, ND). The number of truck trips required to haul away the saltwater is largely dependent on the amount of water produced and the size of the truck. Data obtained from Chesapeake Energy revealed that a well may generate approximately 395 truckloads (i.e., an estimated 2.13 million gallons) of saltwater on average during fracturing and the first year of natural gas production. Data from Chesapeake Energy on a natural gas well's salt water production over time is presented in Figure 2.7.



Source: Chesapeake Energy, ND

Figure 2.7: Truck Traffic Generated by Saltwater Production

Data from Chesapeake Energy reveals that, on average, initial production of saltwater amounts to approximately 2,400 barrels per day, requiring approximately 16 truckloads to haul away. A typical water truck can transport between 5,000 to 6,300 gallons[4] of water per load. By the end of the first week, saltwater production decreases to approximately 1,096 barrels per day, requiring approximately 7 trucks to haul away. By the second week of production, water output drops by about 47% and after 60 days by about 72%. After 3 months, only one truckload per well per day is required to haul away the saltwater; after 6 months, the number drops to about one truckload per well per week. Although saltwater production continues to decline over time, the hauling of saltwater continues to be an issue throughout the life of a well.

Based on the data provided by Chesapeake Energy, approximately ***395 truckloads*** will be required to haul away an estimated 2.13 million gallons of saltwater during fracturing and the first year of production. As of May 2010, 13,902 natural gas wells were on record in the Barnett Shale area (RRC, 2010). These 13,902 natural gas wells would have generated an estimated 5.5 million truck trips for saltwater disposal alone since production began in 2001[5]. Most of the saltwater movements are, however, over relatively short distances. According to the RRC's Oil and Gas Division, 34 saltwater disposal wells in the Barnett Shale area were on record in 2008. Most of these disposal wells (i.e., 26) were located in Newark and East Field.

The transportation impacts associated with hauling such quantities of salt water may be substantial[6]. To understand the infrastructure impacts, it is necessary to know the roads used in the transportation of salt water and the average haul distance.

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[4] One gallon of water weighs approximately 8.34 lbs and an average saltwater disposal truck can move up to 52,500 lbs of water.

[5] These figures assume all wells have been fractured and have been producing natural gas for 1 year.

[6] This high volume of activity has placed a significant amount of stress on the roadway infrastructure. Concerns about roadway damage done by trucks have resulted in many cities requiring payment bonds from energy companies drilling in the Barnett Shale area. In Denton County, for example, some areas of the roadway network have experienced significant damage. As the county engineer pointed out: *"We have found that truck traffic does place a large amount of stress on the roads.* ***Some*** *of the asphalt* ***roads*** *have gotten so damaged during the drilling*

A five-step approach was developed to estimate the facility usage and the average length of haul:

1. Locate active gas wells and disposal wells in the Barnett Shale region.
2. Assume gas wells will be serviced by the closest disposal well, and pair every gas well with a disposal well based on shortest distance.
3. Select a random sample and obtain service routes from Google Maps using shortest path (i.e., not shortest distance).
4. Calculate VMT for random sample.
5. Determine percentage of VMT on each road facility type and average haul distance.

For the first step, RRC of Texas data were used to locate all active salt water disposal wells and all natural gas wells completed in 2007 and 2008. In total, 3,756 gas wells were completed and 57 active disposal wells were operating in the Barnett Shale area. These wells, along with their latitudes and longitudes, were plotted in ArcGIS (see CD included in the back of report) and are illustrated in Figure 2.8

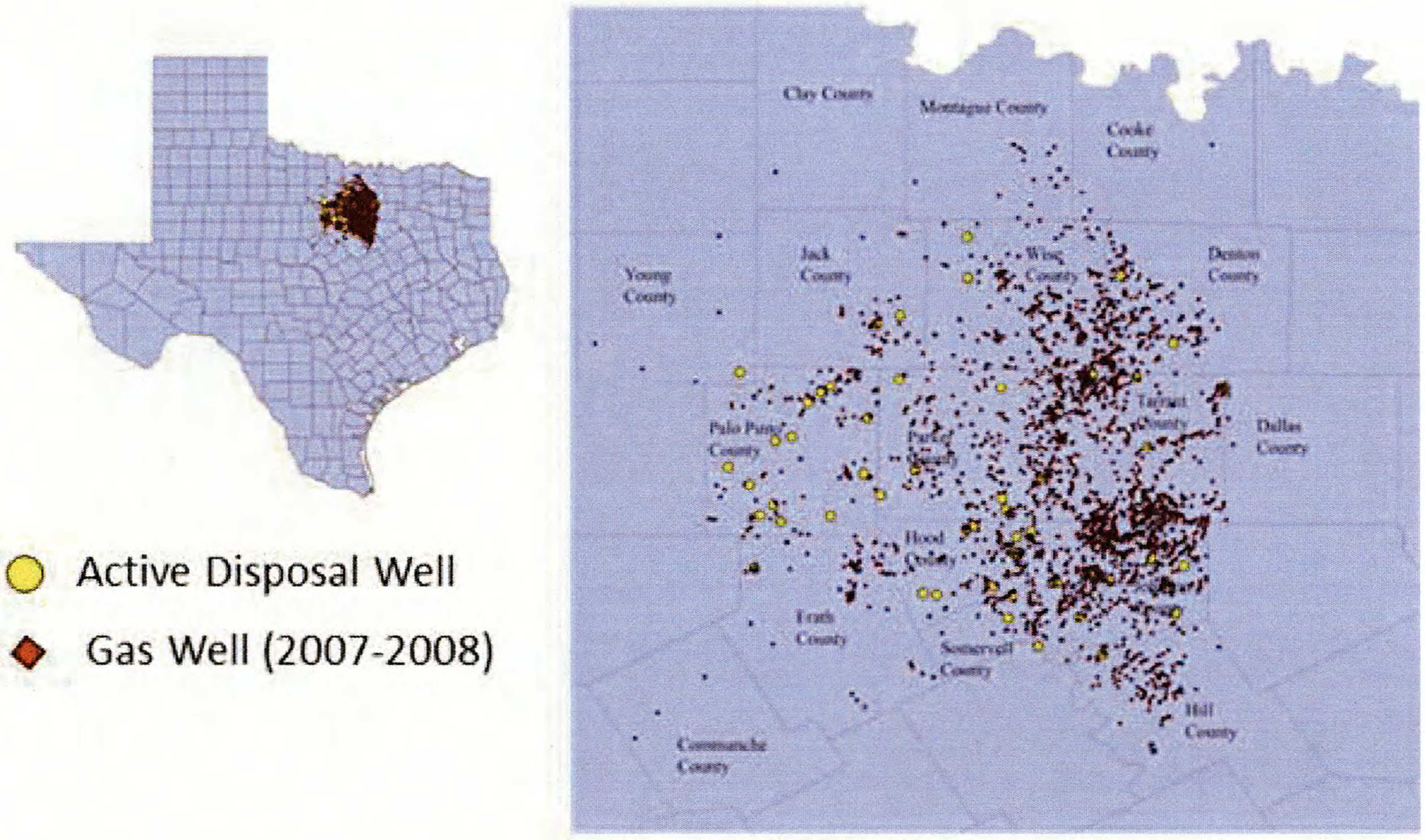

Figure 2.8: Active Gas Wells and Disposal Wells in the Barnett Shale Region

Each gas well on record was subsequently paired with an active disposal well using shortest distance derived from the Vincenty Formula. The Vincenty Formula calculates the shortest distance between *"any two points on the surface of a sphere measured along a path on the surface of the sphere."* Shortest distance was used to pair gas wells with a disposal well. However, to determine the average haul distance and facility usage, actual travel routes were

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*operations that we have **removed** the **asphalt** and **turned** the roads **into gravel** roads. We have also **upgraded** some of the roads to **concrete** to try to improve the life of the roads"* (Denton County Public Works).

plotted using Google Maps. Therefore, a sample of 75 records was randomly selected from the population and plotted using Google Maps (see Figure 2.9).

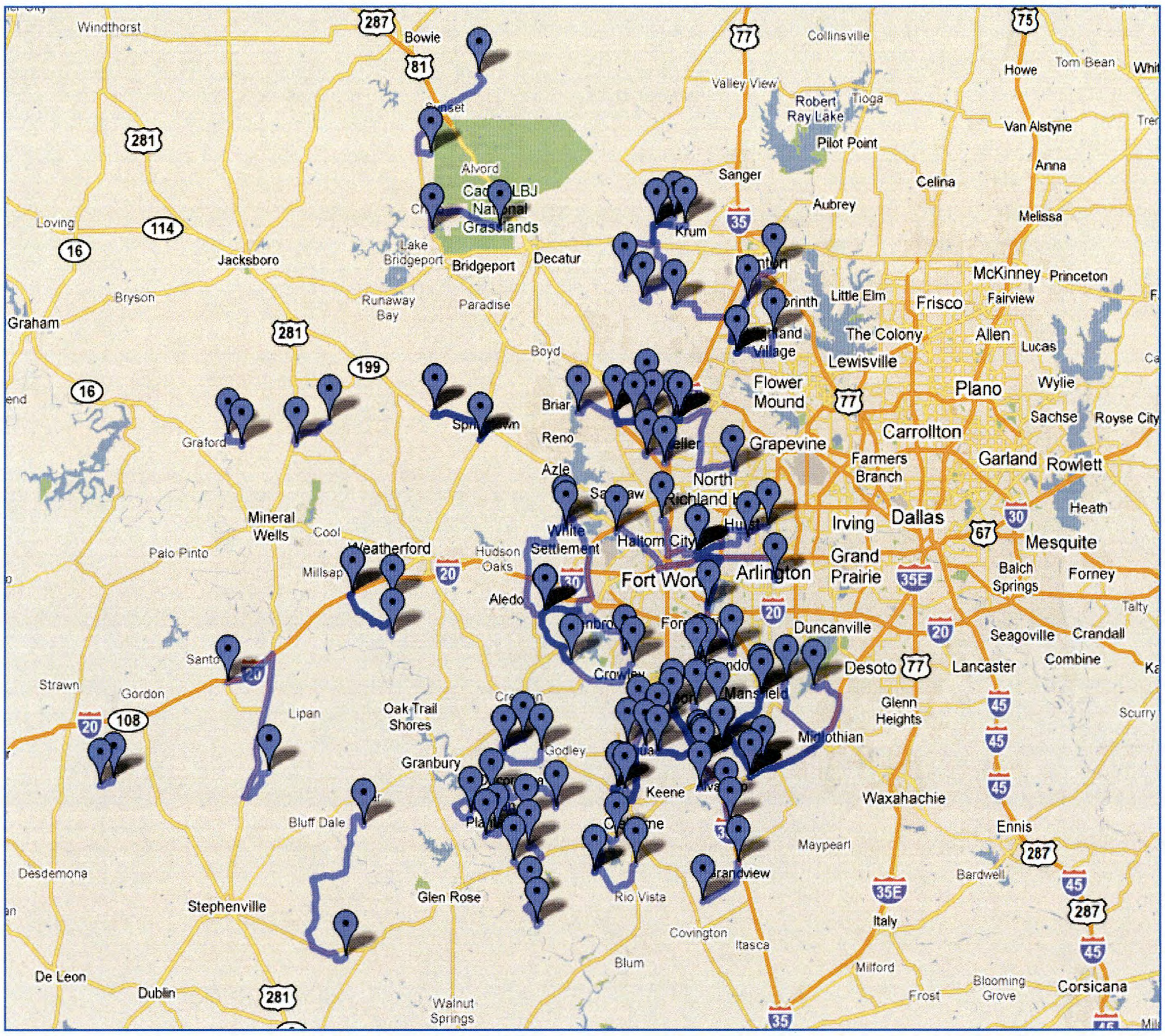


Figure 2.9: Salt Water Disposal Travel Routes in the Barnett Shale Region

From Figure 2.9 it is evident that a substantial share of the traffic occurs on lower functional road classes and, in general, haul distance is substantially shorter than for the construction traffic in the Barnett Shale region. Analyzing the trip lengths for the 75 plotted routes revealed an average trip length of 9.4 miles (standard deviation: 5.34 miles) for hauling salt water. A histogram distribution for the sample is presented in Figure 2.10.

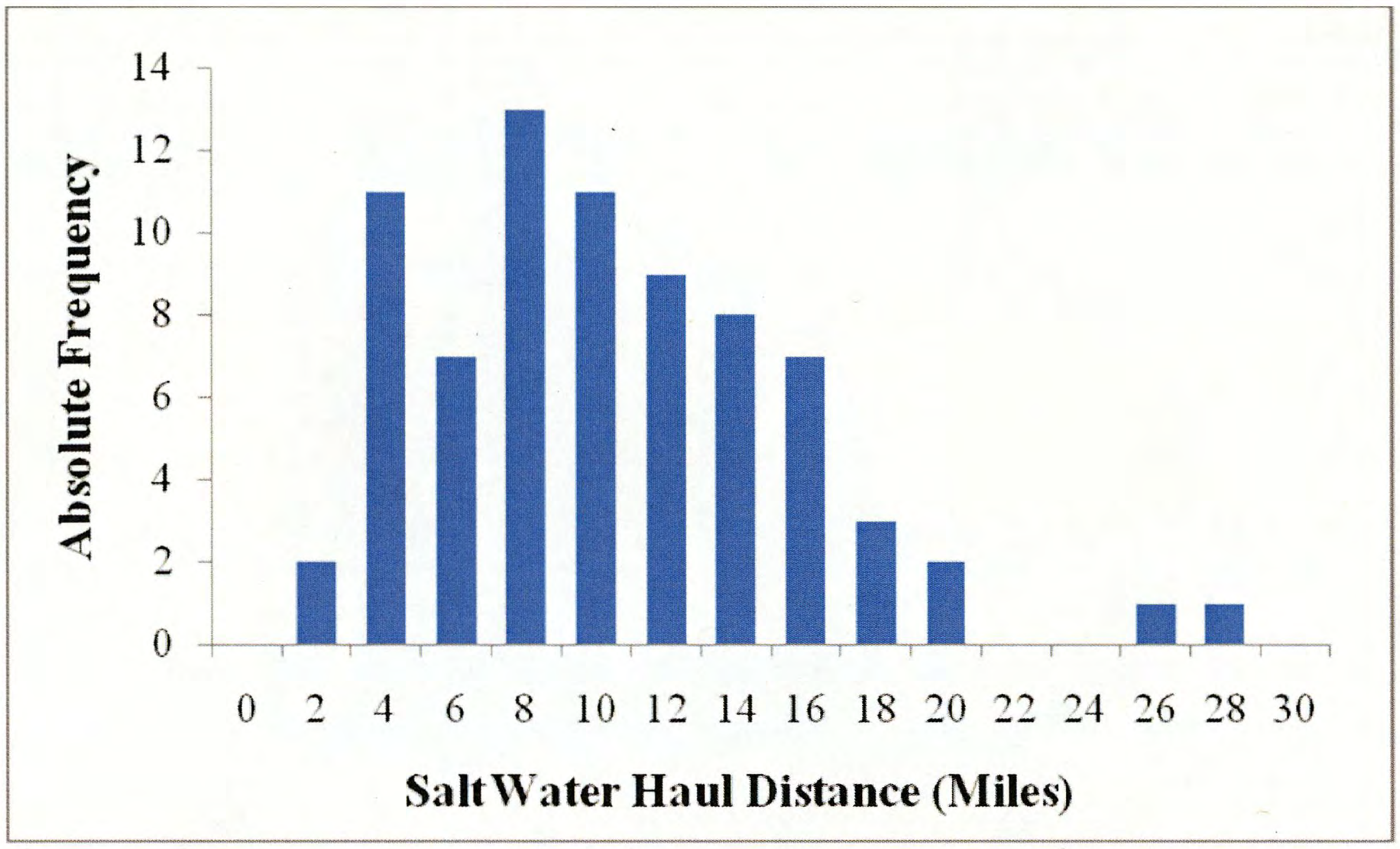


Figure 2.10: Haul Distance for Salt Water Disposal Traffic in the Barnett Shale Region

The total VMT for the sample was calculated at 704.99 miles. Road usage was determined as a percentage of total VMT (see Figure 2.11). Figure 2.11 makes clear that a substantial portion of the salt water disposal traffic occurs on local city streets (30.7%) and FM roads (24.8%).

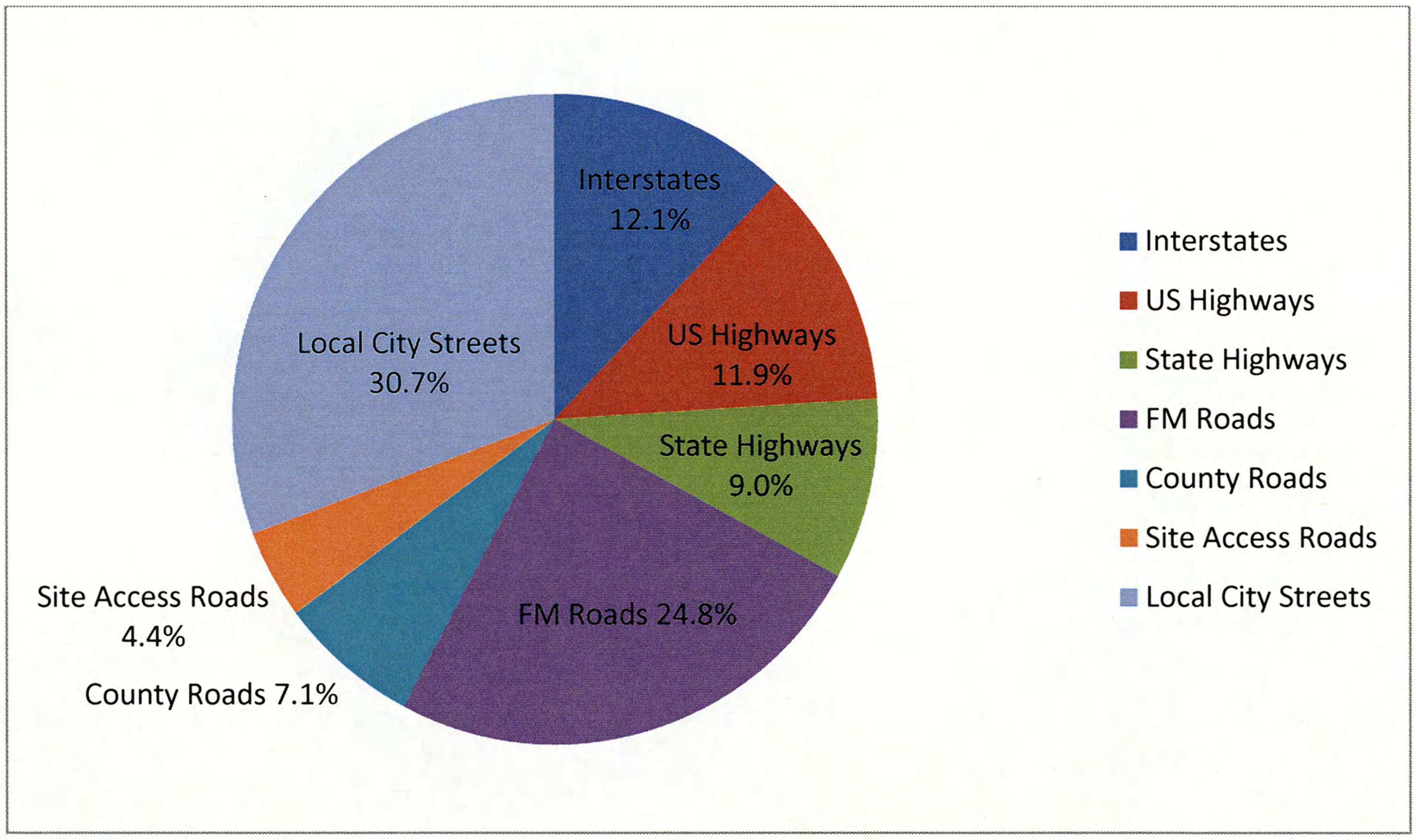


Figure 2.11: Road Usage by Salt Water Disposal Traffic in the Barnett Shale Region

2.2 Energy Supply Chain for Oil

Historically, Texas has been an oil-producing state. Today, most of the oil production occurs in the Permian Basin. The Permian Basin is a 51-county area, which covers most of West Texas and parts of New Mexico (see Figure 2.12).

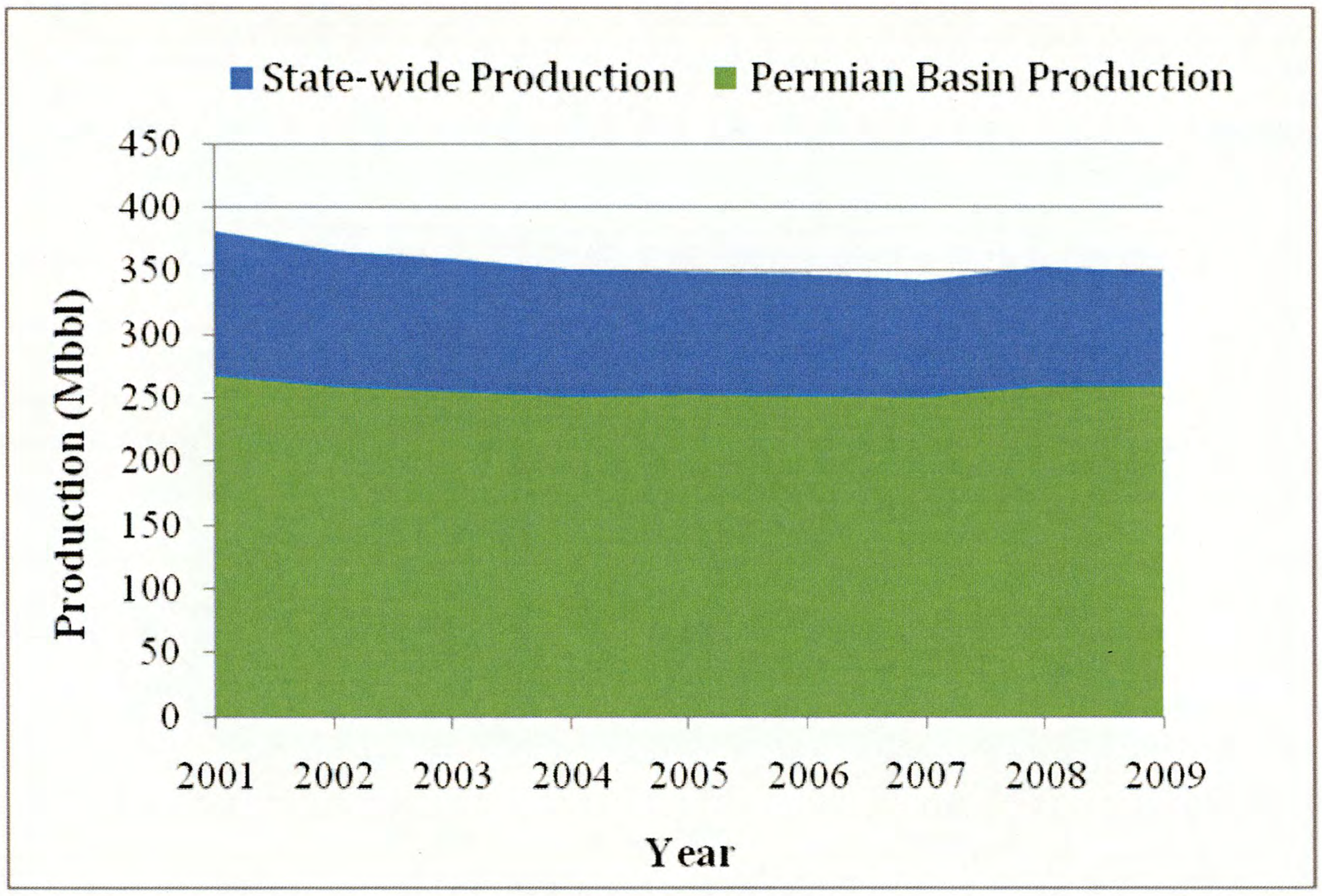
For the purposes of this publication, *Permian Basin Oil & Gas*, the Permian Basin Producing Area includes the majority of the counties in Railroad Commission of Texas Districts 7c, 8 and 8a and Southeastern New Mexico.

Source: Permian Basin Petroleum Association, ND

Figure 2.12: Permian Basin Counties of West Texas

As mentioned, the Permian Basin is one of the largest oil reserves in the U.S. It is estimated to still hold about 30 Bbbl of mobile oil and 45 Bbbl of residual oil, which accounts for about 22% of proven U.S. oil reserves (Dutton, S.P, 2004).

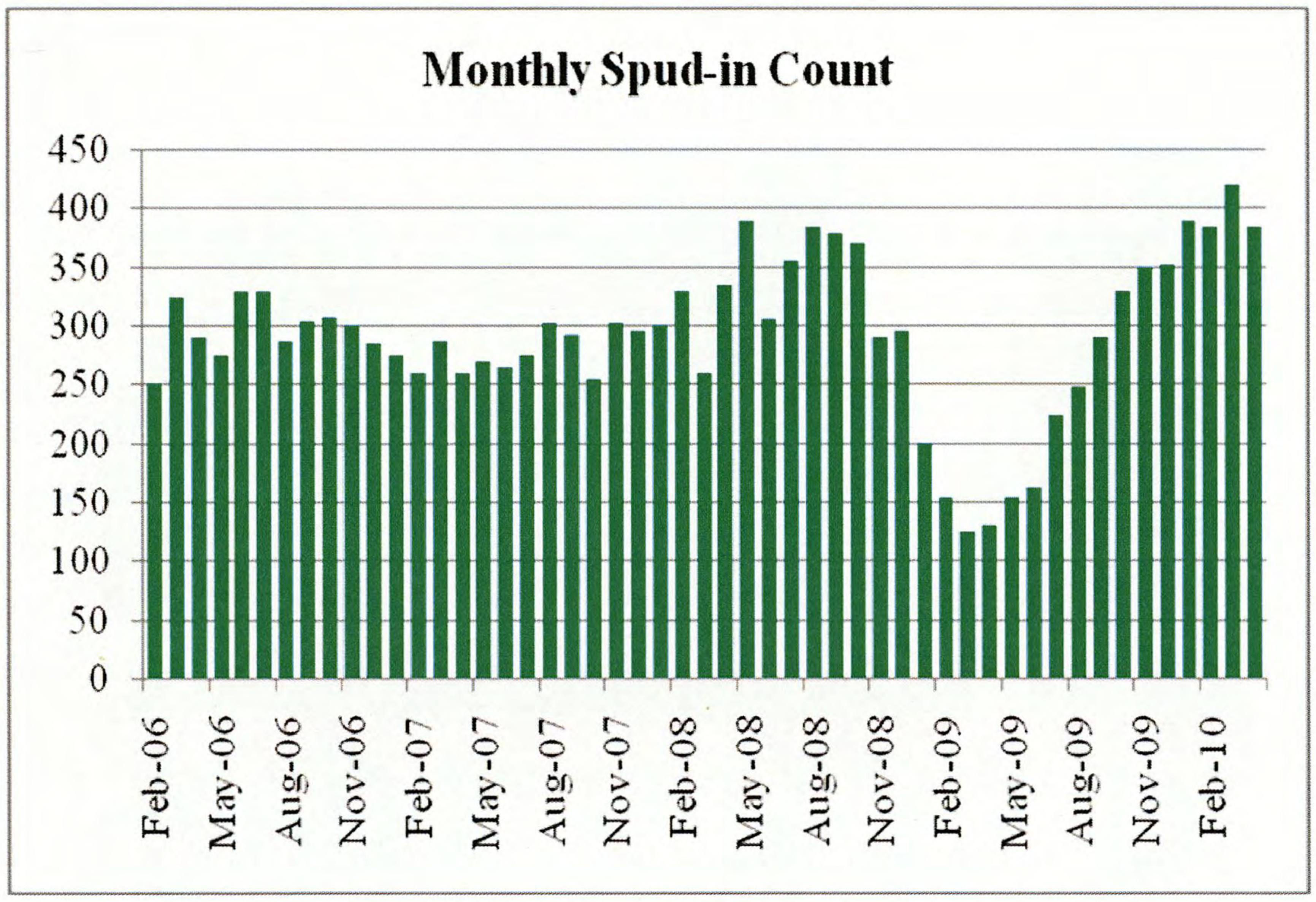
The Permian Basin produces approximately 256 million barrels of crude oil per year, which constitutes about 72% of Texas's total annual oil production. Figure 2.13 illustrates historical oil production in the Permian Basin and in Texas between 2001 and 2009.



Source: RRC Production Query

Figure 2.13: Crude Oil Production in the Permian Basin and the State

Figure 2.13 evidences that oil production in Texas and the Permian Basin has remained relatively constant between 2001 and 2009. Monthly spud-in data from the Permian Basin Petroleum Association also indicated that oil drilling has remained relatively constant in the area over the past 4 years. Figure 2.14 indicates that on average about 293 “holes” are drilled per month in the Permian Basin.



Source: PBPA Records

Figure 2.14: Monthly Spud-in Count in the Permian Basin

The Permian Basin was thus used as the case study for developing supply chains for Texas's oil sector. This and the following sections provide an overview of drilling and production activity in the Permian Basin and how various steps in oil procurement/distribution impact Texas's transportation system.

2.2.1 Developing a Supply Chain for Oil

Crude oil is the primary source for transportation fuels. Crude oil is, however, an unrefined product that is mined and transported to a refinery where it is processed into various types of fuels. These fuels are subsequently transported to distribution centers from where the fuel is transported for final consumption. The procurement and distribution of crude oil and the refined product is moved via a network of road and pipeline facilities. Texas's transportation system moves a substantial amount of traffic associated with the oil industry. It is therefore important to understand how the industry uses and impacts the transportation system, specifically in the Permian Basin where most of the industry is concentrated.

To understand these impacts, a supply chain for the oil energy sector was developed. Similar to natural gas production, the procurement and distribution of crude oil is a multi-staged operation that involves the collaboration of many parties. A supply chain assists in identifying those operations (and parties) that use and impact Texas's transportation system. Figure 2.15 provides an energy supply chain for the oil industry in the Permian Basin of Texas. From Figure 2.15, it is evident that three main traffic-generating activities in the oil supply chain require the use of the transportation system: 1) well construction, 2) crude oil production that involves the movement of oil from tank batteries near well sites to pipeline breakout stations (or tank farms), and 3) fuel distribution from gasoline bulk storage terminals to fuel dispensing facilities.

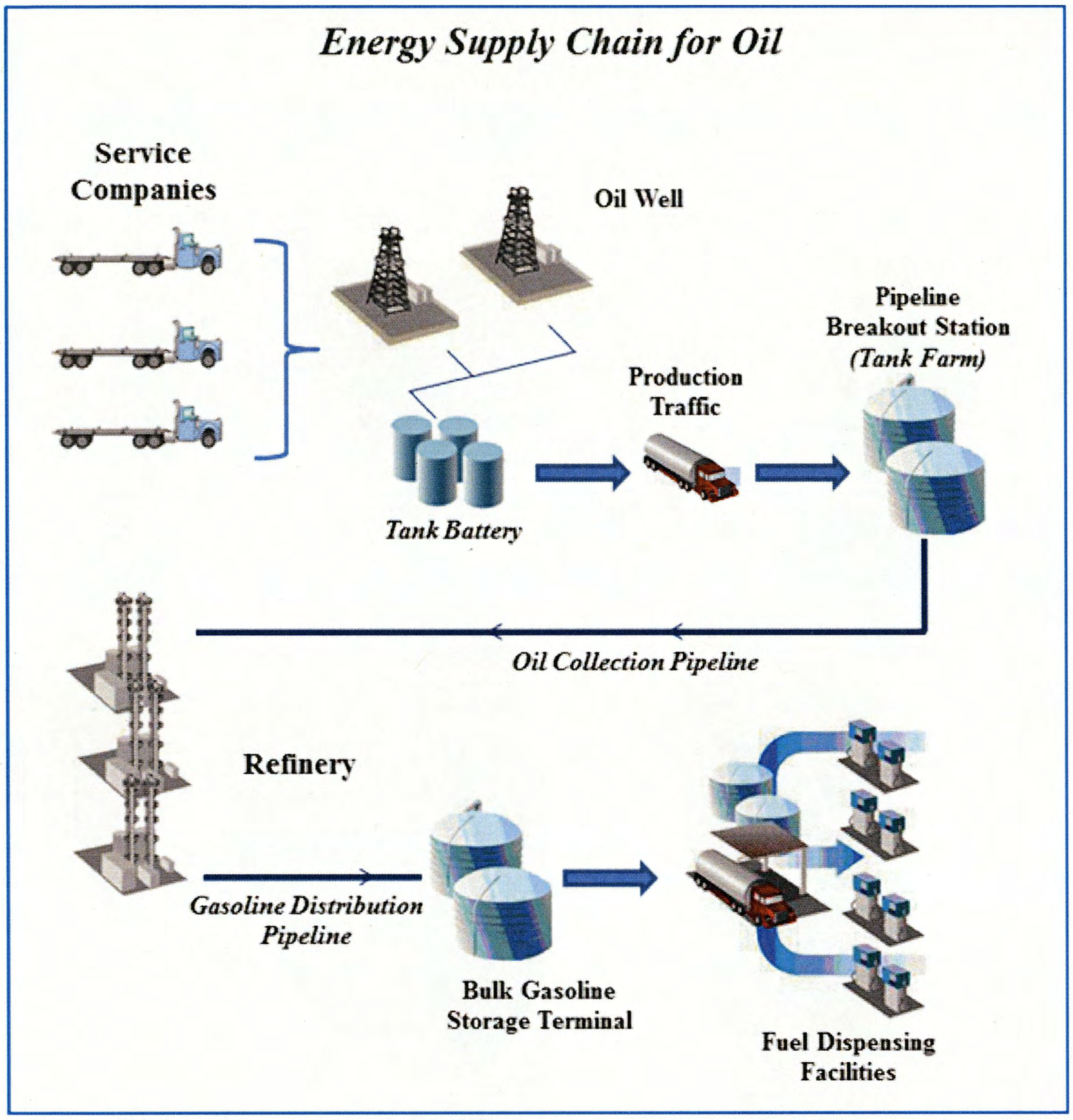
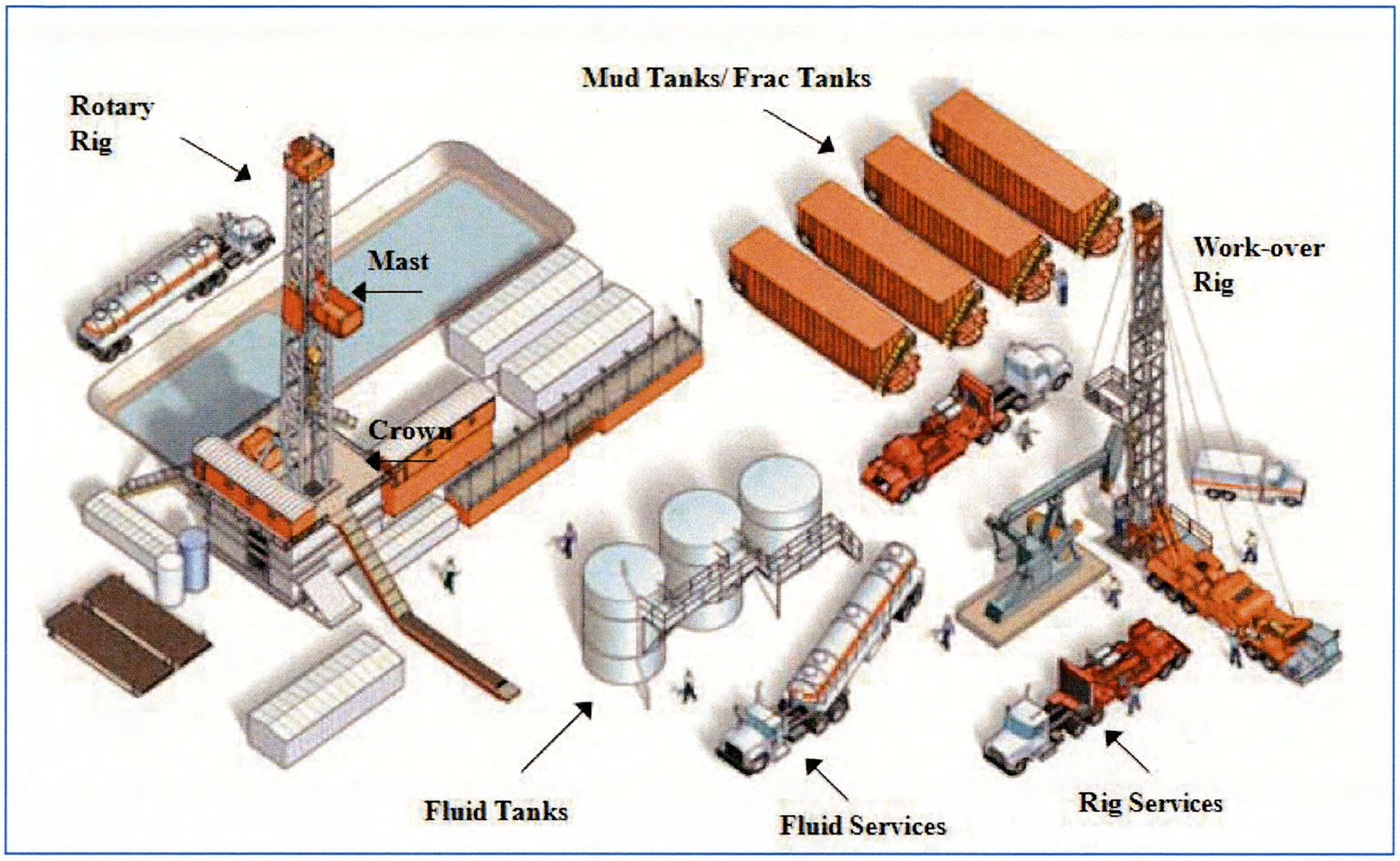


Figure 2.15: Oil Supply Chain

The next sections discuss the construction and production traffic associated with oil well development, as well as the distribution of gasoline fuels from bulk storage terminals to fuel dispensing facilities.

2.2.1.1 Construction Traffic

Construction traffic is defined as the traffic associated with the four-step well development process, i.e., site preparation, rigging up, drilling, and rigging down. The rig site and some of the services associated with the construction of a well are illustrated in Figure 2.16.



Source: Basic Energy Services

Figure 2.16: Rig Site

Figure 2.16 shows that a rig site entails the preparation of the rotary rig—which consists of a base, a crown, and a mast—and the delivery of fluid tanks and other fluid services. In some cases a work-over rig is required on an existing well site. Work-over rigs are used for sand cleanout, repairing liners, and casing of the well-hole, or sidetracking a well-hole to deepen or relocate the bottom of the well to a more productive zone (U.S. Department of Labor, ND).

A 1982 study by the Texas Transportation Institute (TTI) reported that, on average, construction traffic associated with the development of a single well lasts about 35 to 40 days (Mason, 1982). Furthermore, the study showed that the volume of truck traffic associated with construction was substantial. The Average Daily Truck Traffic (ADTT) was 27 trucks, amounting to a total of 1,054 trucks (two-way) during the construction period. This is equivalent to 527 total truck visits (one way) and is similar to the traffic volume associated with natural gas well development. Figure 2.17 illustrates the distribution of construction truck traffic by vehicle type.

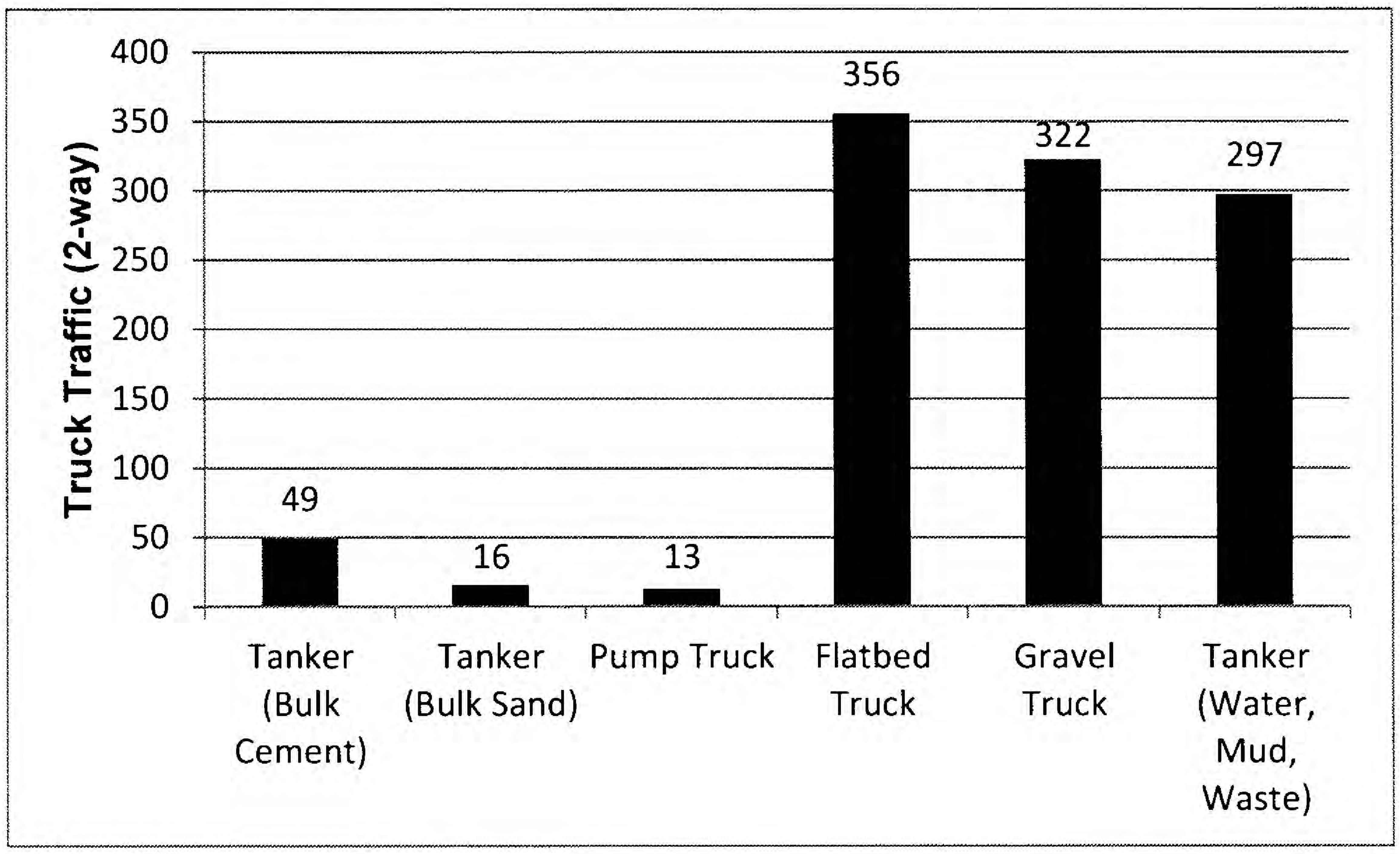


Figure 2.17: Distribution of Construction Traffic by Truck Type

Figure 2.17 evidences that a significant amount of truck traffic is generated by service companies. Flatbed trucks are used to move the rig to the site, while gravel trucks are used to move material for the construction of the site access road. Tanker trucks are required for moving cement, sand, mud, and water to the site and waste water from the site. It should be noted that unlike the natural gas wells in the shale regions of Texas, wells in the Permian Basin produce substantially less saltwater in general. The Permian Basin, however, covers a large geological area, with the result that salt water production may vary from region to region. On average in the U.S., oil wells produce nine barrels of water for every one barrel of oil (Lilo and Rae, 2002). According to an RRC representative, much of the saltwater is re-injected into wells to increase the pressure inside the well-hole and stimulate the flow of hydrocarbons (RRC, 2010). The RRC representative confirmed that saltwater disposal is not as much of a concern in the Permian Basin as it is in the Barnett Shale region. According to the RRC, the hauling of crude oil from wells to pipeline breakout stations generates substantially more traffic than saltwater disposal.

As mentioned earlier, well development may require up to 20 service companies to service the well. The construction traffic is mainly generated by these service companies. Therefore to understand how the construction traffic uses Texas's transportation system, the service companies in the Permian Basin needs to be identified first. From the RRC's Oil and Gas Company Directory, 374 service companies were identified as involved in operations such as drilling, cementing, CO_2 injection, tank installation, welding, mud, and other well services. Figure 2.18 illustrates the number of service companies by county in the Permian Basin.

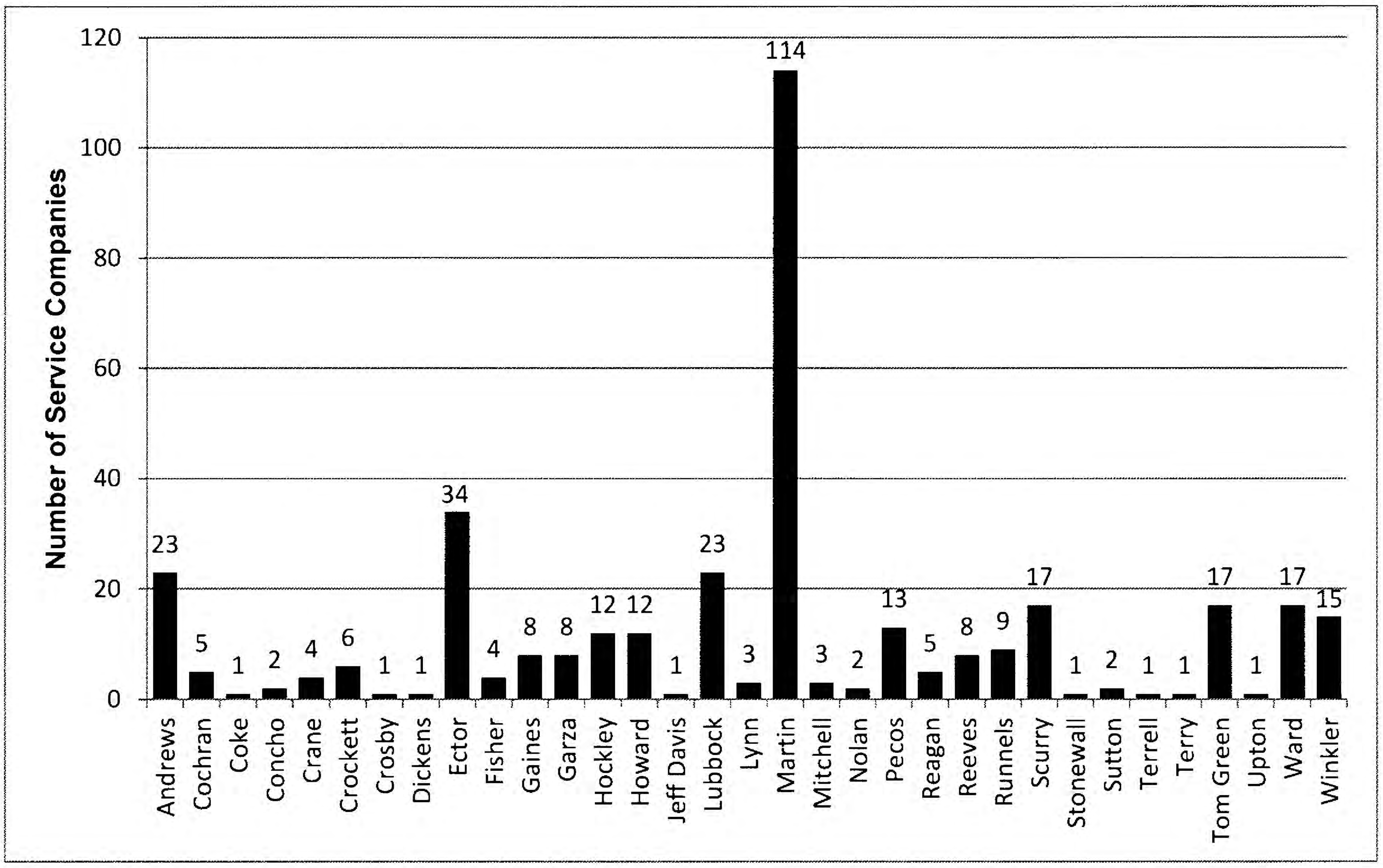


Figure 2.18: Service Companies by County in the Permian Basin

Figure 2.18 indicates that most of the service companies are concentrated in Martin, Lubbock, Ector, and Andrews counties; all of these, with the exception of Lubbock County, are in the center of the Permian Basin.

To understand how the construction traffic uses Texas's transportation system in the Permian Basin, the TxDOT OS/OW database was consulted in the analysis. Similar to the natural gas sector, a sample of routes for OS/OW oil traffic were obtained from the database and used to determine the average haul distance for oil equipment. Thereafter, total road usage was divided by roadway functional class as a percentage of total VMT. In total 1,558 OS/OW Route Permits were issued to the oil industry that started in the Permian Basin and 1,534 OS/OW Route Permits were issued that ended in the Permian Basin over a period of 3 years (i.e., 2007–2009). Of the permits that started in the Permian Basin, 80.8% also ended their routes in the Permian Basin, implying that construction traffic, for the most part, is local. Figure 2.19 presents a density distribution map of trips that started in the Permian Basin, indicating that most trips began in Ector, Ward, Reeves, Pecos, and Crockett counties.

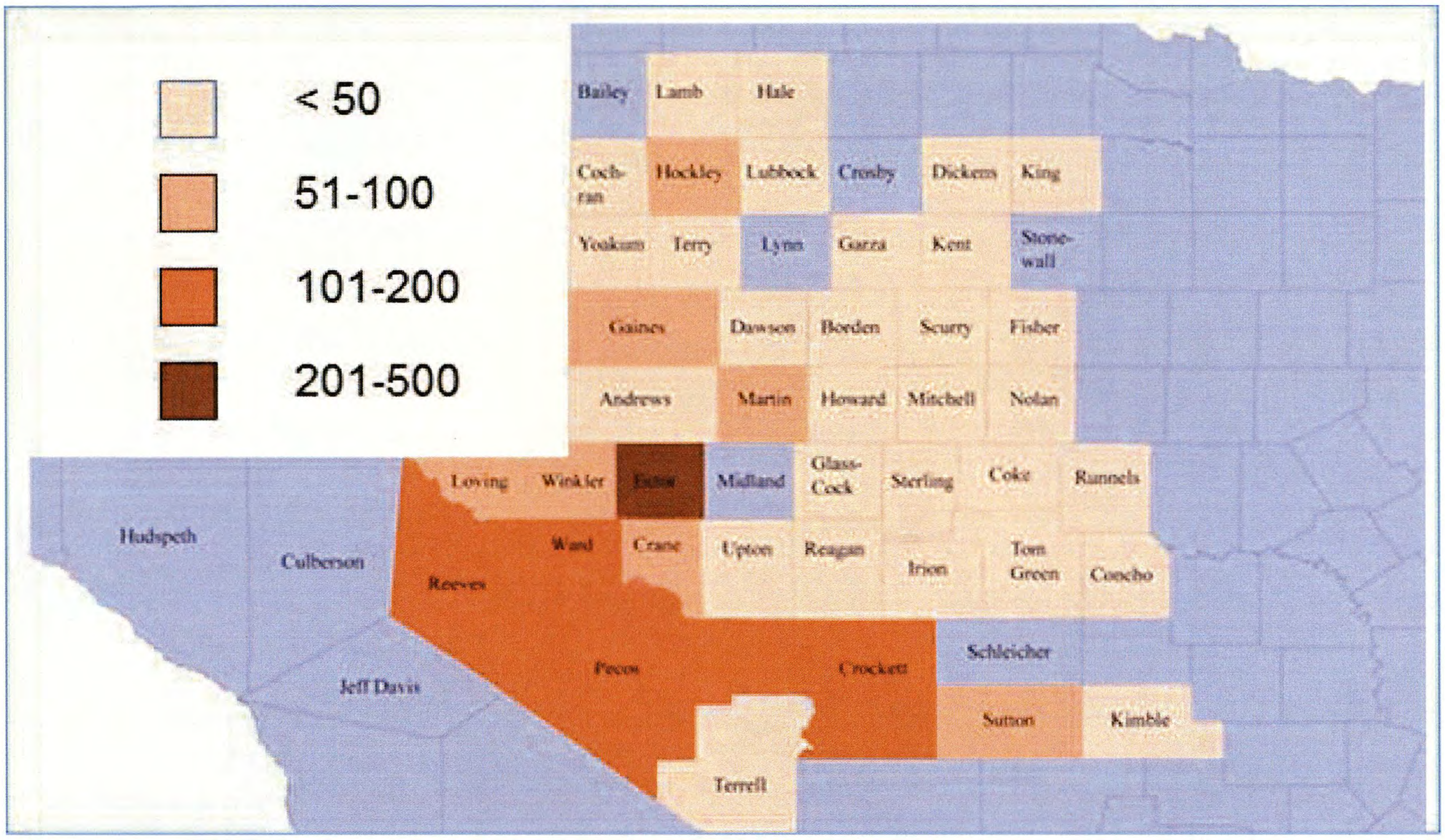


Figure 2.19: Distribution of OS/OW Route Permits in the Permian Basin

To understand the types of roads used for moving construction equipment between sites in the Permian Basin and the average haul distance, a sample of 50 permitted routes was randomly selected. The OS/OW dataset provides information on the start location and end location of each route, along with a detailed route description from the point of origin to the point of destination. This route description was used to plot each route in Google Maps. The length of each trip was subsequently determined using the Google Maps Directions application. Finally, road usage as a percentage of VMT was determined using the mileage traveled on each roadway segment and the total VMT for the sample. Figure 2.20 illustrates the sample of 50 permitted routes that were mapped using Google Maps. The blue lines signify the permitted routes within the sample. The darker the lines, the higher the number of sample trips that moved on the road sections.

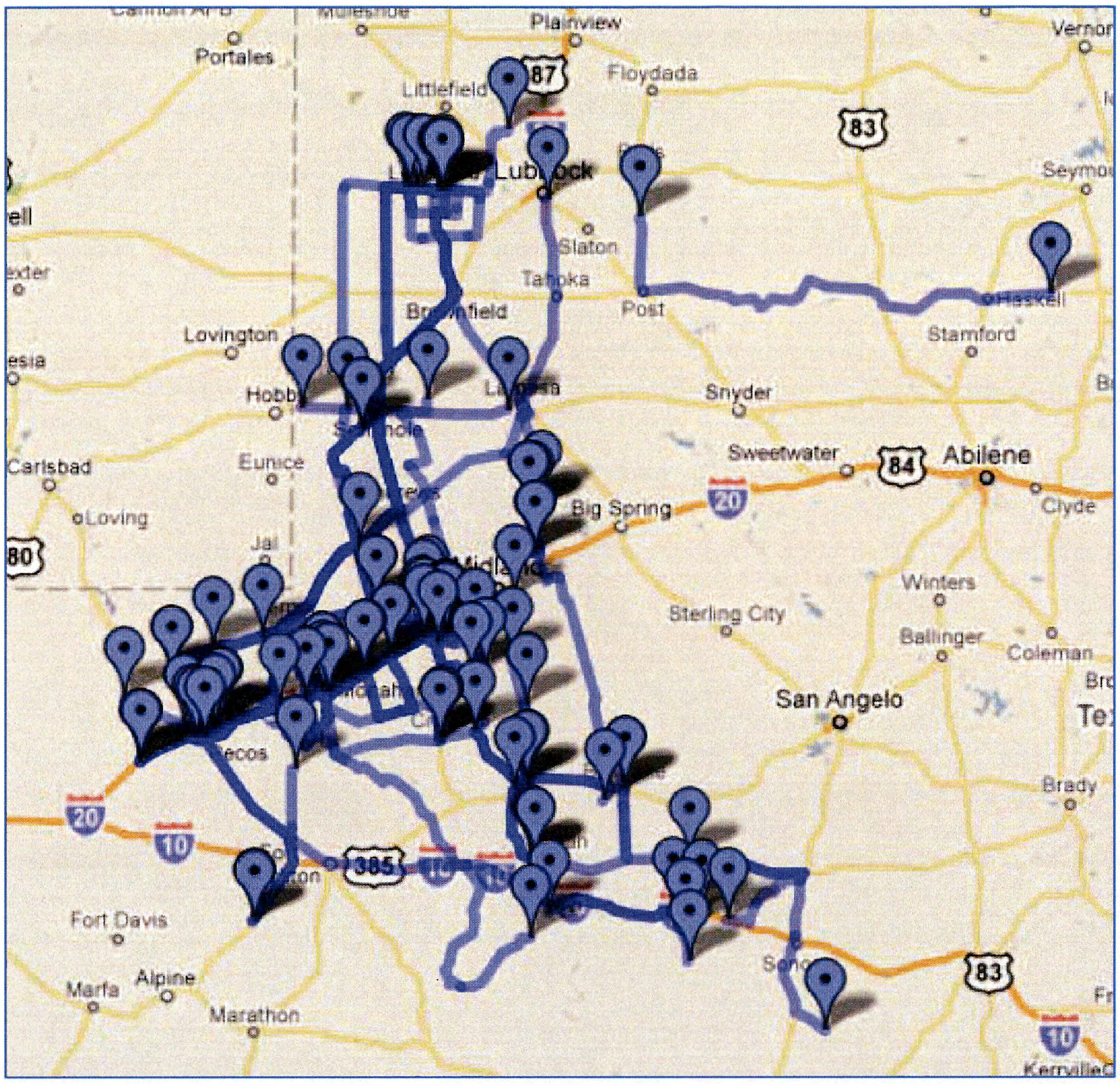


Figure 2.20: Construction Traffic Routes in the Permian Basin

From Figure 2.20, it is evident that a substantial number of trips occur on the IH-20 corridor and along the U.S. and State highways connecting the Midland/Odessa area with the Levelland/Lubbock area. By analyzing the trip lengths for the 50 sample routes, it was determined that the average trip length for hauling oil well equipment was 86.72 miles (standard deviation: 68.18 miles). A histogram distribution for the sample is presented in Figure 2.21.

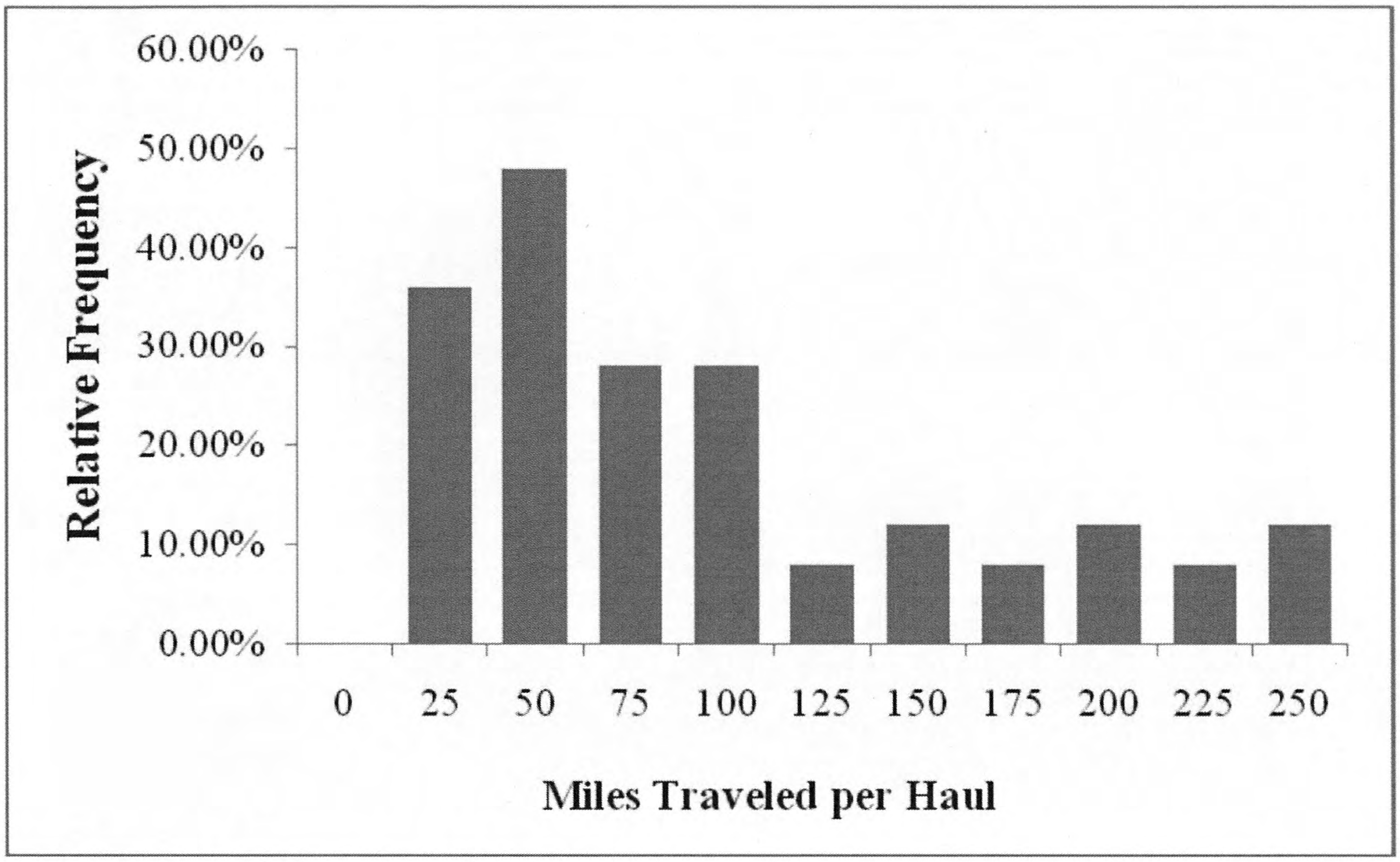


Figure 2.21: Length of Haul Distribution for Construction Traffic in the Permian Basin

The total VMT were calculated and road usage was determined as a percentage of VMT. The total VMT for the sample of 50 routes was 4,336.2 miles. Road usage as a percentage of total VMT is illustrated in Figure 2.22, which shows that construction traffic in the Permian Basin moves almost equally on U.S. and State Highways, and also on FM roads. Interstate highways are used to a lesser extent.

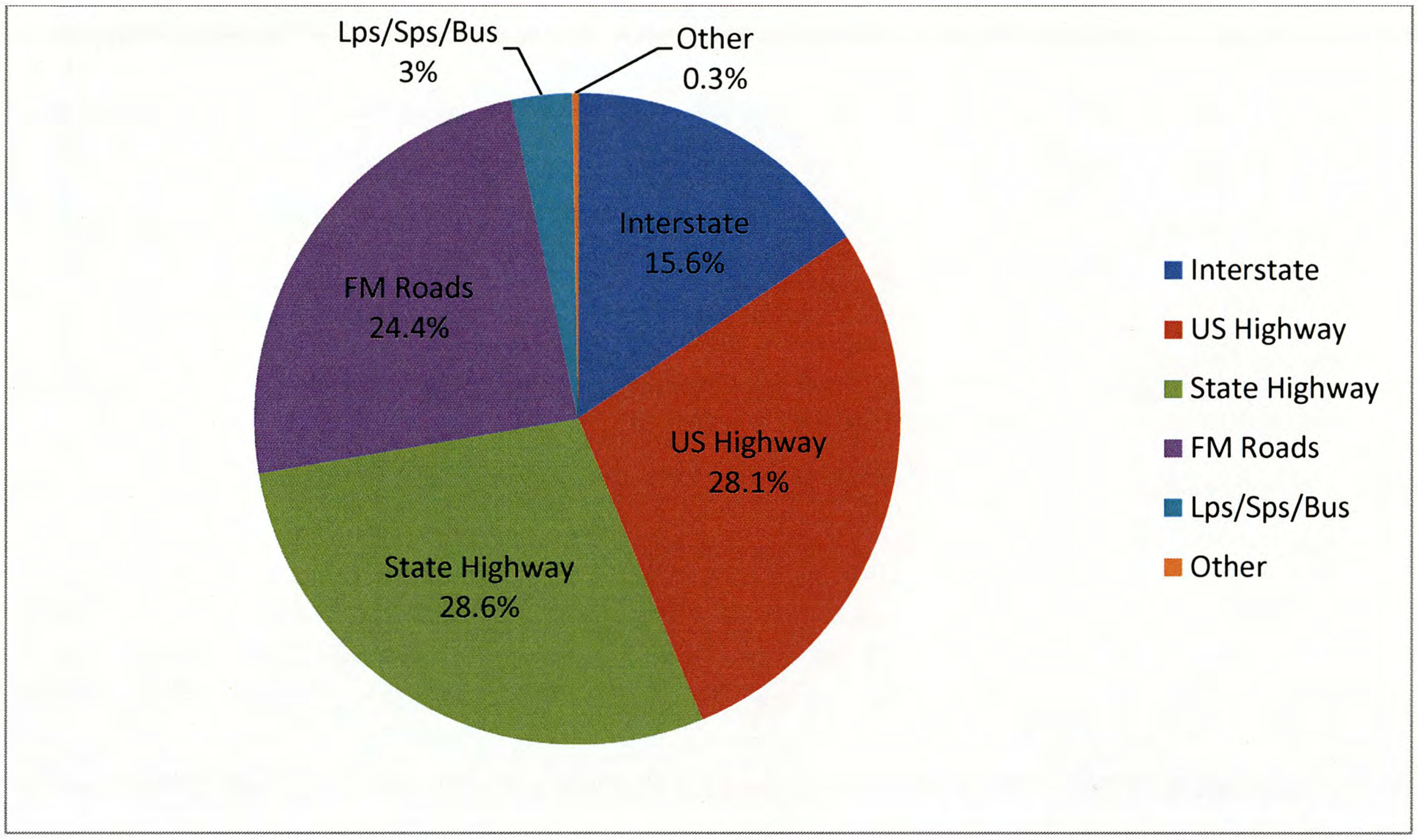


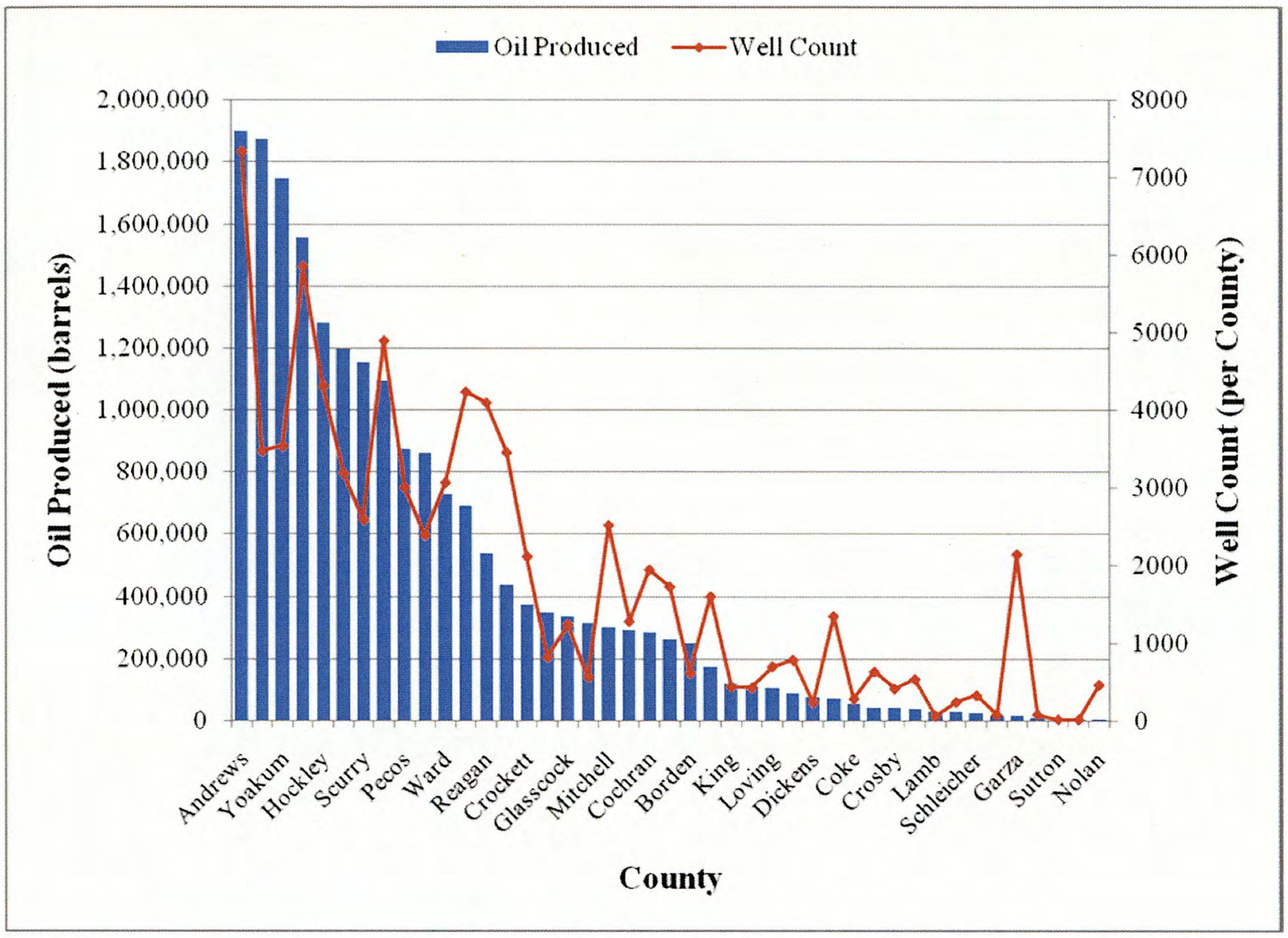
Figure 2.22: Road Usage by Construction Traffic in the Permian Basin

Note that the route analysis focused only on OS/OW traffic that requires a TxDOT permit. This traffic, for the most part, constitutes a small portion of the construction traffic, as only the equipment for the well development process requires a permit. The estimates for average haul distance and road usage for construction traffic are therefore biased towards the movement of heavy rig equipment. However, the route analysis of the OS/OW dataset provided a method for quantifying at least this component of the industry's usage of the transportation system.

2.2.1.2 Oil Production Traffic

Oil production traffic was defined as the truck traffic associated with transporting crude oil from tank batteries near well sites to pipeline breakout stations (or tank farms) from which the crude is then piped to refineries for processing. A TTI study—which monitored an oil well site for 73 days, including a 39-day construction period and a 34-day production period—reported that a typical oil well in East Texas generated 1.5 truck visits per day for collecting the oil and hauling it to a tank farm (Mason, 1982). This equates to approximately 9,000 gallons or 214 barrels of crude oil per day.

The Permian Basin is, however, an older geological resource and much of today's oil is obtained from secondary recovery. The volumes of crude oil produced from today's wells are thus significantly lower. To understand how much oil is produced from a typical well in the Permian Basin, oil production statistics and well count data were analyzed for February 2010. Figure 2.23 illustrates oil well counts and total oil production for each county in the Permian Basin in February 2010.



Source: RRC Production Query

Figure 2.23: Oil Production in the Permian Basin for February 2010

Based on well count information and production statistics obtained from the RRC's Online Research Queries, 79,735 active oil wells produced a total of 19,816,478 barrels of crude oil over a period of 28 days (February 2010). This equates to approximately nine barrels of oil per well per day in the Permian Basin. Thus, a typical oil well in the Permian Basin will require the trucking services of one 6,000 gallon truck every 16 days to haul away the crude oil.

To understand how Texas's transportation system facilitates oil production activity in the Permian Basin, data on the average haul distance for each trip generated and road usage is required. As with the natural gas sector, a 5-step process was developed to help the study team understand how Texas's transportation system facilitates oil production as follows:

1. Locate active oil wells and pipeline breakout stations (tank farms) in the Permian Basin.
2. Assume oil wells will be serviced by the closest tank farm and therefore pair every oil well with a tank farm based on shortest distance.
3. Select a random sample and obtain service routes from Google Maps using shortest path (i.e., not shortest distance).
4. Calculate VMT for random sample.
5. Determine percentage of VMT on each road type and average haul distance.

For the first step, data obtained from the RRC was used to locate active oil wells completed in the Permian Basin in 2007 and 2008. In total, 7,421 completed oil wells were on record. Thereafter, data from the Texas Commission on Environmental Quality (TCEQ) was used to locate all permitted pipeline breakout stations under the Standard Industry Code (SIC) 4612. In total, 191 pipeline breakout stations were identified from TCEQ's Central Registry system, of which 51 were located in the Permian Basin (TCEQ, ND). Figure 2.24 illustrates the location of the pipeline breakout stations and also the location of the oil wells on record in the Permian Basin. As shown, most pipeline breakout stations are located in close proximity to the large oil fields throughout the Permian Basin.

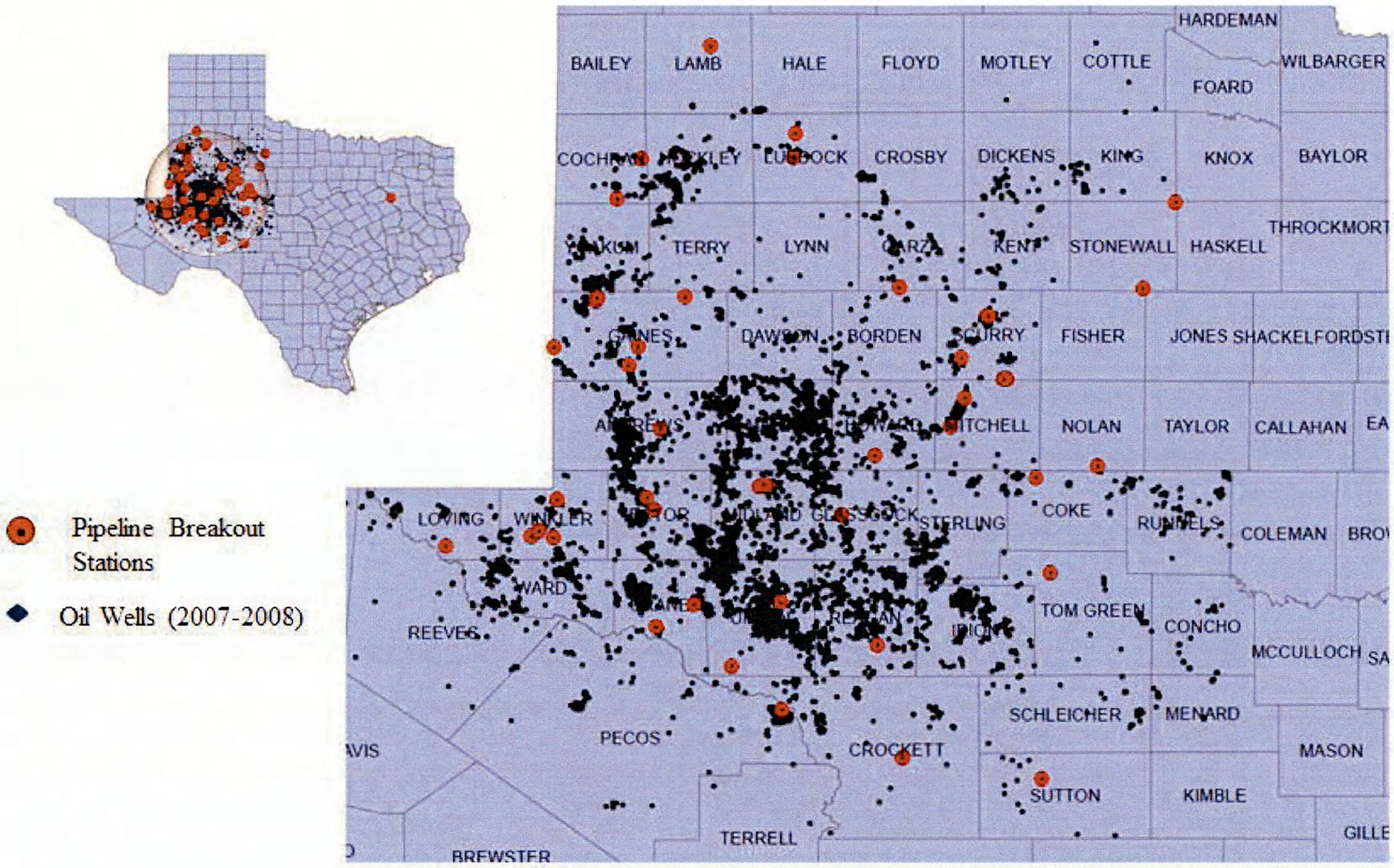


Figure 2.24: Oil Wells (2007–2008) and Pipeline Breakout Stations in the Permian Basin

It was assumed that each oil well on record will be serviced by the closest pipeline breakout station as this would allow for a time- and cost-efficient operation. Therefore, each oil well on record in 2007 and 2008 was paired with a pipeline breakout station in the Permian Basin based on the shortest distance derived from the Vincenty Formula. The shortest distance is, however, a straight-line distance that does not follow the contours of the road. Therefore, to estimate the actual haul distances, and road usage as a percentage of VMT, a sample of routes were plotted using Google Maps. A sample of 50 oil wells was randomly selected for the analysis. The route from each oil well to the nearest pipeline breakout station was plotted using Google Maps for each of the 50 oil wells. Figure 2.25 illustrates the sample of 50 routes that were plotted using Google Maps. Each blue mark represents a starting point (i.e., oil well) or a destination point (i.e., tank farm).

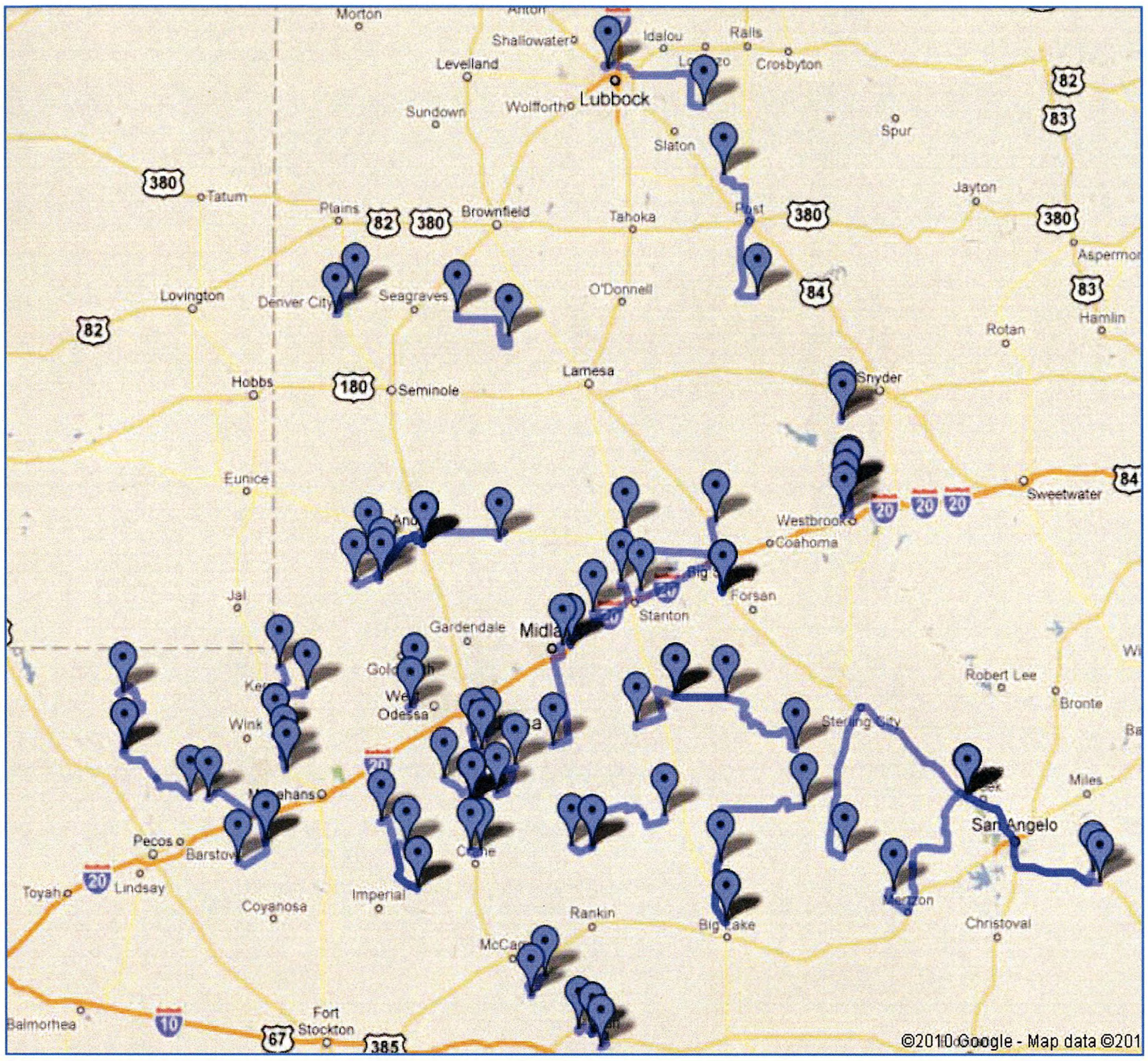


Figure 2.25: Oil Production Traffic Routes in the Permian Basin

As Figure 2.25 demonstrates, most oil production trips occur over short distances. Also, a substantial percentage of the hauls occur on local and county roads. By analyzing the trip distances for the sample of 50 plotted routes, it was determined that the average trip distance for hauling crude oil was 18.2 miles (standard deviation: 12.4 miles). A histogram distribution for the sample is presented in Figure 2.26.

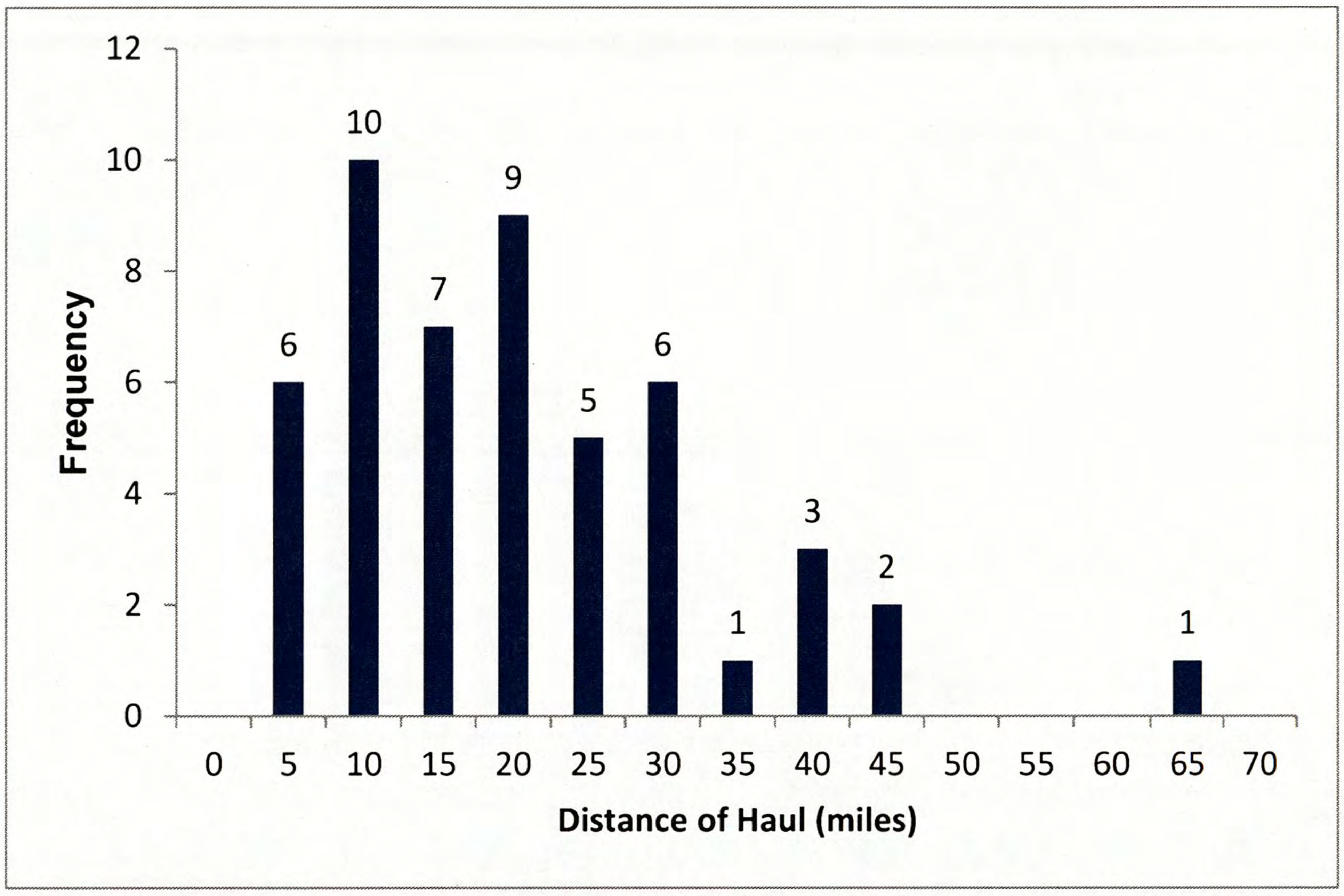


Figure 2.26: Haul Distance for Crude Oil Production Traffic in the Permian Basin

The total VMT for the sample was determined to be 908.9 miles. Road usage was also determined as a percentage of total VMT and is presented in Figure 2.27.

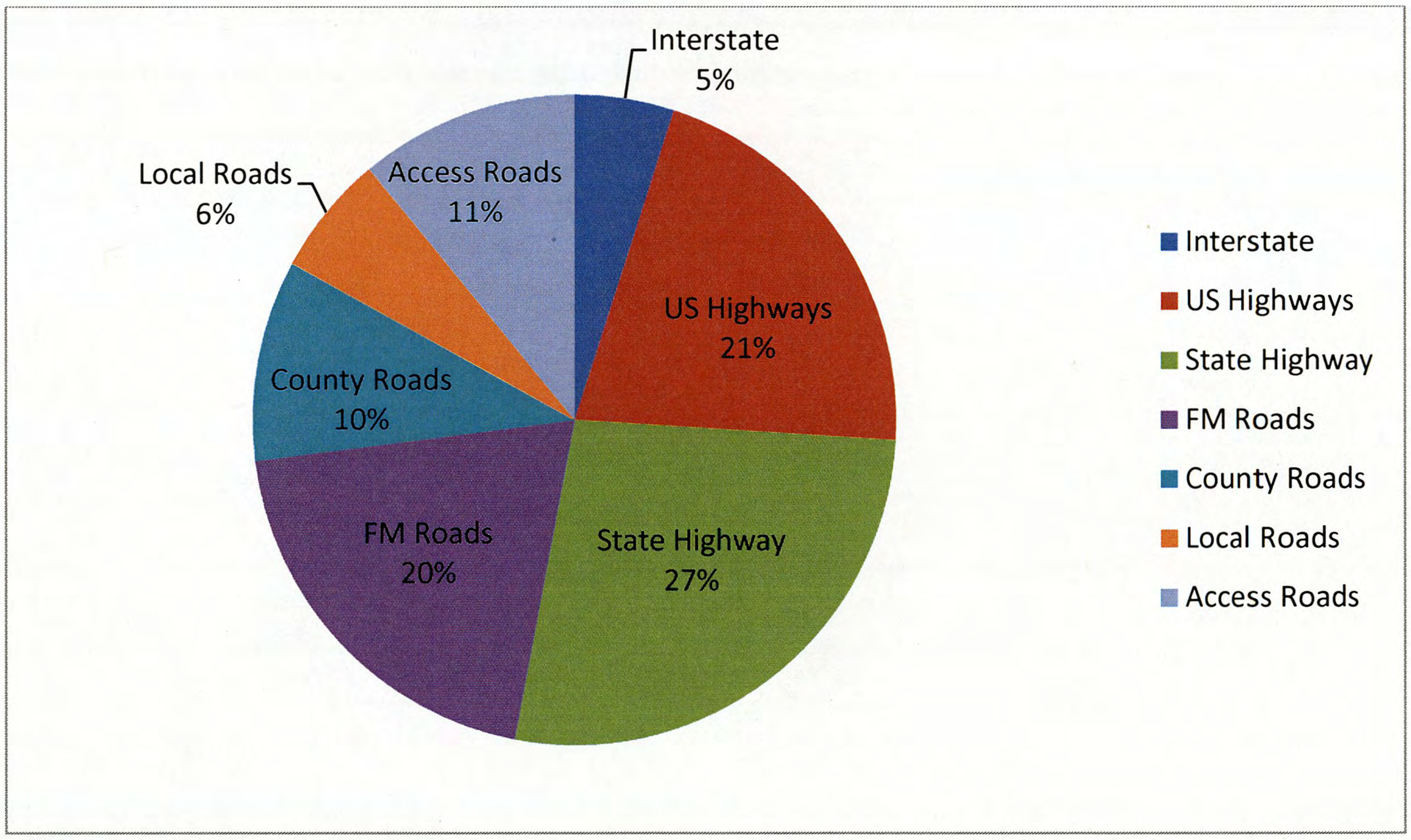


Figure 2.27: Facility Usage by Oil Production Traffic in the Permian Basin

Figure 2.27 indicates that a substantial share of the VMT generated from crude oil production occurred on US Highways (21%), State Highways (27%), and FM roads (20%). Only a small percentage of the VMT occurred on the Interstate System (5%). The remainder of the VMT occurred on local roads (6%), county roads (10%), and private site access roads (11%) built by the well developer.

2.2.1.3 Fuel Distribution Traffic

After the crude oil is collected at pipeline breakout stations (or tank farms), it is then pumped to oil refineries in Texas and, in some cases, to refineries in New Mexico for processing. According to Alon Energy USA—a refinery in Big Spring, TX—most of the oil produced in the Permian Basin is refined in their Big Spring facility (Alon USA, ND). However, according to the U.S. Energy Information Administration, Texas has 23 active oil refineries (US EIA, ND). Depending on the market price, crude oil can be sold to any one of these refineries at any time. The locations of these refineries are illustrated in Figure 2.28.

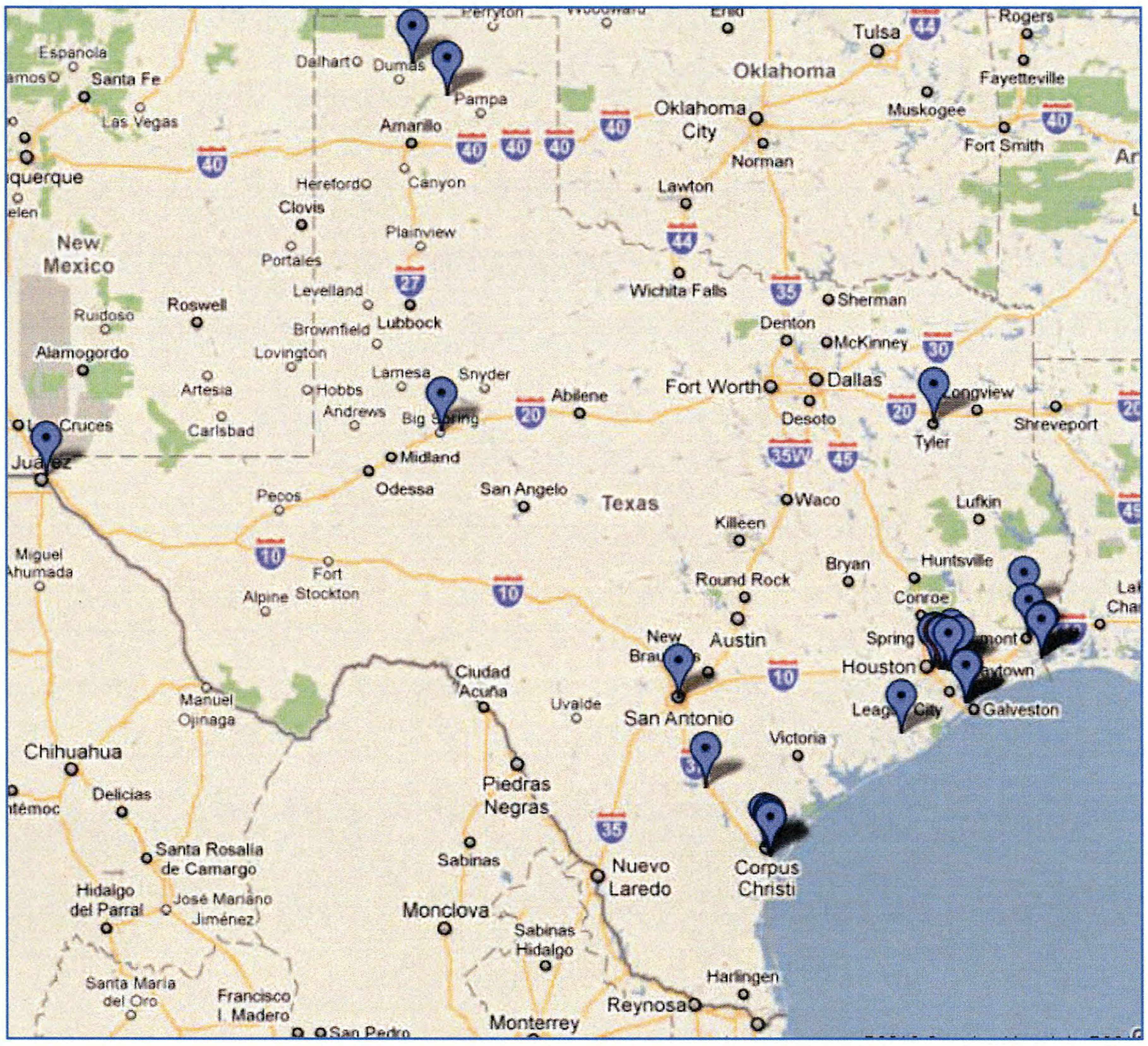
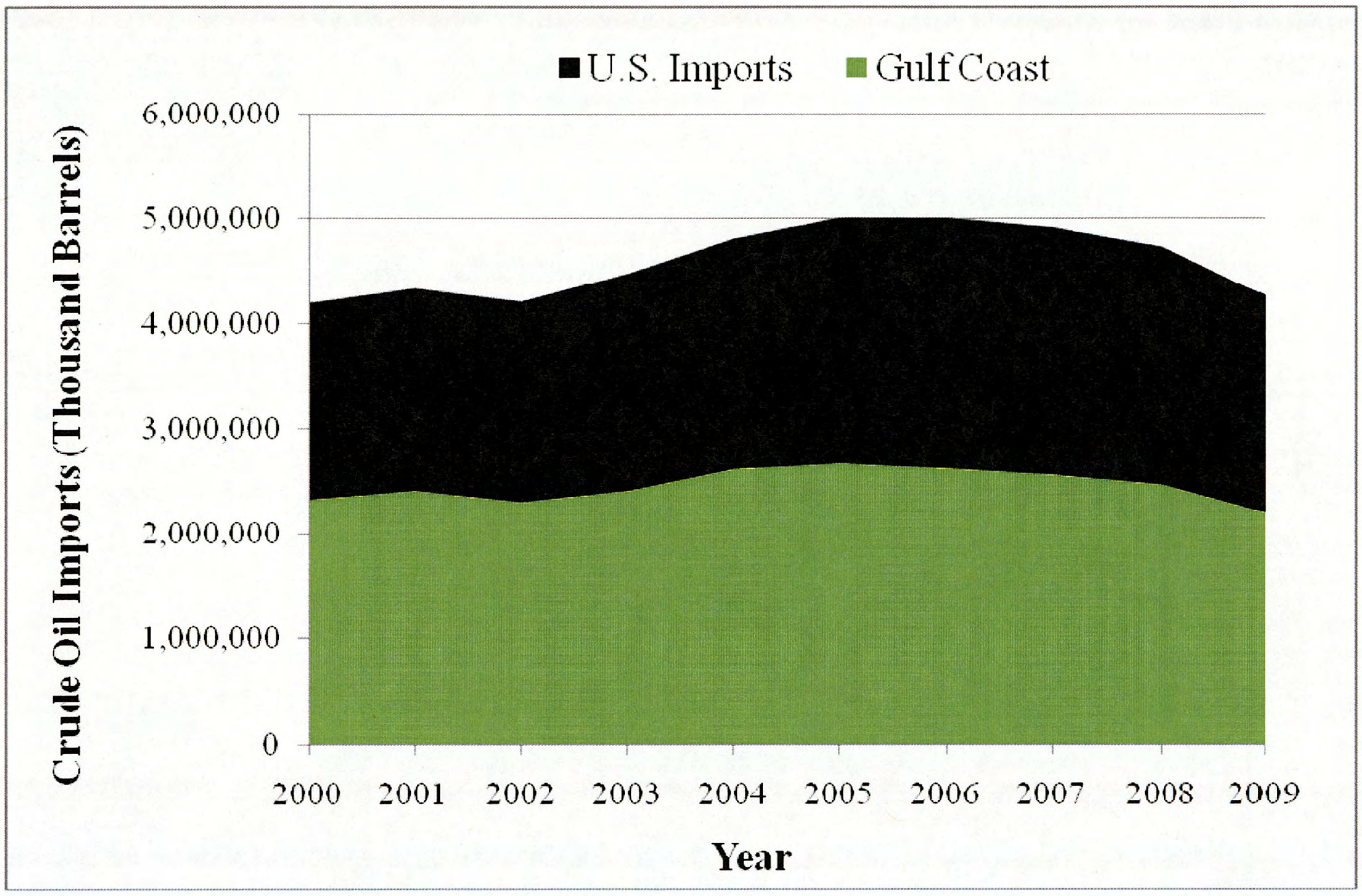


Figure 2.28: Oil Refineries in Texas

Figure 2.28 shows that most of Texas's refining capacity is along the Gulf Coast, specifically around the Ports of Houston, Galveston, and Corpus Christi. In some sense, the Gulf Coast area serves as "a refining house" for the rest of the U.S. Over the last decade, the U.S. has imported four to five billion barrels of crude oil per year. The bulk of these imports (53%) entered the U.S through the Gulf Coast ports. Figure 2.29 illustrates the total U.S. crude oil imports and the amount that is imported through the Gulf Coast.



* Gulf Coast States include Texas, New Mexico, Arkansas, Louisiana, Alabama, and Mississippi

Source: U.S. EIA, ND

Figure 2.29: U.S. and Gulf Coast Crude Oil Imports

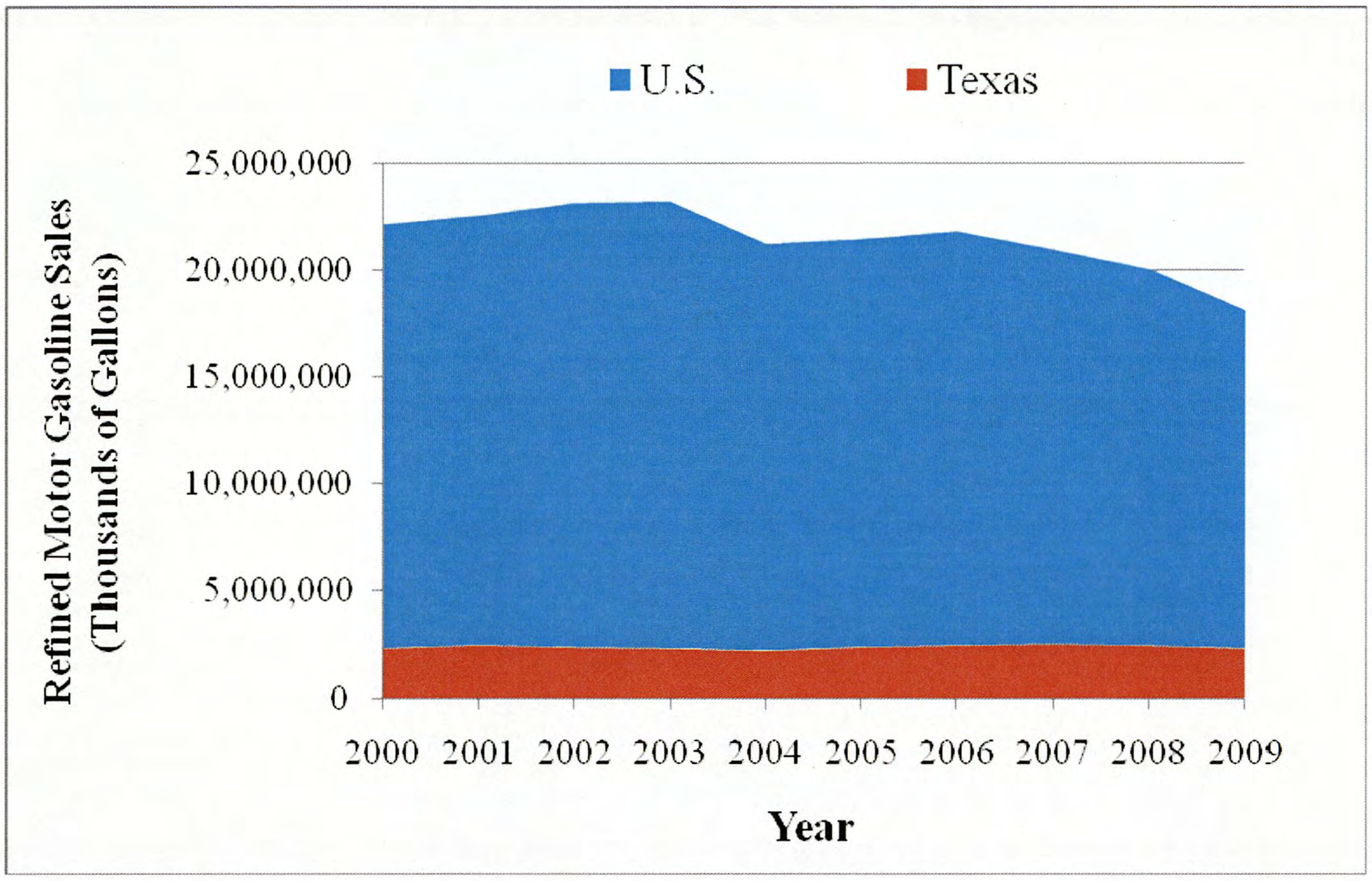
Table 2.3 presents the locations and ranking of Texas's 23 refineries in terms of processing capacity. From Table 2.3 it is evident that all of the Texas Gulf Coast refineries are large-scale operations with the capacity of processing several hundred thousand barrels of crude oil per day.

Table 2.3: Texas Crude Oil Refineries

U.S. Rank (size)	Company Name	Site	Refining Capacity (Barrels/Day)
1	ExxonMobil Refining	Baytown	567,000
3	BP Products North America	Texas City	467,720
6	ExxonMobil Refining	Beaumont	348,500
9	Deer Park Refining Ltd.	Deer Park	329,800
11	Premcor Refining Group Inc.	Port Arthur	289,000
13	Flin Hill Resources LP	Corpus Christi	288,126
14	Motiva Enterprises LLC	Port Arthur	285,000
15	Houston Refining LP	Houston	270,600
20	ConocoPhillips Company	Sweeny	247,000
27	Total Petrochemicals Inc.	Port Arthur	232,000
32	Valero Refining Co Texas LP	Texas City	199,500
40	Valero Energy Corporation	Sunray	171,000
45	Citgo Refining & Chemical Inc.	Corpus Christi	156,000
49	WRB Refining LLC	Borger	146,000
53	Valero Refining Co Texas LP	Corpus Christi	142,000
56	Western Refining Company LP	El Paso	122,000
63	Pasadena Refining Systems	Pasadena	100,000
66	Valero Energy Corporation	Three Rivers	93,000
71	Valero Refining Co Texas LP	Houston	83,000
79	Marathon Petroleum Co LLC	Texas City	76,000
85	Alon USA Energy Inc.	Big Spring	67,000
94	Delek Refining Ltd.	Tyler	58,000
126	Age Refining Inc.	San Antonio	13,500

Source: US EIA

In the refineries, the crude oil is processed into various products that are used commercially in many industries. For example, olefins are used in the plastics industry; paraffin wax is used for candle making; petrochemicals such as benzene are used in the drug and cosmetics industry; asphalt is used in the construction industry; and many other chemical products are used in many other industries. The main products made from crude oil are, however, petroleum-based fuels. These fuels include petrol gasoline, petrol diesel, kerosene, and jet fuel. The bulk of the refined product is petrol gasoline. According to the U.S. Energy Information Administration, one barrel of crude oil (42 gallons) produces 19 to 20 gallons of gasoline (U.S. EIA, ND). Today, the U.S. is the largest consumer of petroleum-based fuels in the world. Figure 2.30 illustrates U.S. and Texas's motor gasoline consumption over the past decade.

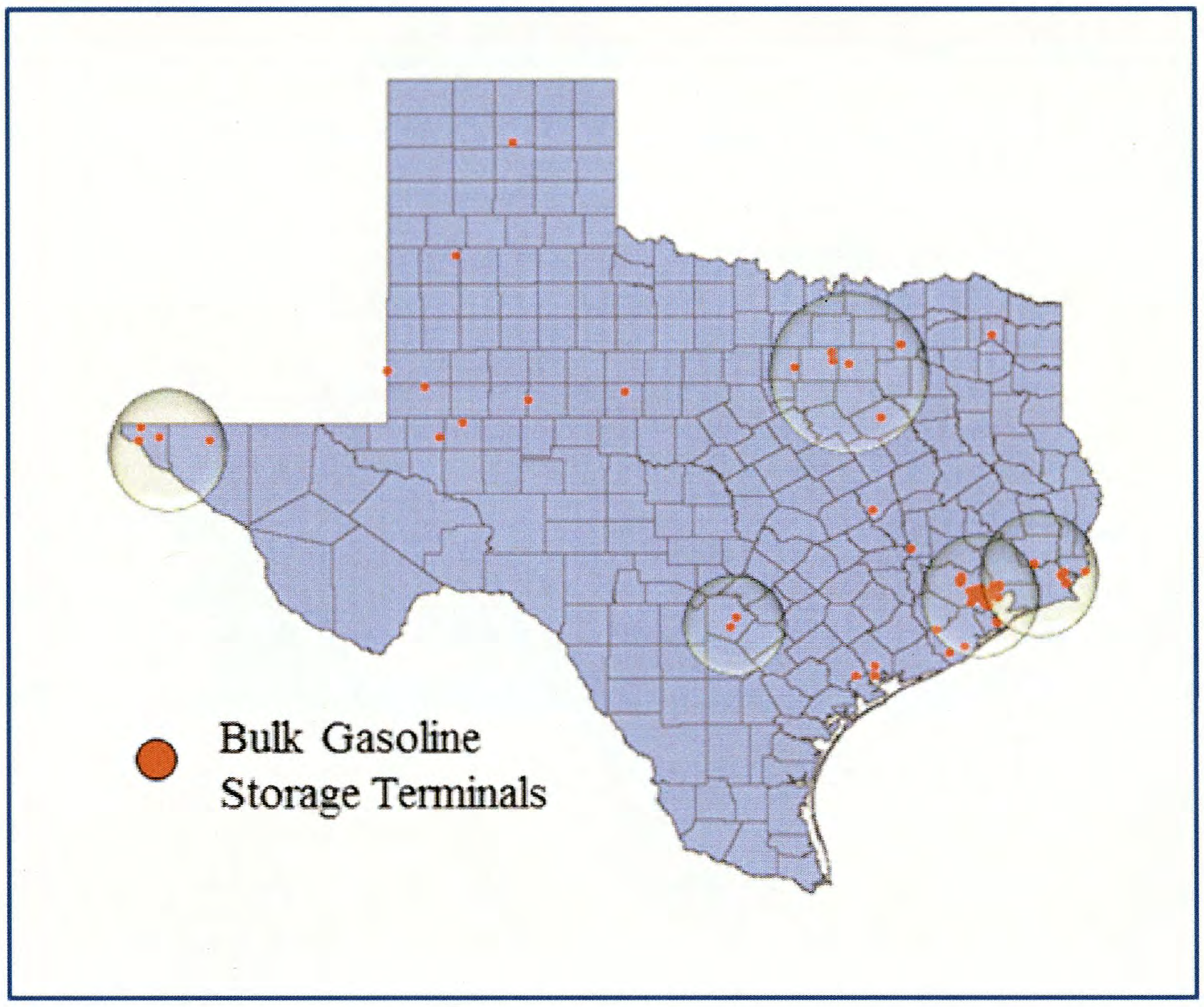


Source: U.S. EIA, ND

Figure 2.30: Motor Gasoline Consumption for U.S. and Texas

Figure 2.30 demonstrates that Texas accounts for approximately 11.5% of average annual U.S. gasoline consumption, which equates to about 2.5 billion gallons per year. The refined gasoline product is transported from the refineries to dispensing stations by pipeline to local market terminals known as bulk gasoline storage terminals. In these bulk gasoline storage terminals, the petrol gasoline product is mixed with ethanol and delivered by truck to local gasoline dispensing stations. The number of bulk storage terminals in a region largely depends on the region's population size and density. Regions with larger populations tend to have more storage terminals. Also, regions with large populations and low population densities, such as Houston and the Dallas-Fort Worth area, tend to have more storage terminals spread over a larger land area.

In total, 94 bulk gasoline storage terminals were identified in TCEQ's Central Registry system under the Standard Industrial Code (SIC) 4613 (TCEQ, ND). The majority (i.e., 89) of these terminals could be located by the research team. Their location (i.e., latitude and longitude) are illustrated in Figure 2.31. Five records in TCEQ's Central Registry system could not be located due to a lack of information on their location.



Source: TCEQ, ND

Figure 2.31: Bulk Gasoline Storage Terminals in Texas

As Figure 2.31 shows, a large number of bulk gasoline storage terminals are located on the Gulf Coast, mainly near Baytown, Deer Park, La Porte, and Pasadena. Also, a substantial number of terminals are located in Texas City, Corpus Christi, and Belvieu in Chambers County near the Louisiana state border. Because many of the major U.S. oil companies have refineries along the Gulf Coast, many of the Gulf Coast terminals are also used for storage of the refined gasoline products before distribution throughout the state and the U.S. via pipeline. A number of bulk storage terminals are also located near the larger metropolitan areas to serve El Paso, Dallas-Fort Worth, and San Antonio. Lastly, it should be noted that the city of Austin is not directly served by a gasoline terminal. Product is thus delivered from surrounding terminals in Grimes County, Robertson County, and Bexar County.

In an effort to gain insight into the gasoline distribution network, two urban centers in Texas were analyzed. Figure 2.32 illustrates the location of gas stations (i.e., red dots) and bulk storage terminals (i.e., blue bubbles) in San Antonio and the surrounding areas of Bexar County. Similarly, Figure 2.33 illustrates the location of gas stations and bulk storage terminals in the Dallas-Fort Worth-Arlington metropolitan area.

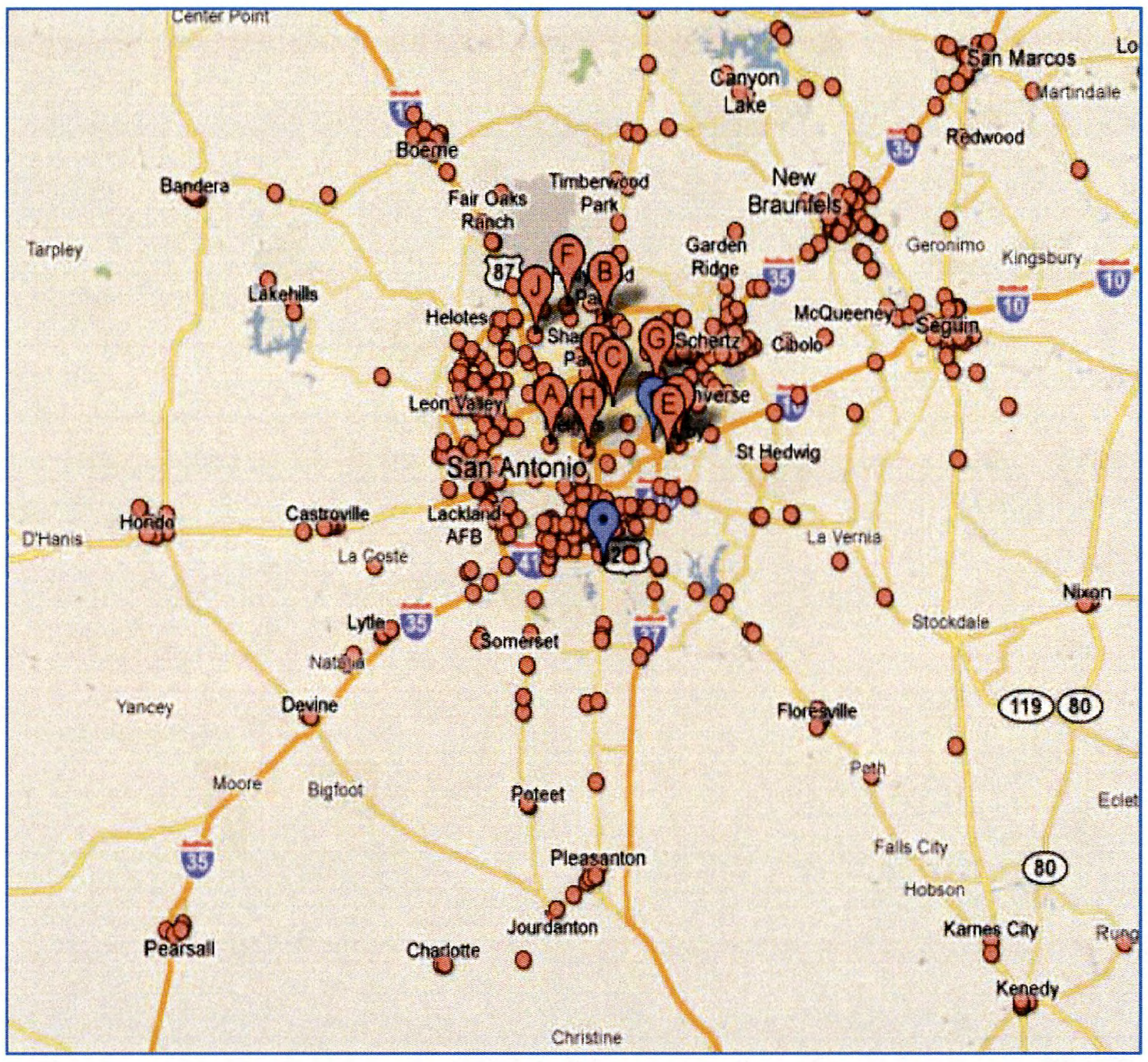


Figure 2.32: San Antonio Gasoline Distribution Network

As Figure 2.32 shows, two gasoline bulk storage terminals serve the entire San Antonio metropolitan area. Google Maps listed 1,749 active fuel dispensing stations in the San Antonio area. Figure 2.33 indicates that four gasoline bulk storage terminals serve the Dallas-Fort Worth-Arlington metropolitan area. Google Maps listed 10,104 active fuel dispensing stations in the metroplex area.

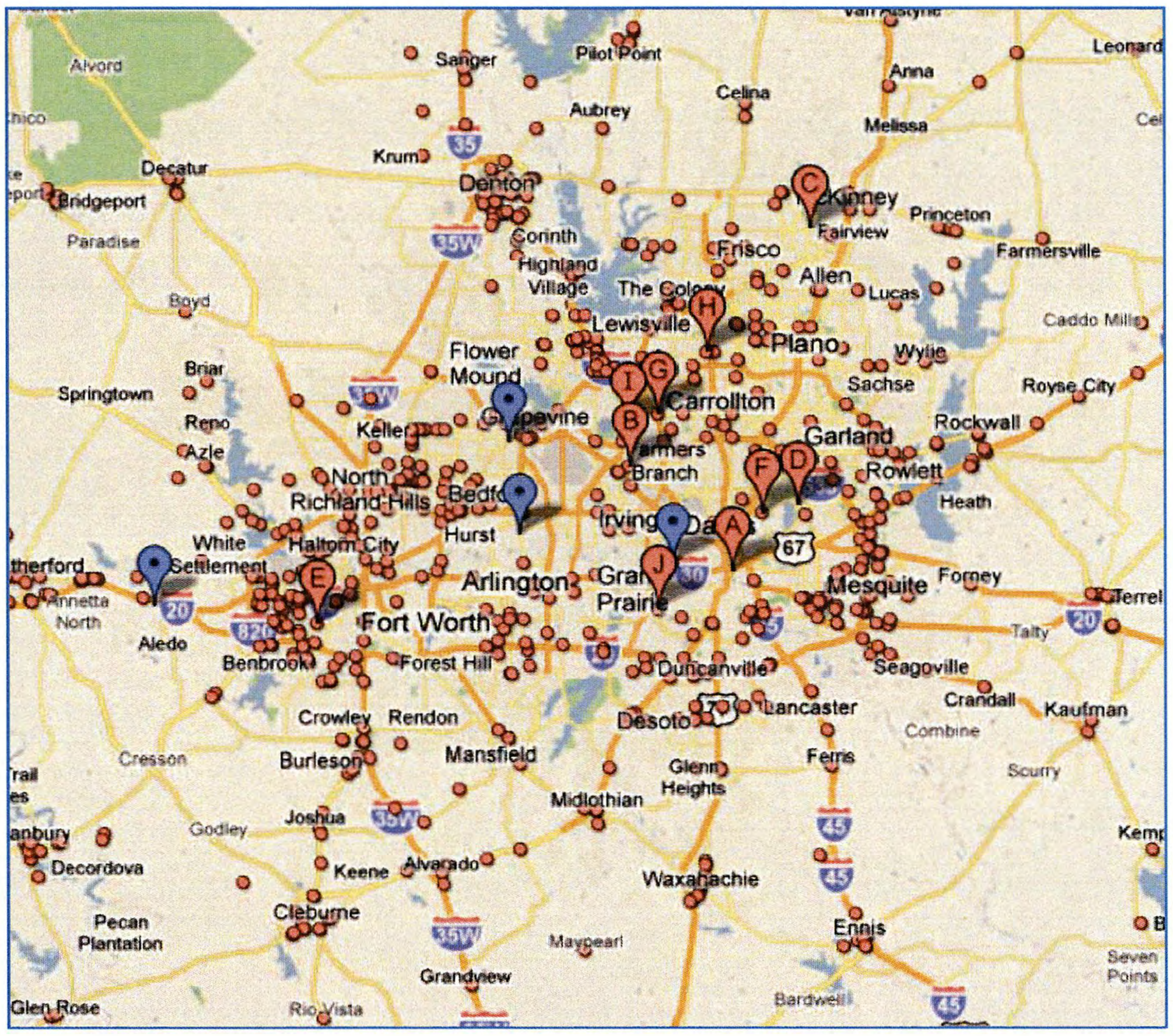


Figure 2.33: Dallas-Fort Worth-Arlington Gasoline Distribution Network

Each gasoline storage terminal serves a specific area. However, the study team did not analyze the transportation impacts associated with fuel delivery to dispensing stations. Many parameters are considered when distributing gasoline to dispensing stations—e.g., variations in storage tank size, variations in consumption volumes at dispensing stations, and fuel delivery schedules. Insufficient data and information prevented the development of a model that accounts for each of these parameters.

2.3 Coal Energy Supply Chain

Coal has been used in Texas for many generations. Today, it serves as one of the main sources of fuel for electricity generation. According to the 2008 Texas State Energy Plan, coal-powered generation provided 37% of electricity production in the state (Governor's Competitiveness Council, 2008), as is reflected in Figure 2.34.

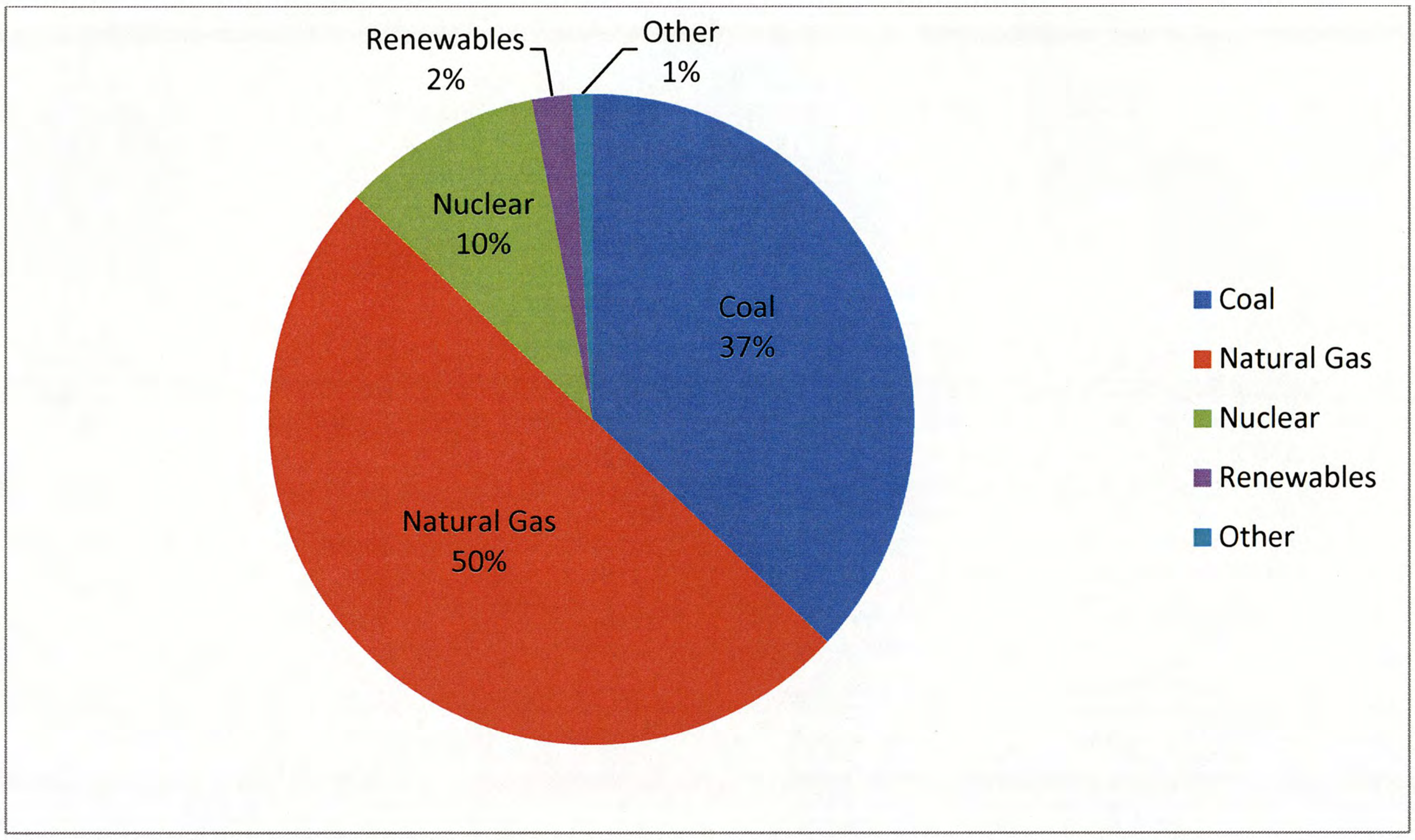
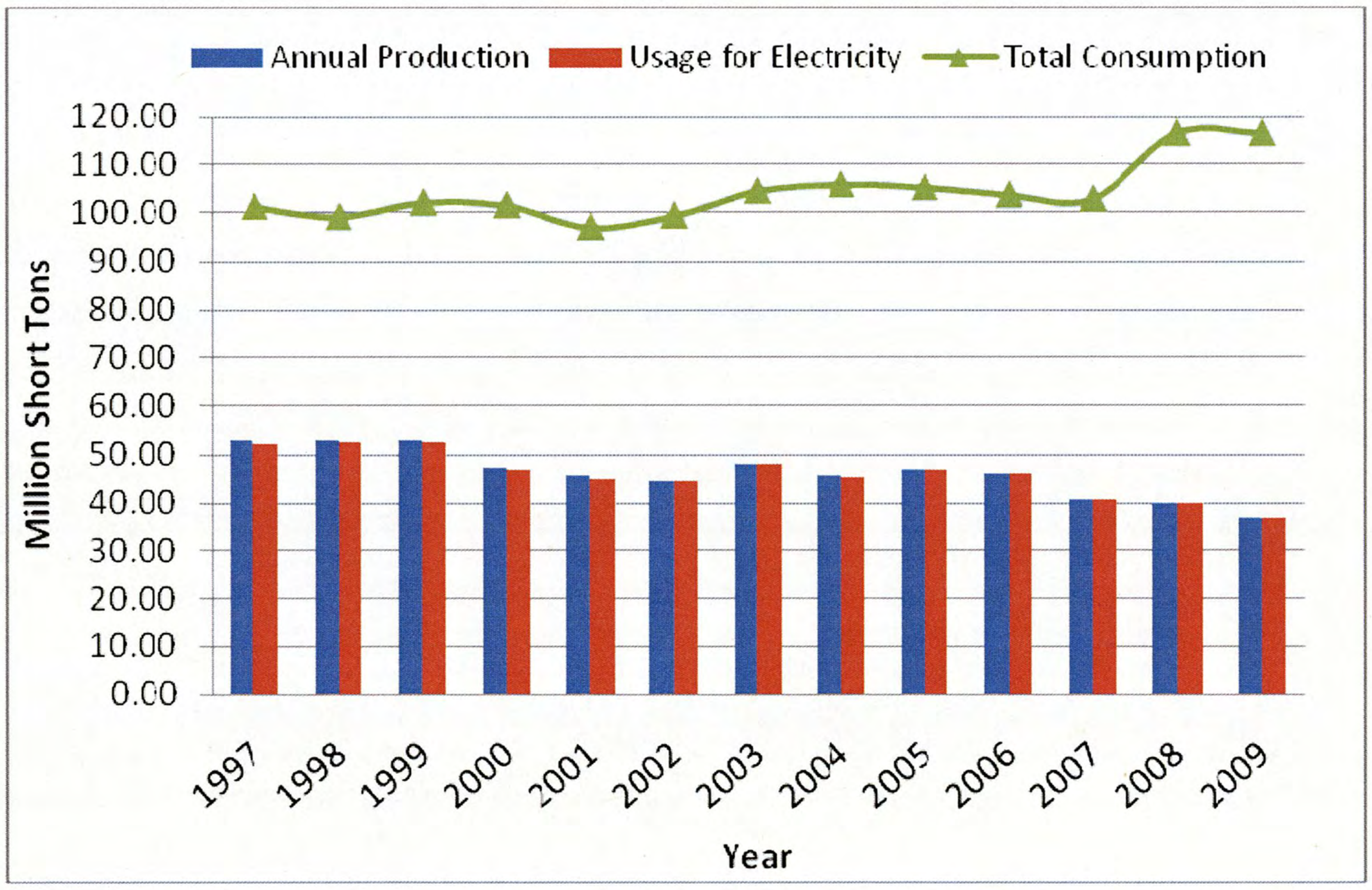


Figure 2.34: State Electricity Production by Fuel Source

In Texas, coal is sourced from the lignite coal mined within the state and out-of-state from the Wyoming Powder River Basin (PRB). Historically, the state has consumed more coal than it can produce (Combs, 2008). In 2008, for example, Texas consumed 116 million short tons of coal, of which only 31.8% came from local sources. Figure 2.35 illustrates the annual in-state production of coal, in-state coal electricity usage, and total state coal consumption.

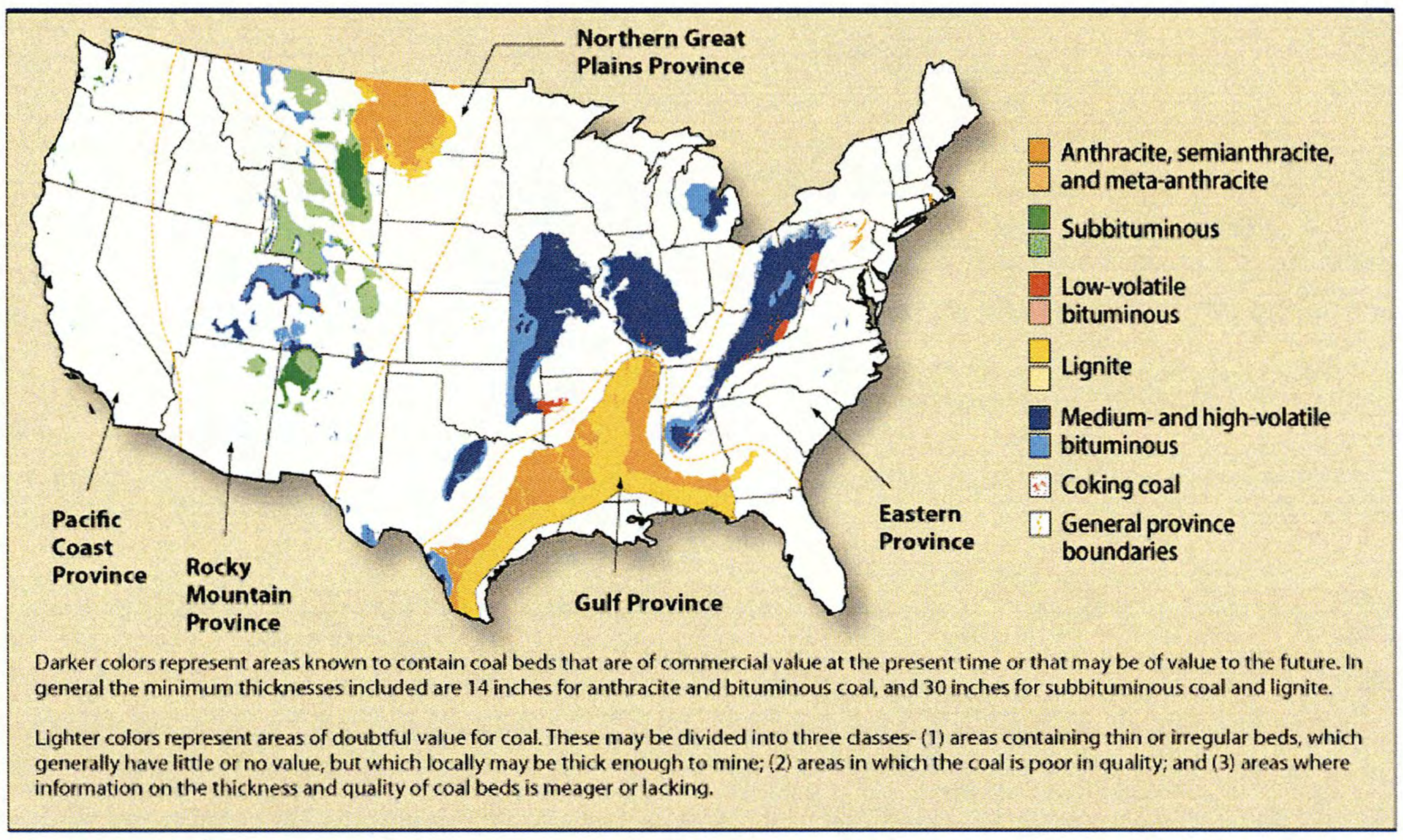


Source: RRC Mining Records, 2010

Figure 2.35: Texas Coal Production and Consumption

2.3.1 In-State Coal Production

In Texas, coal is primarily mined within the lignite belt of the southern U.S., which starts in South Texas near the tip of the Gulf Coast and stretches northeast to areas of Arkansas and Louisiana (Combs, 2008). These areas are marked in yellow in Figure 2.36.



Darker colors represent areas known to contain coal beds that are of commercial value at the present time or that may be of value to the future. In general the minimum thicknesses included are 14 inches for anthracite and bituminous coal, and 30 inches for subbituminous coal and lignite.

Lighter colors represent areas of doubtful value for coal. These may be divided into three classes- (1) areas containing thin or irregular beds, which generally have little or no value, but which locally may be thick enough to mine; (2) areas in which the coal is poor in quality; and (3) areas where information on the thickness and quality of coal beds is meager or lacking.

Source: Combs, 2008

Figure 2.36: Coal Mining Areas in the U.S.

Lignite is a low grade coal that is almost exclusively used for electricity generation. Lignite typically has a low heat content of 6,500 to 7,000 BTUs per pound compared to Powder River Basin coal, which has a heat content of 8,500 to 9,500 BTUs per pound. Lignite also tends to have higher carbon content (i.e., 25 to 35%) than traditional bituminous coal. When combusted, lignite thus releases higher levels of carbon dioxide (CO_2), nitrous oxides (NO_X), sulfuric oxides (SO_X), and particulate matter than bituminous coal.

In Texas, 12 lignite mines are currently in operation. These lignite mines are all surface mines and are all exclusively mine-to-mouth operations that provide lignite coal to an adjacent coal-powered electricity plant (RRC, 2010). Table 2.4 presents the locations of the 12 mine sites in terms of their GPS coordinates.

Table 2.4: Active Lignite Mine Locations in Texas

Mine Name	RRC Permit	Latitude	Longitude
S. Hallsville No. 1	33G	32.4660	-94.4850
Oak Hill	46B	32.2610	-94.7899
Big Brown	3D	31.8172	-96.1060
Jewett	32F	31.4092	-96.2291
Calvert	27F	31.0751	-96.6156
Three Oaks	48	30.3319	-97.2925
San Miguel V	11F	28.6831	-98.4840
Jewett E/F	47	31.3896	-96.2484
Martin Lake	4J	32.1911	-94.5626
Monticello-Winfield	34E	33.1386	-95.0460
Monticello Thermo	5F	33.0961	-95.5615
Kosse Mine	50	31.2818	-96.4943

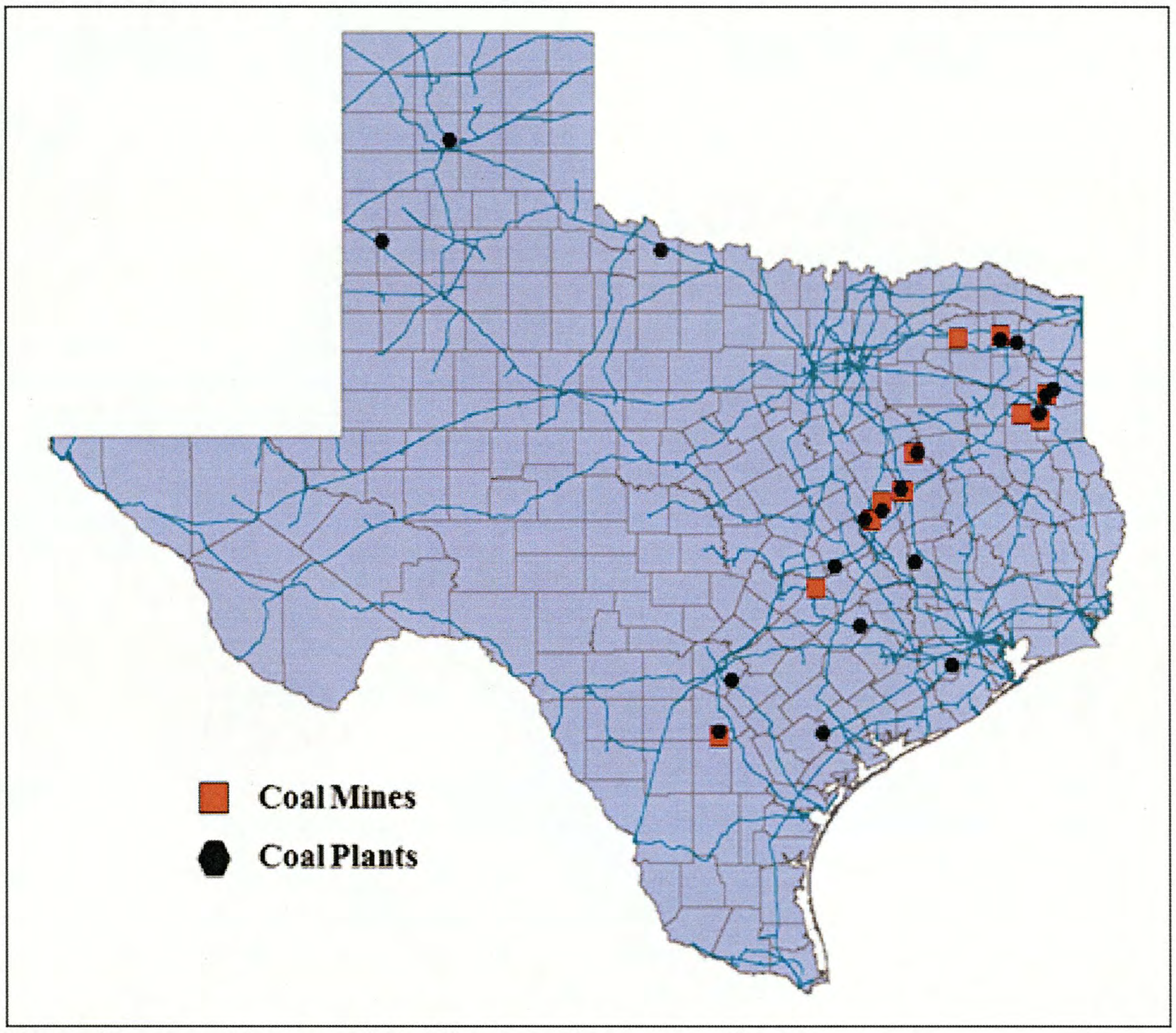
Source: Global Energy Observatory, ND

Currently, the 21 coal-powered electricity generation plants in the state have a total power generation capacity of 22,818 MW (Sourcewatch, ND). Table 2.5 lists the location of the 21 coal-powered electricity plants in terms of their GPS coordinates and their generating capacity.

Table 2.5: Coal-Powered Electricity Generation Plants in Texas

Power Plant	Capacity (MW)	Latitude	Longitude
Big Brown Electric Station	1,187	31.8205	-96.0540
Coleto Creek Power Station	600	28.7133	-97.2133
Fayette Power Project	1,690	29.9097	-96.7536
Gibbons Creek Steam Station	454	30.6179	-96.0822
Harrington Station	1,080	35.2990	-101.7477
J.K. Spruce Station	566	29.3072	-98.3202
J.T. Deely Station	932	29.3072	-98.3202
Limestone Electric Generating	1,706	31.4189	-96.2564
Martin Lake Steam Electric Station	2,380	32.2592	-94.5686
Monticello Steam Electric Station	1,980	33.0878	-95.0381
Norit Marshall Power Plant	2	32.5360	-94.3996
Oklaunion Power Station	720	34.0800	-99.1792
Parish Generating Station	2697	29.4757	-95.6362
Pirkey Power Plant	721	32.4636	-94.4871
San Miguel Electric Cooperative	390	28.7023	-98.4824
Sandow Station	363	30.5642	-97.0639
Sandow Station Unit 4	591	30.5642	-97.0639
Tolk Station	1136	34.1870	-102.5675
Twin Oaks Power Station	349	31.0914	-96.6928
Welsh Power Plant	1674	33.0550	-94.8403
Oak Grove Power Station	1,600	31.1811	-96.4875

The 12 active lignite coal mines and the 21 power plants are illustrated in Figure 2.37.



Note: Texas rail network is illustrated as green lines.

Figure 2.37: Coal Mines and Coal Electricity Plants in Texas

To gain insight into how coal is transported from the mine to the plant, the modes used for transportation, and the role of Texas's transportation system in these operations, the contact details of eight individuals were obtained from the RRC. These 8 individuals act as liaisons for the 12 operating mine sites. Six of the eight individuals were contacted and asked about the mine's operations. Table 2.6 summarizes the information gathered during the interviews—specifically, the power plants served by each mine, the mode of transportation used to move the coal from the mine to the plant, and general comments that were offered during the interviews.

Table 2.6: Active Mine Information Solicited Through Interviews

Mine Name	Servicing Plant	Mode of Haul	Comments
S. Hallsville No. 1	Pirkey Power Plant	Truck and Conveyor Belt	-
Oak Hill	Pirkey Power Plant	Truck to Rail	Private Haul Road to Railway Terminal
Big Brown	Big Brown Electric Station	Truck	Private Haul Road
Jewett	Limestone Electric Generating	Conveyor Belt	Private Haul Road to Conveyor Belt Delivery
Calvert	Twin Oaks Power Station	Conveyor Belt	Private Haul Road to Conveyor Belt Delivery
Three Oaks	Sandow Station	Conveyor Belt and Rail	-
San Miguel V	San Miguel Electric Cooperative	Truck and Rail	Private Haul Road (30 truckloads/day)
Jewett E/F	Limestone Electric Generating	Conveyor Belt	Private Haul Road to Conveyor Belt Delivery
Martin Lake	Martin Lake Steam Electric Station	Truck to Rail	Private Haul Road to Railway Terminal
Monticello-Winfield	Monticello Steam Electric Station	Truck to Tram	Private Haul Road to Electric Rail
Monticello Thermo	Monticello Steam Electric Station	Rail	Kansas City Southern Railway Line
Kosse Mine	Oak Grove Power Station	Truck to Rail	Private Haul Road to Rail

Source: Personnel Communication with mine liaisons

Table 2.6 indicates that a large number of mines use trucks that move on private roads to haul the coal from the mining pit to a collection pile. From there, it is loaded onto rail cars and railed to the power plant. Some mines also use a conveyor belt system that directly links the power plant to the pit. Only one mine, the Monticello Winfield mine, relies on a tram system to move the mined lignite coal to the power plant. In general it was observed that the trucking hauls are very short (i.e., less than 2 miles) and occur on private roads. Also, the rail haul is over relatively short distances varying from 2 to 14 miles.

2.3.2 Out-of-State Coal Production

On an annual basis, about 60% of the coal consumed in Texas comes from out-of-state sources. According to the State Energy Conservation Office, most out-of-state coal originates from the Powder River Basin of Wyoming and Montana, and is shipped to electricity generation plants exclusively by rail (Combs, 2008). According to a survey conducted by the Comptroller, the rail transportation costs can constitute two-thirds to three-quarters of the final cost of Powder River Basin coal.

2.3.3 Developing an Energy Supply Chain for Coal

From the information gathered, it is clear that coal used for electricity generation in Texas originates from in-state lignite coal mines and from the Powder River Basin of Wyoming and Montana. Active lignite mines, in all cases, are within close proximity to the coal-powered electricity plants. A variety of modes ranging from conveyor belts to tram systems are used to transport the coal from the mine to the power plant. On the other hand, the out-of-state coal is transported exclusively by rail. Based on this information, a supply chain for coal energy was developed. This supply chain is illustrated in Figure 2.38.

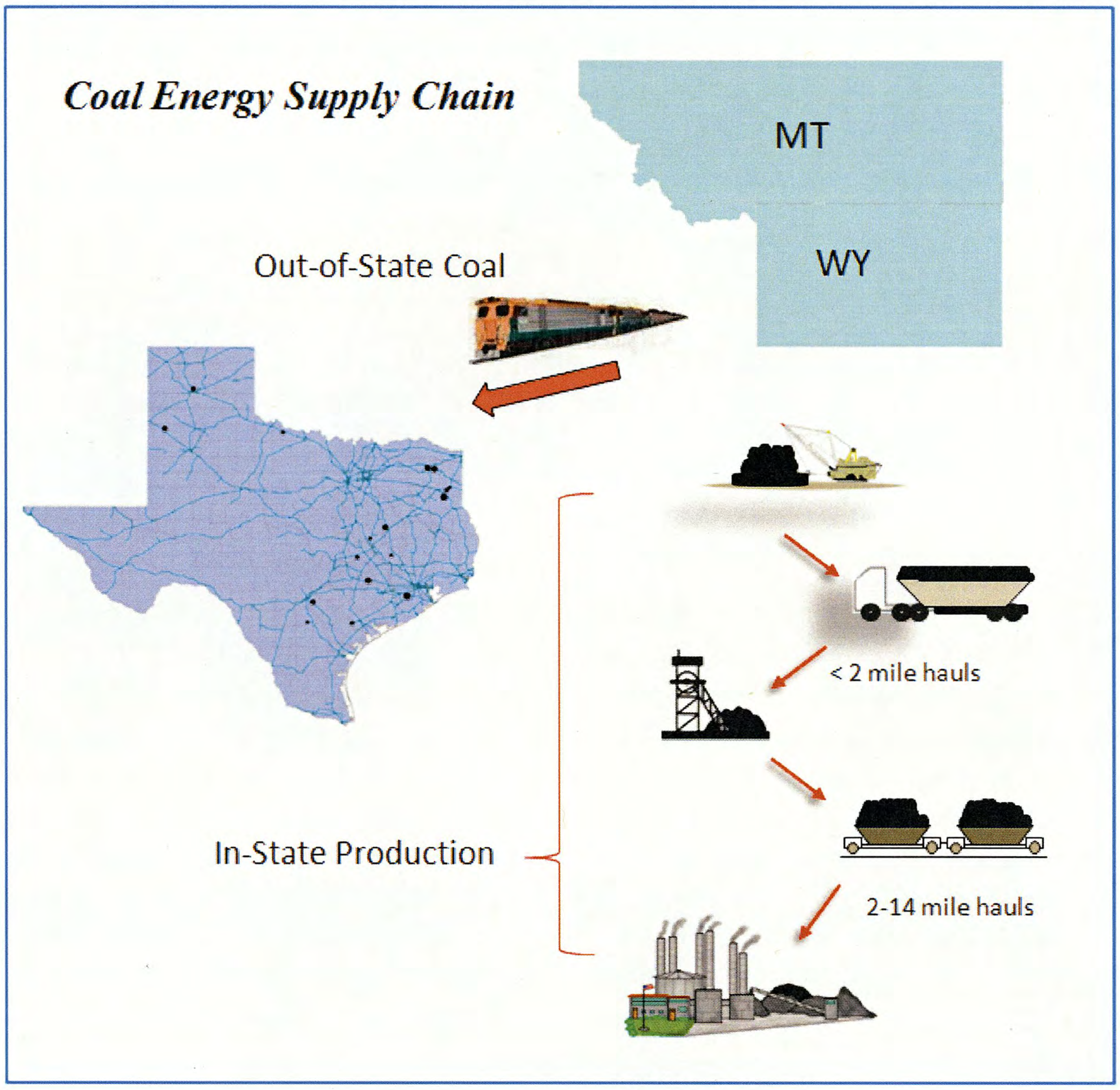


Figure 2.38: Energy Supply Chain for Coal

Over the last decade, the wind industry has become a growing part of the U.S. and Texas's energy sector. In 2009, 35,603 MW of wind energy were installed in the U.S. out of which 27.3% (9,711 MW) were installed in Texas (AWEA, ND). Figure 2.39 illustrates the growth of the wind energy industry in terms of installed capacity in the U.S. and in Texas between 2000 and 2009.

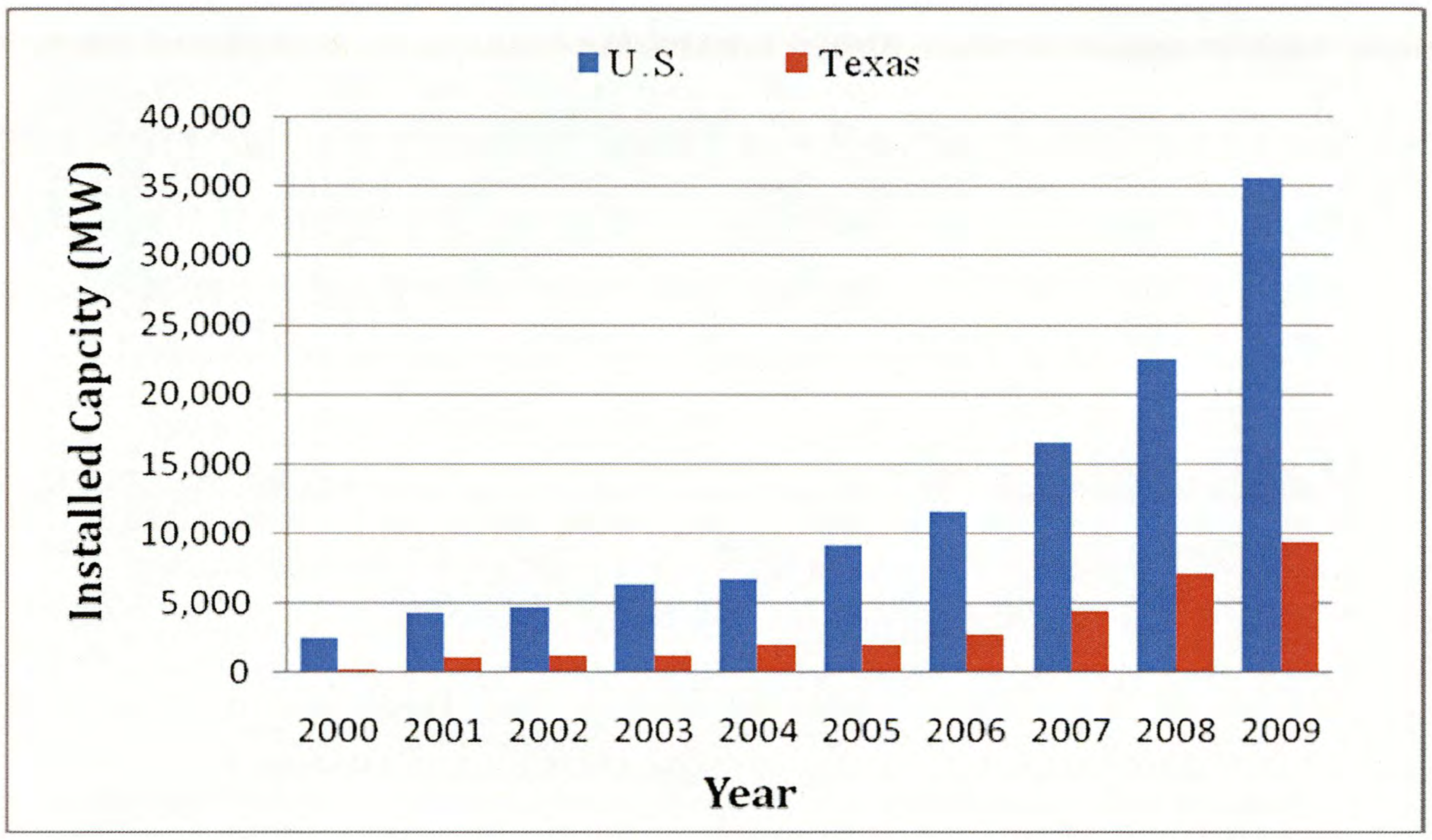
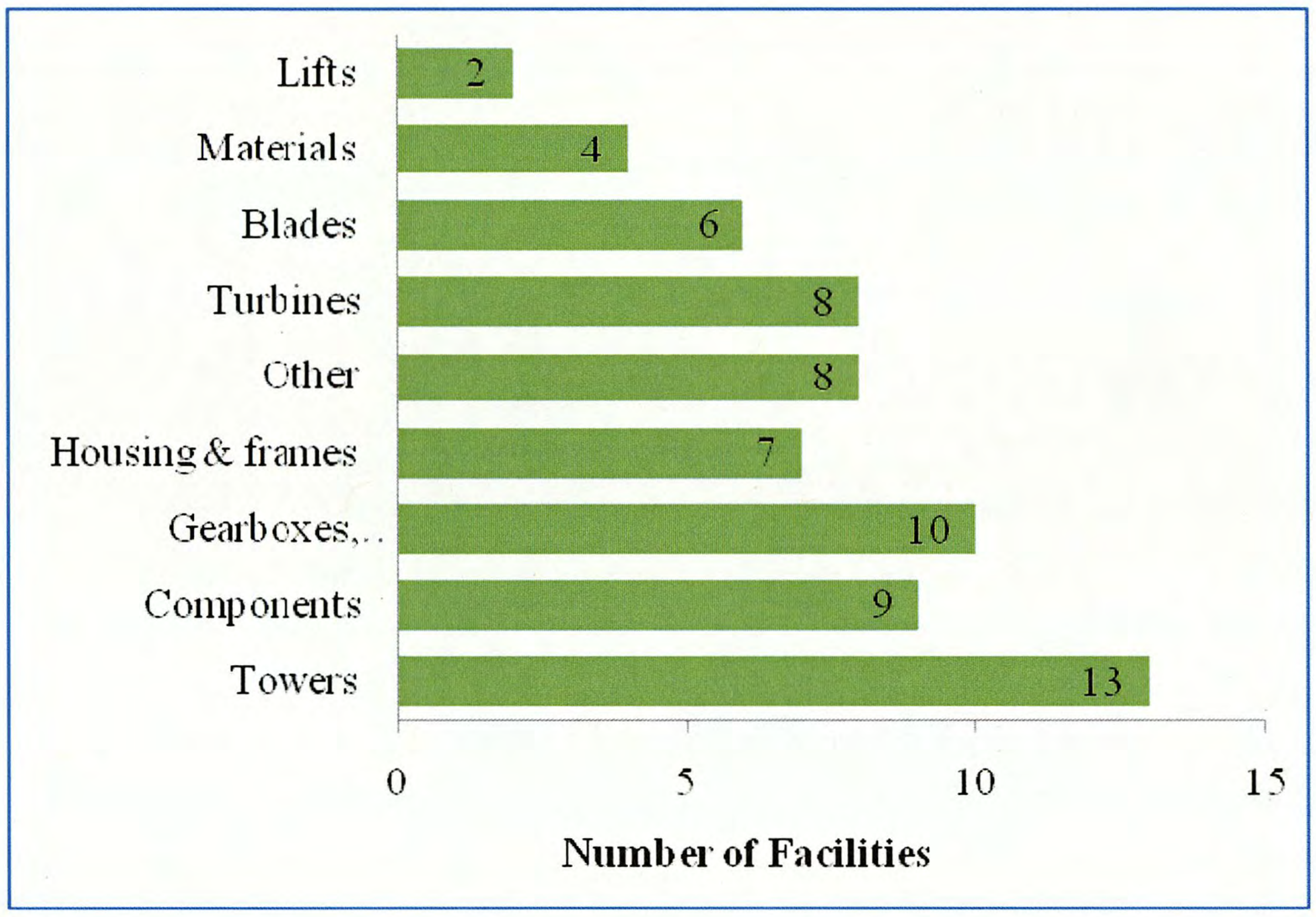


Figure 2.39: Installed Wind Capacity in U.S. and Texas

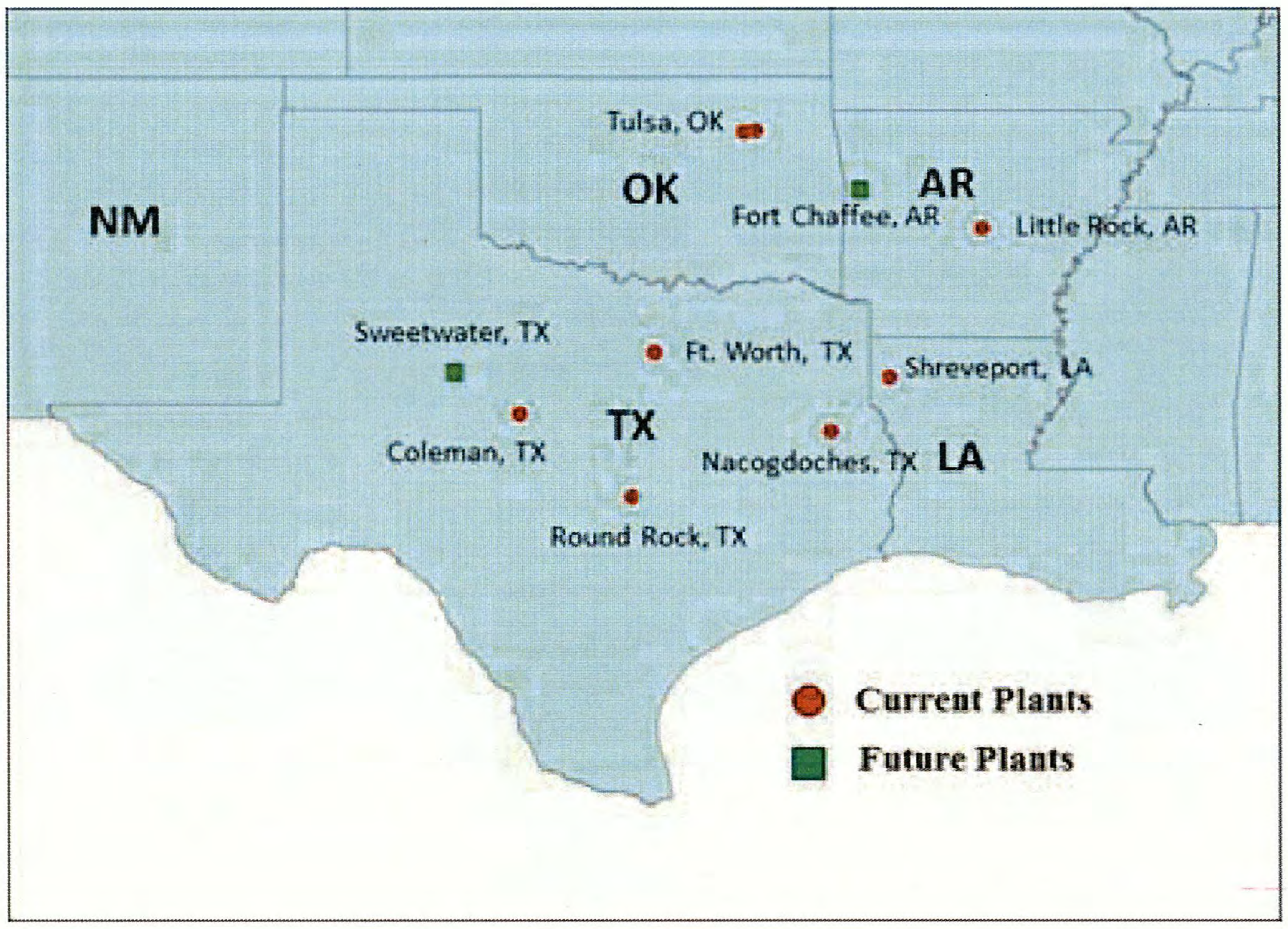
Much of the development of the wind energy industry in the U.S. and in Texas has been driven by federal and state incentives. For example, in Texas, the Renewable Portfolio Standard obliges electricity retailers serving open markets to purchase a percentage of their electricity from renewable sources. These regulations were implemented in 1999 and are expected to remain until the end of 2019 (Wiser, 2001). Similarly, the federal government provides a production tax credit (PTC) of 2.1 cents/kilowatt-hour to commercial wind farm developers. This allows wind power generation to be more competitive with traditional sources of electricity, such as natural gas or coal. Furthermore, wind energy advocates are currently promoting a National Renewable Electricity Standard (RES), which would require that 25% of the U.S. electricity demand be met by renewable sources by 2025 (AWEA, ND).

The existing and anticipated government incentives have increased the demand for wind energy, which resulted in the growth of the U.S. wind manufacturing sector. In 2004, domestically manufactured wind components represented less than 25% of total installed wind capacity. At the start of 2010, 50% of the windmills installed in the U.S. were manufactured domestically (AWEA, 2010). Furthermore, in 2008, according to the U.S. DOE, 37 manufacturing facilities were producing various windmill components in the U.S. (U.S. DOE, 2008). In 2009, 67 manufacturing facilities were in the U.S., and construction of 20 new facilities were to begin in 2010. The current manufacturing facilities by type of windmill component are presented in Figure 2.40. Current and announced manufacturing plants in the Southwest region of the U.S. are illustrated in Figure 2.41.



Source: AWEA, 2010

Figure 2.40: Windmill Component Facilities in the U.S.



Source: AWEA, 2010

Figure 2.41: Current and Announced Manufacturing Plants in the Southwest Region

Because wind mills require continuous maintenance and replacement of broken parts, a significant number of companies in the U.S. specialize in blades, gear units, towers, bolts, sensors, electronic components, cables, ladders, lift systems, and other miscellaneous supplies required for the daily maintenance and operation of a wind farm (U.S. DOE, 2008). The production of generators (i.e., nacelles) has mainly been done overseas. However, recent trends in the market have shown that the U.S. is attracting more and more wind manufacturers. Currently several wind turbine production plants operate in the U.S., including the following:

- Clipper Windpower in Cedar Rapids (IA),
- Acciona Energia in West Branch (IA),
- GE Energy in Erie (PA) and Greensville (SC),
- DeWind Inc. in Round Rock (TX), and
- Vestas in Windsor (CO).

Other companies such as Nordex USA and Mitsubishi Power Systems are also expanding in the U.S. For example, in 2009 Nordex began construction on a wind turbine manufacturing facility in Jonesboro/Chicago, Arkansas. The Nordex plant is expected to be completed in 2010, and by 2014 it is expected to have 700 employees and annually produce 300 wind turbines. Meanwhile, Mitsubishi Power Systems America announced the construction of their $100 million dollar wind turbine manufacturing facility near Fort Smith, Arkansas. Construction is expected to begin in early 2011, and when completed the facility will have around 400 full-time employees.

The gradual location of the wind manufacturing industry in the U.S. can change the current wind energy distribution network. For example, most wind turbine components are currently imported from countries such as China and India through the Gulf Coast ports. According to a company representative of Suzlon, a major wind energy manufacturer in India, all of the company's generators and 30% of the towers are produced overseas and imported through Port Freeport in Texas. From Port Freeport, the components are either transported by truck or rail to their final destination (Personal Communication with Suzlon Wind Energy, 2009). Similarly, Siemens and Mitsubishi Power Systems import their components through the ports of Houston and Corpus Christi. The ports of Corpus Christi, Freeport, and Houston have thus established themselves as the main gateways for wind mill components from overseas. From the ports these components are typically hauled by truck to their final destinations. Truck transport is currently the more pragmatic mode of choice as it is fast and efficient. However, if manufacturing plants begin to locate along the Great Plains wind corridor, which includes much of the Texas Panhandle, the distribution network can be expected to change, and as a result, alternative modes of transportation such as rail can become the more pragmatic mode of choice. If such is the case, then rail traffic moving wind mill components can be expected to increase. And as a result collection/distribution centers along the railway network can be expected to appear to service the adjacent wind development areas. This would result in shorter hauls of wind mill components on the Texas highway network, and hence a decreased overall impact on the system. The following sections, however, provide information and data on the role of Texas's transportation system in facilitating the current wind energy supply chains.

2.4 Developing a Wind Energy Supply Chain

Wind farm construction can generate a significant amount of traffic that can impact rural road networks. The impacted area will greatly depend on the size of the project. For example, the Horse Hollow Wind Energy Center near Taylor, TX has 421 installed units and sits on an area of about 49,000 acres of land (NextEra Energy, 2009). Typically wind mill units are placed about 1,000–1,650 feet apart from each other, and approximately 300–500 feet away from the main road (Clipper Windpower, ND).

A project can take anywhere from 6–12 months to complete depending on its size. The 60-MW Whirlwind wind farm development in Floyd County, for example, had a 6-month (i.e., May to October) construction schedule (Young, 2008). During the construction period a significant amount of traffic can be expected. Because the construction of a wind mill and the traffic associated with the process is not well documented, the following section aims to briefly describe the stages of construction and the associated traffic based on the volume of materials hauled to the site. Construction of a wind mill can be divided into several stages:

- site preparation,
- wind mill foundation installation,
- wind mill delivery and assembly, and
- underground cable installation.

The next sections discuss site preparation, wind mill foundation installation, and the transportation of the wind mill components.

2.4.1 Site Preparation, Windmill Foundation, and Cable Installation

Similar to the oil and gas industry, site preparation requires heavy bulldozers for grading and building a road to service the pad site. In Texas, service roads are typically constructed from caliche base material. Approximately 4,000–4,500 tons of caliche is required per mile of service road. Standard service road dimensions are presented in Table 2.7.

Table 2.7: Standard Dimensions for a Road Servicing a Wind Mill Site

Width	20 ft.
Depth	8 in.
Length	0.25–0.5 mi.
Material	1,000–2,250 T

After the service road has been constructed, the foundation is prepared. Preparation of the foundation involves the excavation of a site about 8 feet deep and 100 feet in diameter. Afterwards, a mud mat of 4 inches in depth and 60 feet in diameter is laid out to prepare the site for the construction of the foundation. Figure 2.42 provides an illustration of the site preparation process.

Source: Stacey Young, TxDOT Lubbock District

Figure 2.42: Site Preparation (Excavation and Mud Mat)

The foundation for a wind mill is constructed in several stages. First the outside structure is prepared and reinforced with steel rebar. Then it is built up to the base of the service road and reinforced with concrete. For a 2.3-MW wind mill, the foundation can be up to 8.5 feet in height, requiring 85,300 lbs of steel rebar and 350 cubic yards of cement. The overall weight of a 2.3-MW wind mill foundation, when completed, is about 1.59 million lbs. or 795 tons. Figure 2.43 illustrates the foundation construction process.

Source: Stacey Young, TxDOT Lubbock District

Figure 2.43: Foundation Construction Process

Once the foundation is set in place, it is laid over with the base material and wind components are delivered on site (see next section). Assembly begins with the main section of the tower. Two cranes are used for the assembly. The first two tower sections are installed with the smaller crane, while the last tower section, the nacelle, and the rotor are installed with the larger crane. The blades are connected to the rotor on the ground and then hoisted up by the crane and attached to the nacelle. Figure 2.44 illustrates this process.

Source: Stacey Young, TxDOT Lubbock District

Figure 2.44: Assembly of a Wind Mill

Once the wind mill is assembled, the remaining steps include the installation of underground cables. Wind energy is moved from the wind turbine through underground cables to power transformers that are linked to high voltage transmission lines. These are subsequently linked to substations that reduce the voltage to distribute the energy to customers via the energy grid.

The construction of the service road and foundation preparation can generate a significant amount of truck traffic. Based on the amount of materials required during these processes, general estimates can be made regarding the truck traffic generated. Table 2.8 presents preliminary estimates for a single wind mill site. These estimates do not include many of the deliveries such as steel rebar, bolts, cooling fans, and other miscellaneous accessories that are crucial for the assembly of the unit.

Table 2.8: Estimates of Truck Traffic Associated with a Single Wind Mill Site

Siemens 2.3 MW	Quantity	Truck Hauls
Concrete for Pad	600–710 T	35
Base Material for Pad	5,000 T	223
Service Road	1,000–2,250 T	78

Based on Truck Weight Limits of 58,420lbs GWV on FM Roads

Based on these statistics, a 200-unit wind farm development, for example, would generate 67,200 truck trips over a 6- to 12-month period.

Wind farm development could therefore have a significant impact on the roadway infrastructure, especially on rural FM roads that were not designed for high volumes of traffic or heavy loads. During the construction of the Whirlwind wind farm in Floyd County, TxDOT monitored the roadway conditions of FM 97 before and after the development. Table 2.9 presents some of the information collected.

Table 2.9: "Before and After" Conditions on FM 97

FM 97	ADT	% Trucks	ADTT	Distress Score
2007	340	9%	30	100
2008	2000	11%	122	52

Source: Stacey Young, TxDOT Lubbock District

Table 2.9 makes clear that during the year of construction, ADT increased by almost 600%. Truck traffic also significantly increased. In fact, during the month of August, truck traffic on FM 97 accounted for 45% of the ADT. As a result, the distress score on FM 97 decreased nearly by half during the 6 months of construction. Much patchwork had to be done to rehabilitate the road to bring it back to an acceptable condition, especially near the shoulders of the roadway where most of the damage had occurred. Figure 2.45 illustrates some of the damage to the road.

Source: Stacey Young, TxDOT Lubbock District

Figure 2.45: Damage on FM 97 Resulting from Windfarm Development

2.4.1.1 Transportation of Wind Mill Components

Before the installation of a wind mill can begin, wind mill components must be delivered on site. Eight main OS/OW components need to be delivered to the site for each wind mill:

- hub or the rotor,
- nacelle,
- windmill tower, which comes in three separate sections, and
- the three blades that attach to the rotor.

These components are listed in Table 2.10, along with their respective dimensions in relation to the size of the wind turbine.

Table 2.10: Dimensions for a Typical Siemens 2.3 MW Unit

Siemens 2.3 MW	Dimensions
Hub/Rotor	
	Sweep Diameter: 310.5 ft
	Weight: 63 K lbs
Nacelle	
	Height: 12.5 ft
	Width 11.5 ft
	Length: 37.5 ft
	Weight: 193 K lbs
Tower (3 parts)	
Main	Height: 52.8 ft
	Diameter: 14.1 ft bottom/13.1 ft. top
	Weight: 133.1 K lbs
Mid-Section	Height: 89.7 ft
	Diameter: 13.1 ft
	Weight: 132 K lbs
Top-Piece	Height: 118.2 ft
	Diameter: 13.1 ft bottom/7.1 ft top
	Weight: 109.4 K lbs
Blades (3)	
	Length: 148.4 ft
	Weight: 27.1 K lbs

Source: Stacey Young, TxDOT Lubbock District

The dimensions of these components require specialized vehicles to haul them to their final destinations. Typically, a Schnabel and steering dolly combination are used to move the tower components and a 13-axle trailer is used to move the nacelle. Table 2.11 presents some descriptions and dimensions of the specialized vehicles used to haul the wind mill components along with their gross vehicle weights when loaded. Note, however, that because wind mill components come in different sizes depending on the power capacity of the unit (typically 1.6–2.5 MW) various combinations of specialized vehicles can be used to move the same component. It should also be noted that larger units (3.0–5.0 MW) can weigh significantly more than the values presented in Table 2.11.

Table 2.11: Specialized Vehicles Used for Moving Wind Mill (1.5 MW) Components*

Vehicle	Component	Width	Length	Height	Weight (lbs)
13-Axle Schnabel w/ 6-Axle Steerable Dolly	Tower, Main Section	15'1"	177'	15'8"–16'4"	232,000
11-Axle Schnabel w/ 6-Axle Steerable Dolly	Tower, Mid-Section	15'1"	159'11"	15'8"–16'4"	199,000
Schnabel Dolly	Tower, Mid-Section	14'2"	122'	14'6"	128,800
5-Axle Stretch Lowboy	Tower, Mid-Section	14'2"	104'	17'4"	112,000
Dolly Trailer	Tower, Top-Section	11'6"	124'	14'2"	91,000
13 Axle Trailer	Nacelle	12'6"	120'6"	14'6"	218,000
Specialized Blade Trailer	Blade	8'6"	175'	14'6"	78,000
Double Drop Trailer	Hub/Rotor	11'2"	50'	14'	85,000

*From presentation by GE Energy

Source: Danny DeLeon, TxDOT Corpus District

Because of the size of these vehicles and the cargo they haul, special routing accommodations must be provided for each component. TxDOT's permitting office assigns routes to be followed by all trucking companies involved in hauling wind mill components. In route assignment, special care is given to the roadway infrastructure, including maximum loads that can be carried by bridges along the route and vertical clearance distances. Also, care is taken to avoid large metropolitan areas (TxDOT Permitting Office, 2009).

Data from TxDOT's OS/OW database revealed that, on an annual basis, 13,000 to 20,000 route permits are issued to the wind energy industry for moving windmill components on the state's roads. In general, a windmill requires 8 to 10 OS/OW permits to move the various components (i.e., 1 permit for the nacelle, 1 permit for the rotor hub, 3 permits for the blades, and 3–5 permits for the tower) from the point of origin to the wind farm site.

To understand how Texas's transportation system supports and is used by the wind energy sector, a supply chain was developed that captures the movement of wind components within the state and across state boundaries. Data for 2007, 2008, and 2009 from the OS/OW database were analyzed. As mentioned earlier, the OS/OW database records permits issued by TxDOT to haulers of non-standard loads. It captures 103 variables about the vehicle, the route, and cargo being transported for each permit entry included in the database. The relevant variables (i.e., fields) used in this analysis are presented in Table 2.12.

Table 2.12: Relevant Field Entries Used from TxDOT's OS/OW Database

Field No.	Field Description
1	Permit Number
2	Load Description
6–7	Width
9–10	Height
12–13	Length
21	Gross Vehicle Weight
25–29	Route Information
30–53	Axle Spacing
54–78	Reported Weight On Axle
79–103	Number of Tires per Axle

The OS/OW data was used to track vehicles hauling components from their points of origin to their points of destination. This provided information about the industry's use of Texas's road network and where wind traffic enters the state. The analysis of the OS/OW database also provided the research team with an understanding of the roads most impacted by the wind sector and the average distance of haul. Figure 2.46 presents a supply chain that attempts to illustrate how the wind energy sector uses Texas's transportation system.

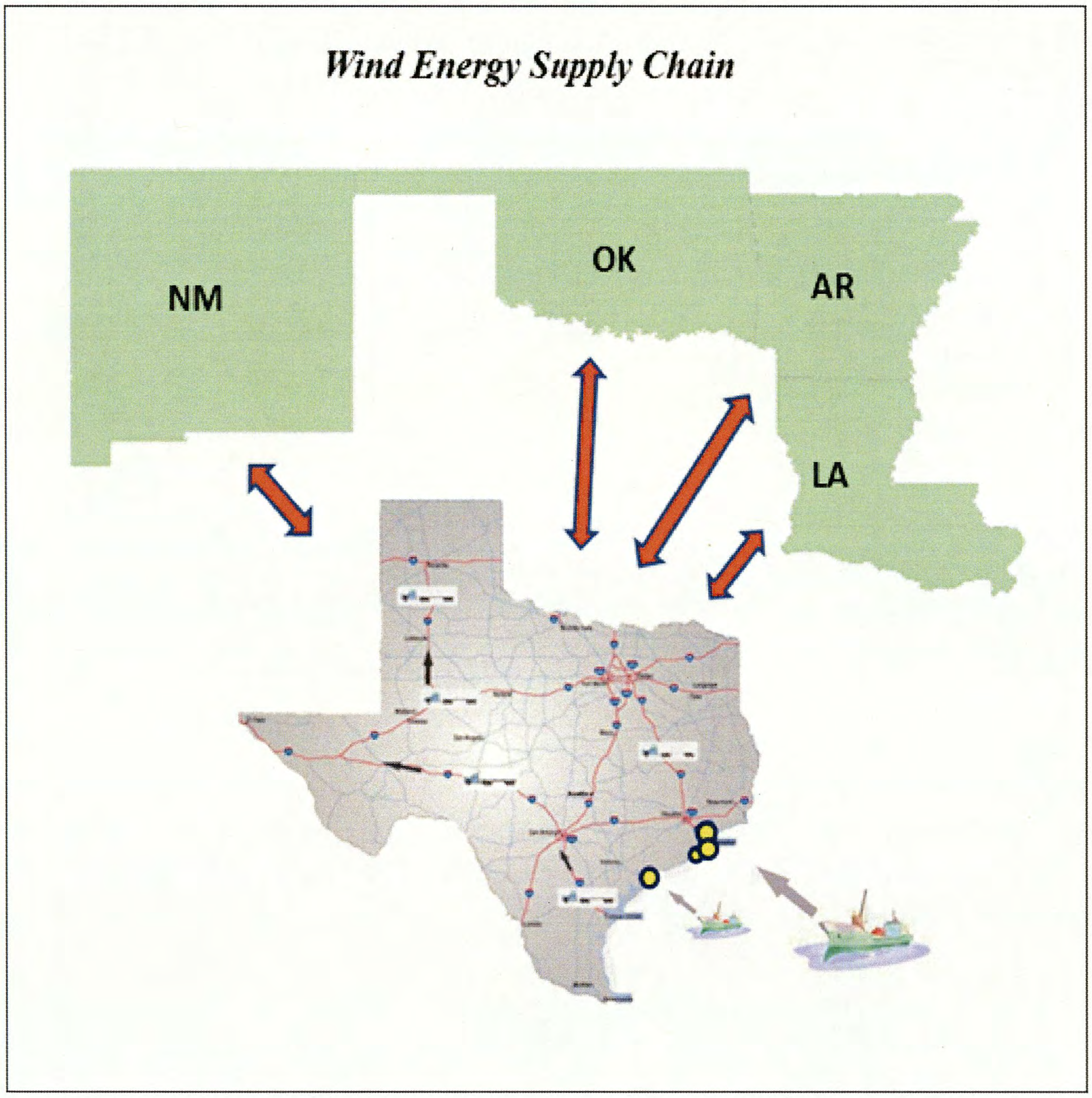


Figure 2.46: Wind Energy Supply Chain for Texas

Figure 2.46 indicates that windmill traffic in Texas originates mainly from the ports along the Gulf Coast and from the four surrounding states of Arkansas, Louisiana, New Mexico, and Oklahoma. An analysis of the route information from the OS/OW database showed that approximately 25 to 30% of the annual windmill traffic originates from the bordering states of Arkansas, Louisiana, New Mexico, and Oklahoma; most of this traffic enters the state from New Mexico and Oklahoma. Furthermore, a substantial share of the windmill components enter Texas through the ports of Houston, Galveston, Corpus Christi, Beaumont, and Freeport. Approximately 42% of all permits issued per year to the industry originate from these five ports. In-state manufacturing facilities are also important generators of windmill activity. Specifically, two manufacturing plants owned by Trinity Structural Towers in Fort Worth and Coleman, respectively, generated 15 to 20% of the permits issued to the industry. The information is summarized in Table 2.13.

Table 2.13: Route Origins for OS/OW Windmill Traffic in Texas (2007–2009)

Route Start Locations		**FY 2007**	**FY 2008**	**FY 2009**
Out-of-State Points of Origin	Arkansas	1.4%	2.5%	1.6%
	Louisiana	5.1%	2.9%	4.6%
	New Mexico	11.5%	8.9%	10.7%
	Oklahoma	8.6%	16.3%	8.3%
	Subtotal	***26.61%***	***30.59%***	***25.15%***
Points of Origin at the Ports	Houston	21.6%	18.8%	13.7%
	Galveston	2.2%	3.1%	4.0%
	Corpus Christi	14.3%	13.3%	11.9%
	Freeport	1.9%	5.8%	10.0%
	Beaumont	3.9%	1.9%	2.2%
	Subtotal	***43.84%***	***42.79%***	***41.82%***
In-State Production	Coleman	12.7%	12.6%	11.9%
	Fort Worth	7.0%	4.5%	3.6%
	Subtotal	***19.70%***	***17.14%***	***15.46%***
Total Permits Issued		**13,687**	**18,957**	**14,444**

A similar analysis was conducted for route destinations. Analyzing the OS/OW data revealed that 26 to 42% of the permits issued to the wind industry terminated in the bordering states, particularly Oklahoma. In-state destinations accounted for 58 to 74% of the issued permits, with Coleman and Sterling City being the two major destinations. Table 2.14 summarizes these findings.

Table 2.14: Route Destination for OS/OW Windmill Traffic in Texas (2007–2009)

Route End Locations		FY 2007	FY 2008	FY 2009
Out-of-State Points of Destination	Arkansas	1.5%	2.6%	3.8%
	Louisiana	4.9%	2.6%	1.4%
	New Mexico	1.1%	1.3%	6.2%
	Oklahoma	29.3%	19.8%	30.4%
	Subtotal	***36.74%***	***26.27%***	***41.81%***
In-State Points of Destination	Coleman	12.2%	10.1%	6.7%
	Sterling City	8.5%	7.4%	5.9%
	Other	42.5%	56.2%	45.6%
	Subtotal	***63.26%***	***73.73%***	***58.19%***
Total Permits Issued		**13,687**	**18,957**	**14,444**

Subsequently, the research team determined the types of roads impacted by the movement of windmill components. Route information from the OS/OW database was used to identify the routes used by the sector. Specifically, the OS/OW database captures a permit's starting and ending location and a description of the route. A random sample of 97 records was extracted from the 2009 OS/OW database and each record's route was plotted in Google Maps. The sample provided a representative distribution of the roads used in the transportation of windmill components and allowed for the calculation of the average haul distance. The total VMT for the 97-record sample was determined to be 39,193.85 miles. Road usage as a percentage of total VMT is illustrated in Figure 2.47.

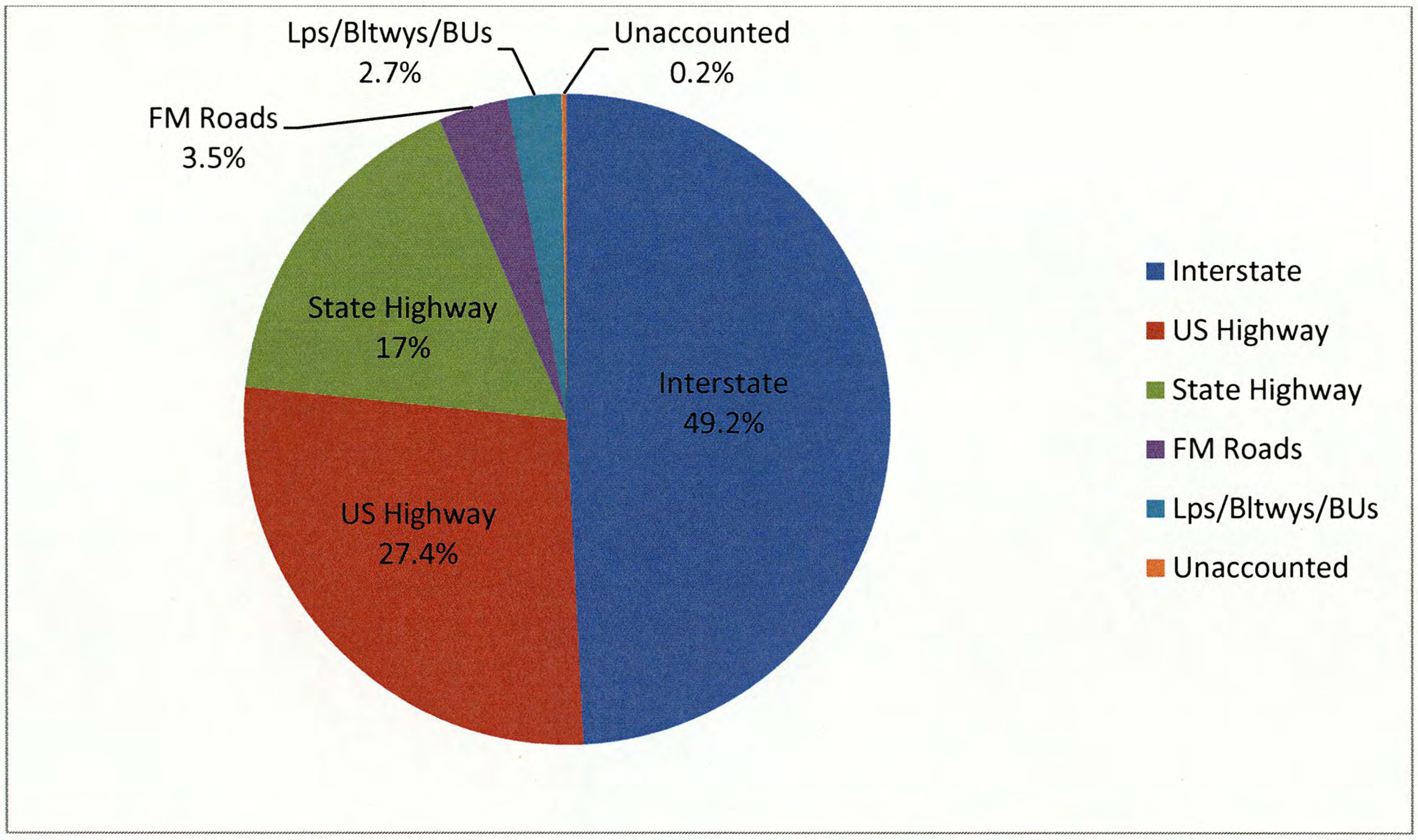


Figure 2.47: Road Usage as a Percentage of VMT

As Figure 2.47 shows, most of the VMT associated with the movement of windmill components occurred on the higher functional road classes, such as the Interstates (49.2%) and the US Highways (27.4%). In terms of the Interstate system, most of the VMT occurred on IH 10 (41.8%), IH 20 (18.2%), and IH 45 (18.8%). FM roads represented about 3.5% of total VMT. This is to be expected as FM roads are typically the final link in the supply chain. FM roads are, however, a critical component of the supply chain as travel on these roads represents short but very frequent trips during site development.

From the sample of 97 plotted routes, a distribution of the haul distances was developed (see Figure 2.48). Analyzing the trip lengths for the 97 plotted routes revealed an average trip length of 415.97 miles (standard deviation: 220.73 miles) for hauling windmill components in Texas.

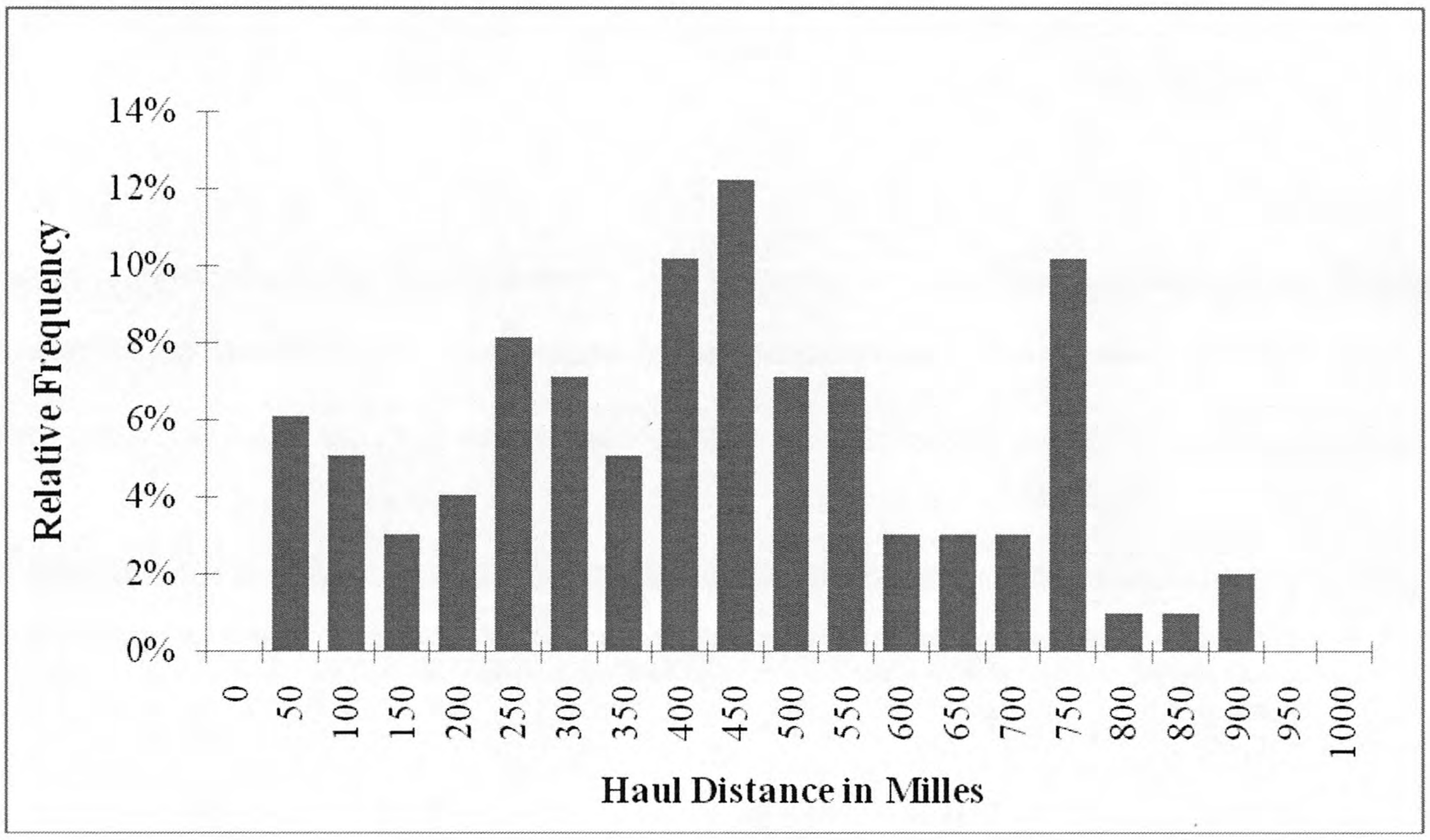


Figure 2.48: Haul Distance for Windmill Components

2.4.1.2 Analysis of Windmill Traffic from Ports

The route analysis discussed in the previous section provided the research team with a unique opportunity to analyze windmill traffic originating from Texas's ports and to identify specific road sections within the state that move a higher than average amount of windmill traffic. The research team found that most of the windmill traffic from the Port of Houston seems to use IH 45. However, near Huntsville the traffic was typically routed around the city using State Highway 19 and FM 2821. These routes are illustrated in Figure 2.49.

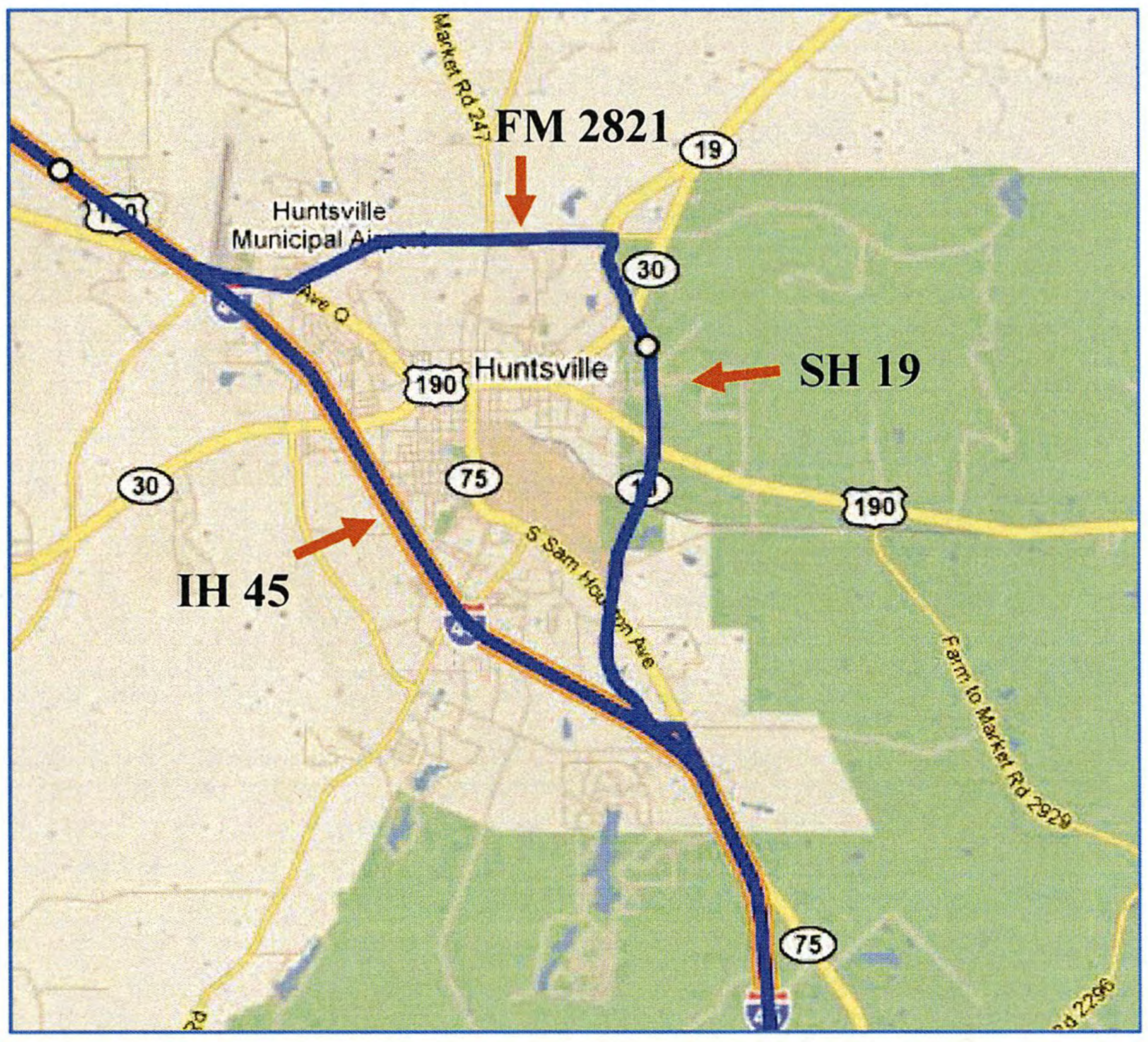


Figure 2.49: Huntsville Area Impacted

Two other areas were also identified that facilitate the movement of a substantial amount of windmill traffic. Loop 1604 around the city of San Antonio moves a substantial amount of through traffic originating from the ports of Houston and Corpus Christi, and IH 35W north of the Dallas-Fort Worth area facilitates the movement of windmill traffic in and out of the state of Oklahoma. These routes are highlighted in Figure 2.50 and 2.51.

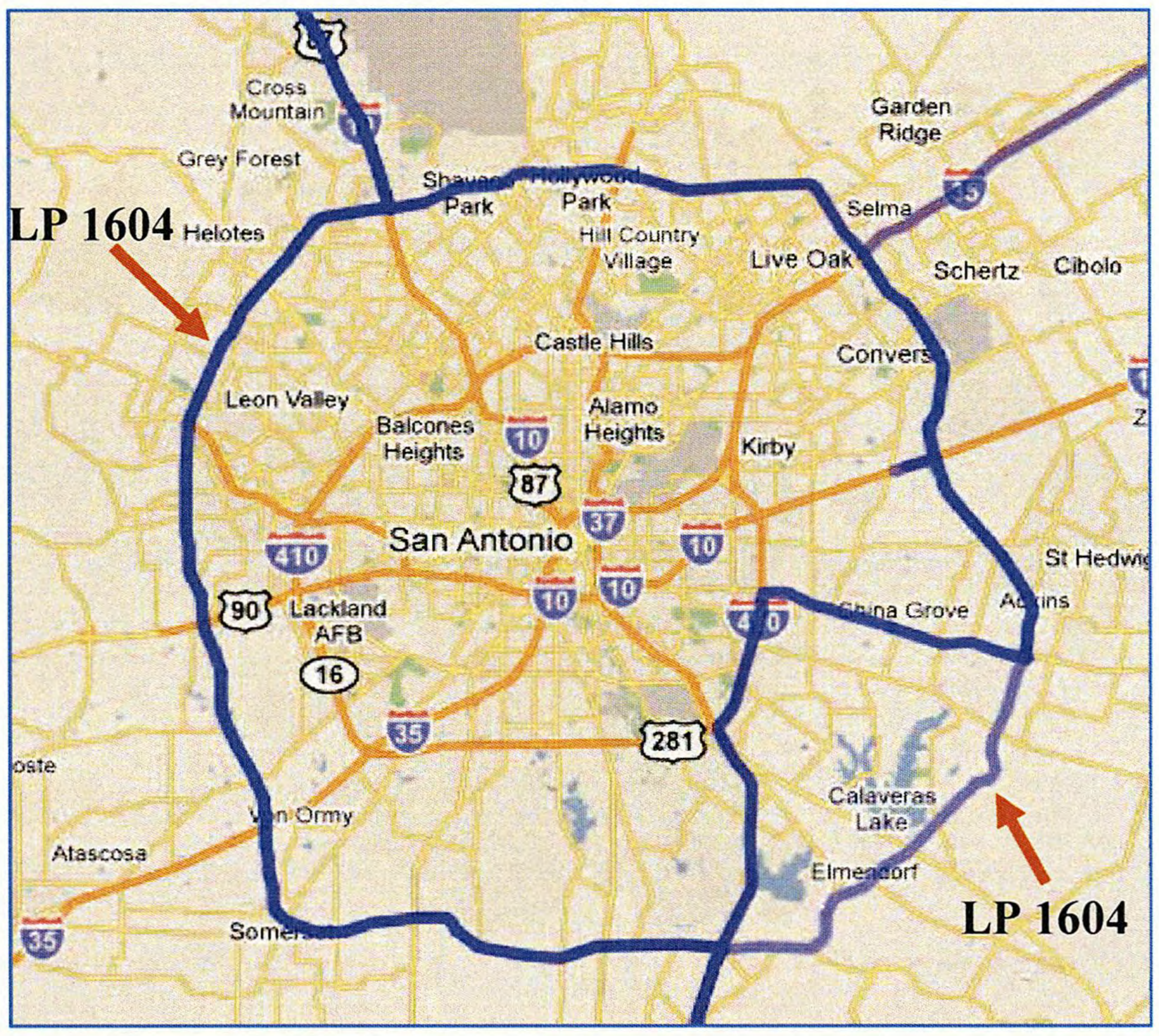


Figure 2.50: San Antonio Area Impacted

Figure 2.51: IH 35W, North of Dallas-Fort Worth

2.4.1.3 Role of Rail Transportation in the Wind Energy Supply Chain

In Texas, windmill components are transported by truck and rail. It is therefore important to explore the roles of both modes in the wind energy supply chain. Table 2.15 presents the advantages and disadvantages of the two modes as they pertain to the wind energy industry.

Table 2.15: Advantages and Disadvantages of Truck and Rail

Mode of Transportation	Advantages	Disadvantages
Truck	• Short and long-distance transportation • Flexibility of schedule • Direct access to construction site • Shipment of individual parts	• Oversized/overweight routing regulations • Higher transportation costs
Rail	• Economical for long-distance transportation • Economical for transportation of bulk quantities	• Oversized/overweight routing regulations • Retrofitting of rail cars • Limited access to final site

Truck transportation of windmill components is currently the most pragmatic mode of choice. The trucking mode provides long and short distance transportation and flexible scheduling. The biggest advantage, however, is that the trucking mode is able to deliver the windmill components directly to the construction site. Because most wind development sites are located in remote rural locations, they are often accessible only by road. Therefore, even if the components were shipped by rail, the final link would still have to be made by truck. Point-to-point delivery is one of the main reasons why truck transportation—although more expensive—is still the more pragmatic mode of choice (AWEA, ND).

Table 2.15 makes clear that rail holds some advantages over truck transportation—specifically the ability to move large quantities over long distances, which tends to be more economical. BNSF reported that six rotor hubs or two nacelle units can fit in one railroad car and be transported without any specific modifications to the rail car. This study also showed that transportation costs can be drastically reduced by switching to rail. Specifically, BNSF demonstrated that it can reduce the transportation costs to the developer by $1 million when transporting 30 new windmills from Corpus Christi to Glenrock, WY by rail (BNSF, 2010). To move a single windmill by truck, on the other hand, requires 8 to 10 OS/OW vehicles and 16 to 20 escort vehicles.

The American Wind Energy Association (AWEA) also reported that transportation costs can be reduced by 15 to 25% if windmill components are moved by rail instead of truck (AWEA, ND). These types of savings make rail transportation a financial alternative to trucking for the wind industry. Several rail companies have thus begun to make investments such as retrofitting rail cars to accommodate oversized nacelle units, towers, and blades. BNSF and UP have also made significant infrastructure investments in wind loading and unloading transload centers. Two of BNSF's 22 wind transload centers in the U.S. are in Texas—i.e., one in Lubbock and one in Sweetwater. UP currently operates 9 wind transload centers in the U.S.—of which one is in Abilene, TX—and is planning another 14 transload centers around the country. Wind transload centers could potentially reduce the hauling distance of wind components by truck as rail would move the wind components to a transload site near the development site. Trucking would be used to move the components from the transload site to the development site, albeit over a much shorter distance. According to BNSF, the company has strategically located its wind transload centers to be within 150 to 200 miles of most major current and future wind development sites (BNSF, 2010). Figure 2.52 illustrates BNSF's wind transload sites along with all major ports served by the railway. Similarly, Figure 2.53 illustrates UP's current and planned transload sites.

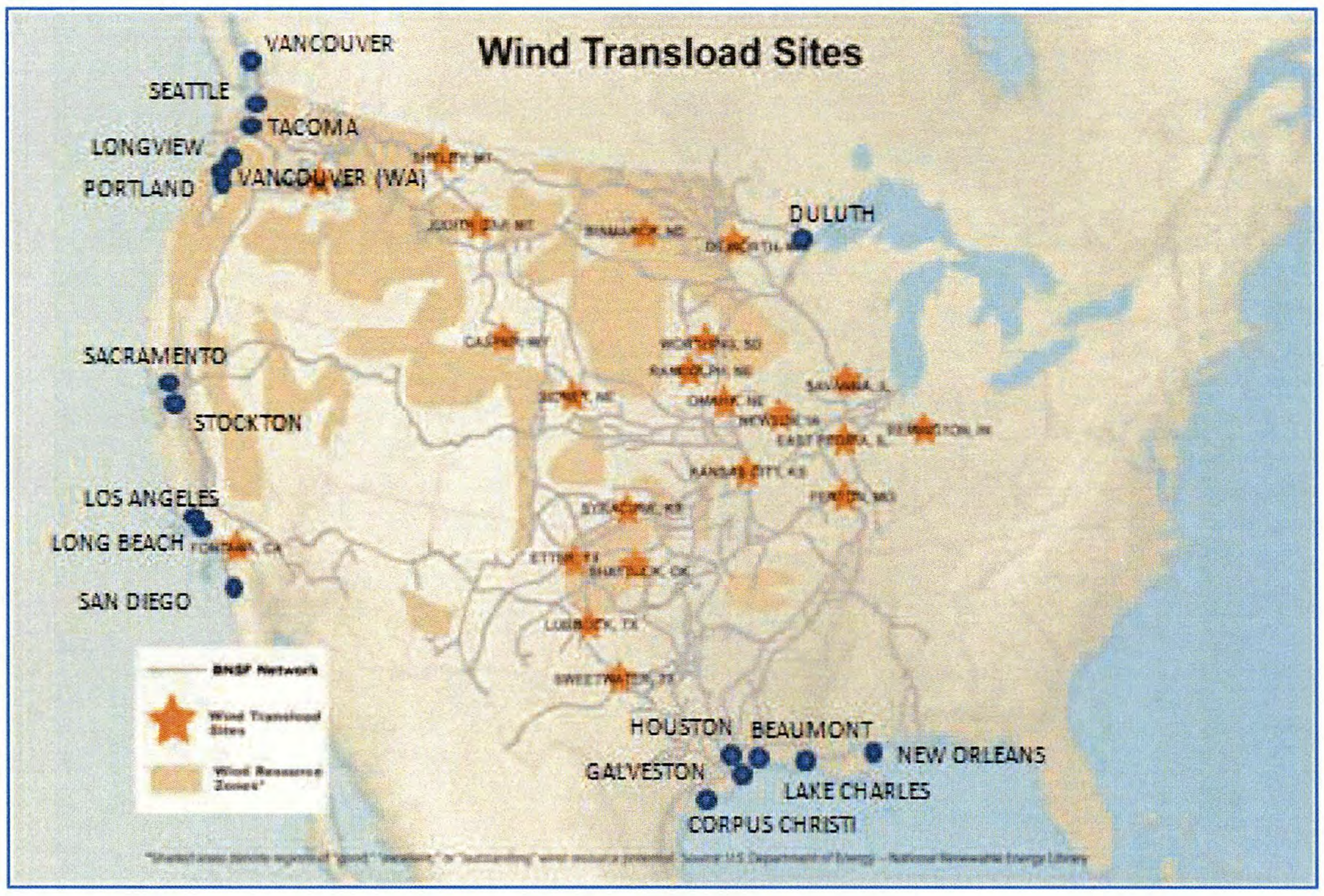
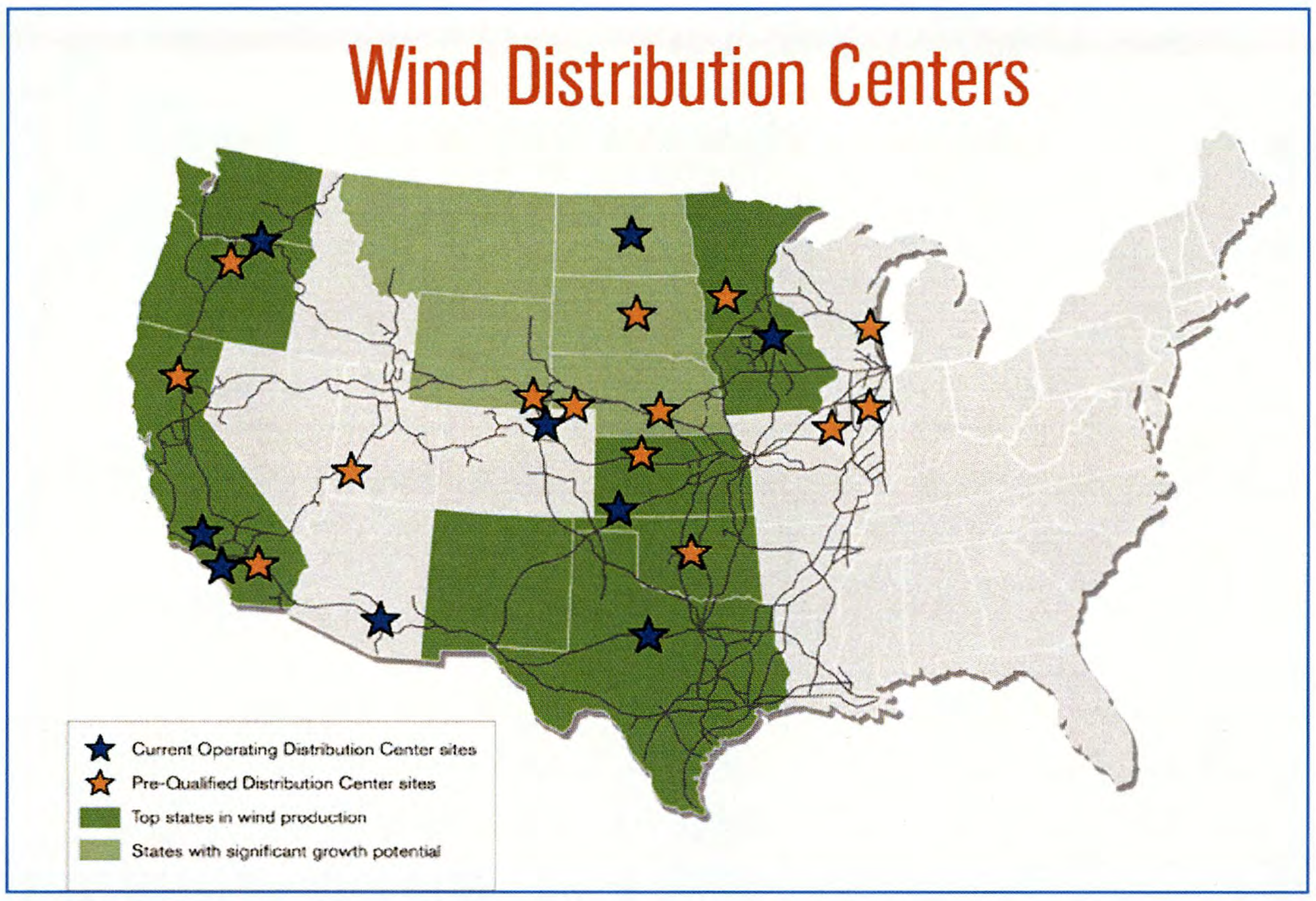


Figure 2.52: Wind Transload Sites and Ports Linked to the BNSF Rail Network



Source: Union Pacific Railway, ND

Figure 2.53: Current and Proposed Wind Transload Sites on UP Network

Given the substantial investments by the railroad industry to move windmill components, the potential exists for some diversion of truck to rail for the transportation of windmill components. Rail can thus become more competitive when transporting windmill components because it is cheaper to move large quantities of product over longer distances. Trucking will, in this case, be used for the shorter distance trips to move the components from the transload centers to the wind farm site. Having said this, the rail network also presents limitations. Similar to truck transportation, the rail transportation of OS/OW windmill components requires route studies to ensure that horizontal and vertical clearances are met along the railroad's ROW and that weight limitations on bridges are not violated.

2.5 Bio-Fuel Energy Supply Chain

Bio-fuels are an emerging fuel source that is blended with petroleum diesel and gasoline. There two main types of bio-fuels are ethanol and bio-diesel. Currently ethanol products represent the bulk of the bio-fuel industry. Bio-diesel production represents only about 6 to 8% of the entire bio-fuels market.

The bio-fuels market has largely been driven by government mandates—specifically, the Renewable Fuel Standard (RFS) program that was established under the 2005 Energy Policy Act and further expanded under the 2007 U.S. Energy Independence and Security Act. The RFS program mandates that a certain percentage of petroleum consumption be substituted with renewable fuels. Furthermore, the RFS sets criteria and thresholds for greenhouse gas emissions from renewable fuels and for the feedstocks used in the production of the bio-fuel product (EPA, 2010). Figure 2.54 illustrates the volume requirements for renewable fuels under the 2007 U.S. Energy Independence and Security Act.

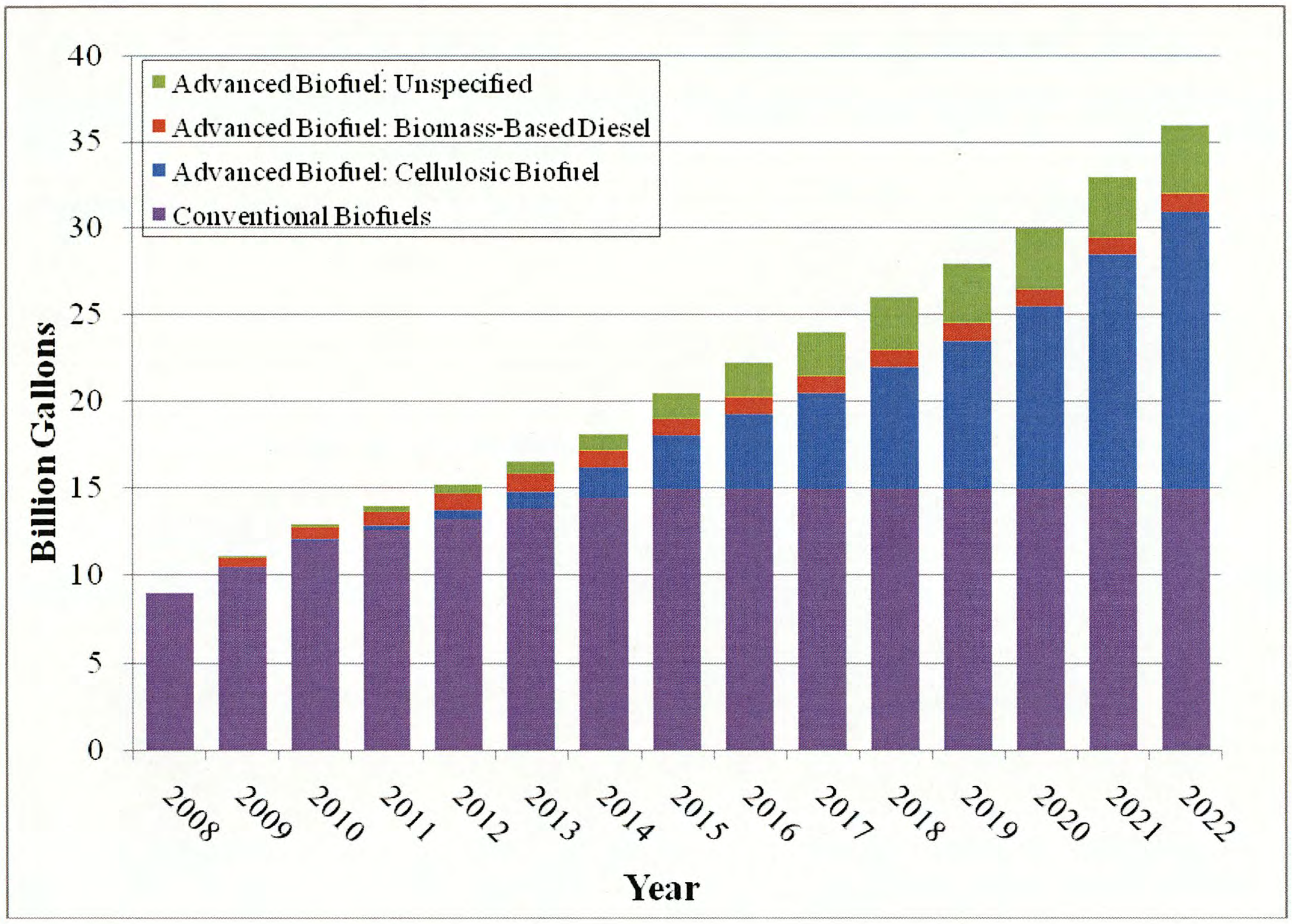


Figure 2.54: RFS Program Volume Requirements

Figure 2.54 indicates that the RFS program requires that by 2022, 16 billion gallons of the 36 billion gallon mandate have to be derived from cellulosic biomass. The program also specifies that at least one billion gallons of bio-fuels must be a biomass-based diesel fuel. Finally, the program limits conventional bio-fuel production (i.e., corn-based ethanol) to 15 billion gallons of the total mandate. Today, however, corn-based ethanol comprises the bulk of all bio-fuel production while cellulosic bio-fuel synthesis still remains largely in the initial stages of development.

The RFS program has stimulated the bio-fuel industry in the U.S. and in Texas. As of July 2010, 216 official ethanol plants (RFA, ND) and 133 bio-diesel plants (NBB, ND) were operating in the U.S. Most are located in the Midwestern states of Illinois, Indiana, Iowa, Nebraska, and Minnesota. In July 2010, three ethanol plants were located in the Texas Panhandle and ten bio-diesel plants were operating throughout the state.

In Texas, the bio-fuel industry is concentrated in three areas: 1) the Texas Panhandle, 2) the Dallas-Fort Worth area, and 3) the Houston/Gulf Coast area. The Texas Panhandle offers several advantages that include proximity to the BNSF rail network and close proximity to the Panhandle's cattle and pig feedlots, which provide a market for distiller grains (an ethanol byproduct) and animal manure (that can be used for electricity generation). The Dallas-Fort Worth area is home to several small and mid-sized bio-diesel companies that collect used cooking oil from restaurants, animal fats, and other feedstocks to convert into bio-diesel, which is then sold at a limited number of dispensing stations in the area (Red River Biodiesel, ND). The Houston area, on the other hand, provides bio-fuel producers with access to the local Houston market and the international market. The area is home to several large-scale bio-diesel production facilities. Information regarding bio-fuel plant locations, production capacities, and types of feedstock used as of July 2010 are presented in Table 2.16.

Table 2.16: Bio-Fuel Plant Information for Texas

Type	Company	Location	Feedstock	Production (Mgy)
Ethanol	Levelland/Hockley County Ethanol, LLC	Levelland	Corn	40
	White Energy	Hereford	Corn/Milo	100
	White Energy	Plainview	Corn	110
Bio-Diesel	Agribiofuels, LLC	Dayton	Multi	12
	Biodiesel Industries of Greater Dallas-Fort Worth	Denton	Multi	3
	Direct Fuels	Euless	Multi	10
	Green Earth Fuels of Houston, LLC	Galena Park	Multi	90
	RBF Port Neches, LLC	Port Neches	Multi	180
	Red River Biodiesel Ltd.	New Boston	Multi	15
	REG Houston, LLC	Seabrook	Multi	35
	Texas Biotech, Inc.	Arlington	-	0
	Texas Green Manufacturing, LLC	Littlefield	Tallow	1.25
	The Sun Products Corp	Pasadena	Palm	15

Source: Renewable Fuels Association and National Bio-Diesel Board; Updated July 2010

Table 2.16 shows that most bio-diesel plants in Texas—with the exception of the Galena Park and the Port Neches facilities—are small operations that produce between 1.25 and 35 million gallons of bio-diesel per year.

2.5.1 Developing a Supply Chain for Ethanol

To understand the current and future impacts of the bio-fuel industry on Texas's transportation system, a supply chain was developed that identifies major transportation related activities associated with bio-fuel production; specifically points of origin, destination, and the modes used to transport the products. Because the ethanol industry represents the largest share of the bio-fuel market, a supply chain for ethanol production in Texas was developed. Bio-diesel production, however, includes similar activities, but obviously the feedstock employed in the synthesis process differs.

Figure 2.55 illustrates an ethanol supply chain for Texas.

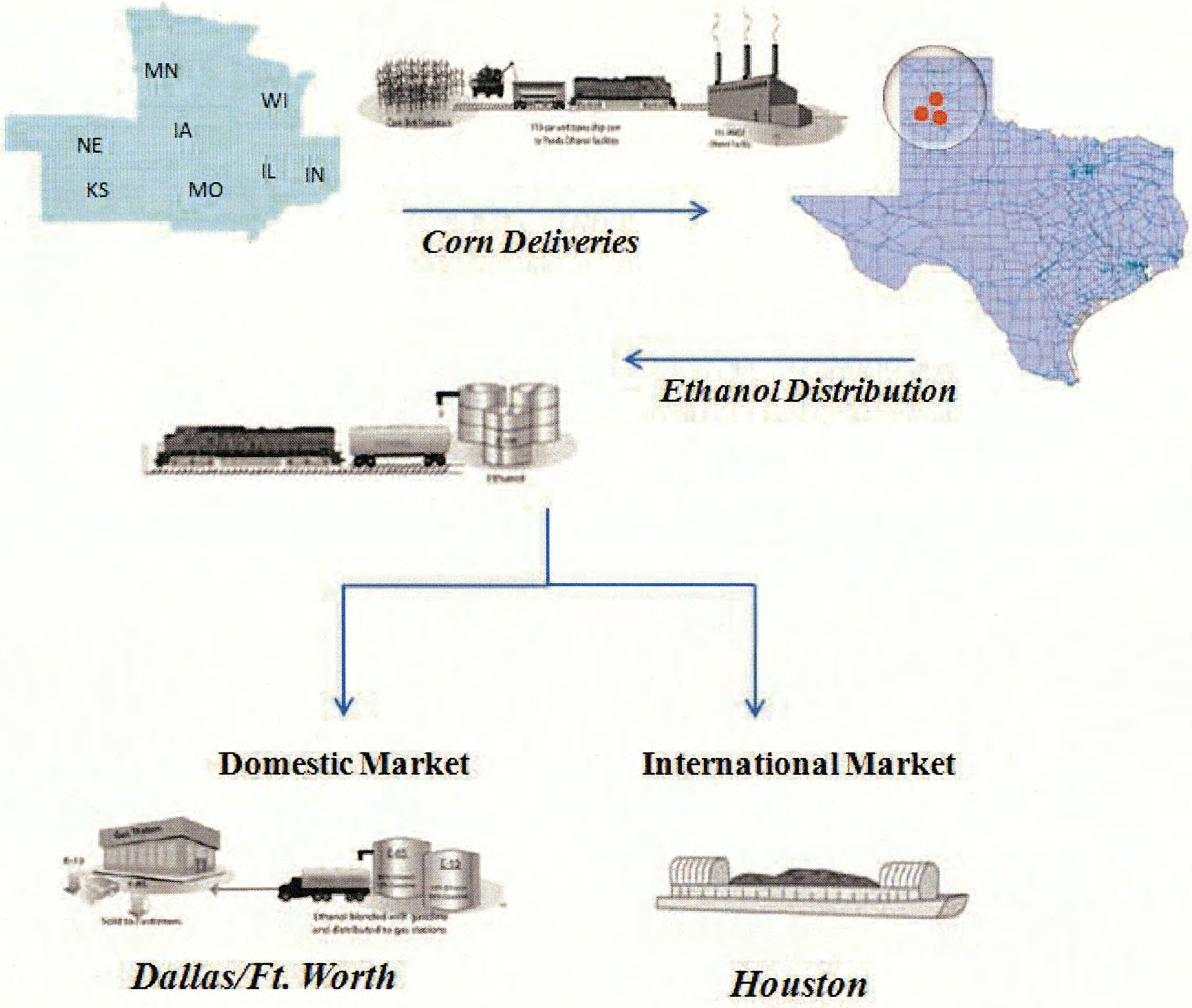
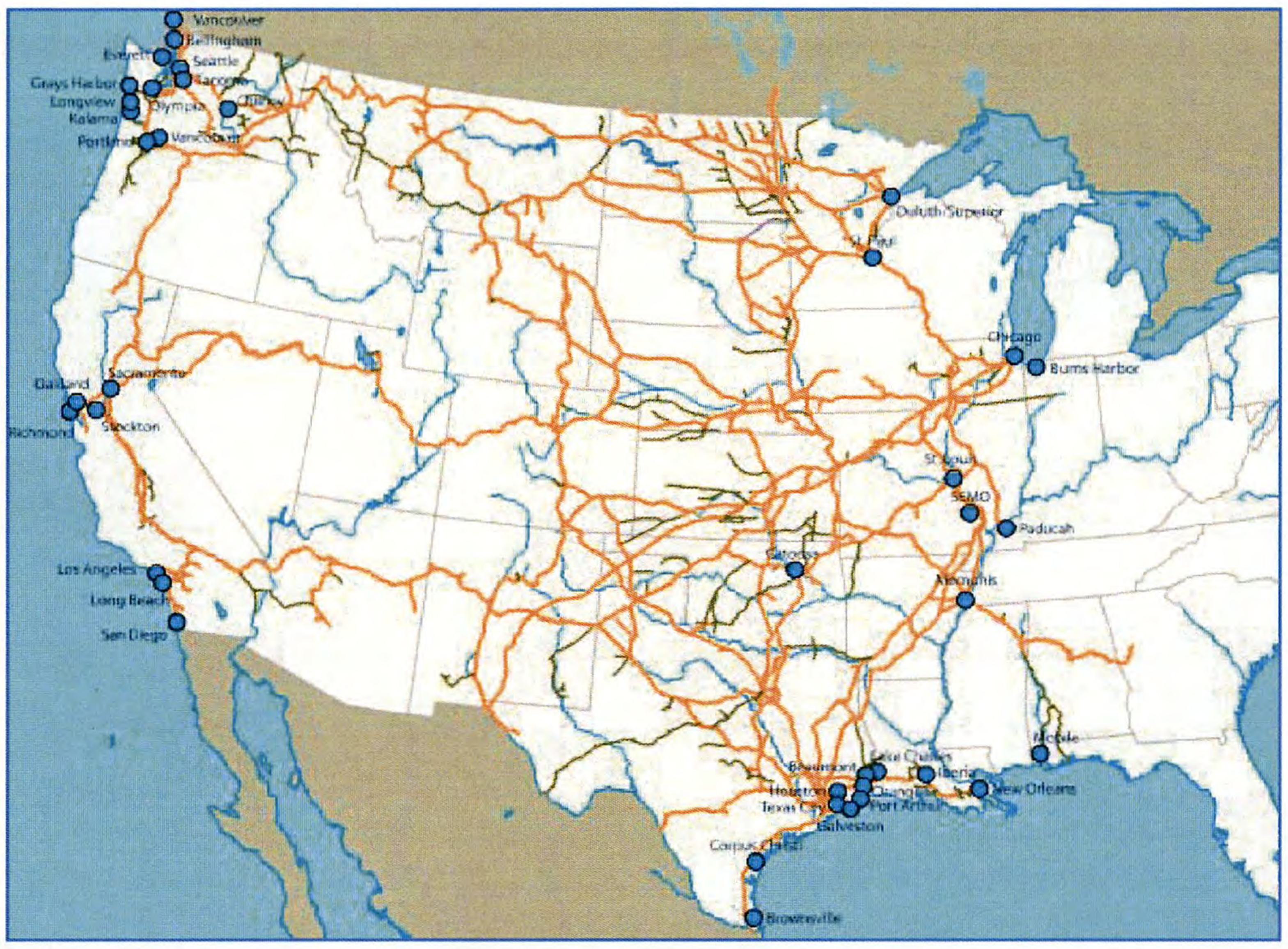


Figure 2.55: Ethanol Supply Chain

Figure 2.55 shows how ethanol production requires the movement of various commodities to and from the bio-refinery. The corn feedstock can be transported from the field to the bio-refinery by truck or rail. In the U.S., trucking is the predominant mode used for moving corn from the farm to the refinery. In 2004, for example, 98% of the corn delivered to bio-refineries for processing was by truck. This is largely because most ethanol plants in the U.S. are located within 50 miles of their feedstock and therefore truck transportation—although typically more expensive per-mile traveled—is convenient and economical because of the relatively short haul distances and the savings in storage costs. In Texas, however, rail is the predominant mode for feedstock delivery. Texas's bio-refineries rely on Midwestern corn for the synthesis process, requiring bulk deliveries for economic and efficiency reasons. Corn is thus typically delivered in 85 to 110 unit-car trains. Most of the corn is moved into Texas on BNSF's Southern Transcontinental Route (Boske and Woodward, 2008). Figure 2.56 illustrates the BNSF rail network.



Source: BNSF Railway

Figure 2.56: BNSF Railroad Network

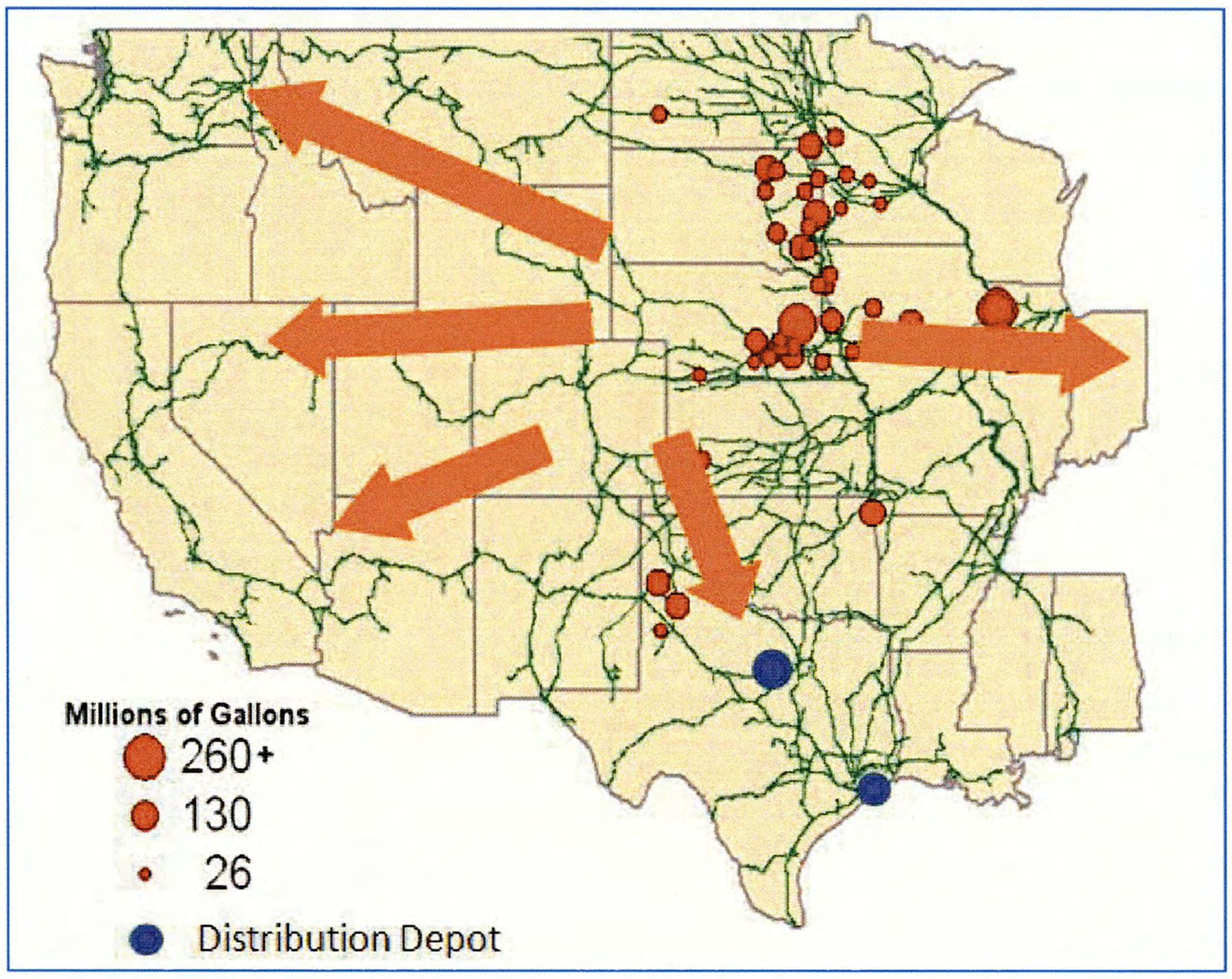
Once the corn is delivered to the bio-refinery, it is processed into corn ethanol and distiller grains. Distiller grains are typically sold to local feedlots as a high protein animal fodder, while ethanol is transported to domestic and international markets. Rail is the primary mode for ethanol transportation. In 2005, about 2.9 billion gallons of ethanol were transported by rail, representing approximately 60% of the ethanol modal share. Trucks transported 30% of the ethanol shipments and barges transported 10% of the ethanol shipments. Ethanol is not moved by pipeline because it is corrosive and has a tendency to attract water into oil pipelines. However, current research focuses on the feasibility of transporting ethanol-gasoline blends through pipeline networks (Boske and Woodward, 2008).

Ethanol is moved by rail in 85- to 100-car unit trains. A standard 30,000-gallon rail tank car for flammable liquids (DOT 111A) is used to move ethanol. In the case of trucking, a standard 6,000- to 9,500-gallon gasoline tanker truck (DOT MC306) is used to move ethanol. In the case of barge transportation, 420,000- to 630,000-gallon tankers are used.

2.5.1.1 Domestic and International Markets

One of the main challenges facing the bio-fuels industry is inadequate infrastructure. Challenges arise from transporting, blending, and dispensing the bio-fuel products. For example, a lack of pipeline infrastructure in the Midwest—where most of the U.S. ethanol is produced—and ethanol's corrosive properties limit the feasibility of transporting ethanol by pipeline. This increases the overall cost of ethanol. In 2005, ethanol cost $1.86 per gallon, of which $0.16 represented the transportation costs (Boske and Woodward, 2008). Collecting the ethanol product from bio-refineries is also challenging, because facilities are dispersed and not connected by pipelines. According to BNSF, few facilities are large enough to produce bulk unit-train shipments. Many refiners in the Midwest thus form partnerships and combine their ethanol shipments to ensure unit-train loads, thereby making rail more affordable (Aventine, 2007).

Rail companies, such as BNSF and UP, provide single carload deliveries, gathered train deliveries, and unit train deliveries. BNSF, for example, provides single carload ethanol and biodiesel services to major consumption areas throughout the western two-thirds of the U.S. In Texas, BNSF provides single carload services to El Paso in the west and Houston, Pasadena, Deer Park, and Beaumont on the Gulf coast (BNSF Railway, ND). BNSF also provides an Ethanol Express service—a 95-unit car train service—to two major consumption areas in Texas: 1) the Gulf Coast area through their Texas City terminal, and 2) the Dallas-Fort Worth metropolitan area through their Fort Worth terminal. Figure 2.57 illustrates these two major destination points and the general volume of ethanol shipments moving over the company's rail network.



Source: Thantry, 2007

Figure 2.57: BNSF Rail Distribution Network for Ethanol

Furthermore, Table 2.17 presents major origins and destinations for ethanol and biodiesel shipments in Texas by BNSF.

Table 2.17: Origins and Destinations for Bio-Fuel Shipments by BNSF

Service	Unit Train Service	Single Car Service
Origins	Levelland Hereford Plainview Texas City	Houston Pasadena Deer Park
Destinations	Fort Worth Texas City	Houston Pasadena Deer Park Beaumont El Paso

Source: BNSF Railway, ND

As Table 2.17 shows, bio-fuel shipments primarily originate in the Texas Panhandle or on the Gulf Coast. Ethanol shipments by rail terminate primarily in Fort Worth, the Gulf Coast, and El Paso. The largest ethanol market in the state is Fort Worth. Table 2.18 presents information on the two primary bio-fuel bulk storage facilities in Fort Worth, indicating that both facilities serve the Dallas-Fort Worth metropolitan area. The Musket Corporation facility is served by BNSF and the Kinder Morgan facility is served by UP.

Table 2.18: Ethanol Blending Terminals in the Southwest

Terminal	**1**	**2**
Owner	Musket Corporation	Kinder Morgan
Location	Mark IV Industrial Park	4500 S. Main Road
City	Fort Worth	Euless
Servicing Railroad	BNSF	UP
Unloading Capability	95-car unit train	84-car unit train
Loading Capacity	8 trucks/hr	Multi-lane truck loading
Storage	240,000 barrels	130,000 barrels
Servicing Market	Fort Worth/Dallas	Fort Worth/Dallas

Source: Thantry, 2007 & Kinder Morgan, ND

Shipping rates from origins in Texas and the Midwest to destinations in Texas are presented in Tables 2.19, 2.20, and 2.21 for single carload services, gathered train services, and unit train services.

Table 2.19: BNSF Shipping Rates for Single Carloads

Single Carload Service Rate (per car)	**Texas Destinations**		
Points of Origin	**Ft Worth**	**Gulf (0370)**	**El Paso**
Southwest IA (0080)	$4,575	$4,975	$5,225
Southwestern NE (0210)	$4,475	$4,875	$5,125
TX Panhandle North (0340)	$3,500	$3,900	$4,225

Adapted from BNSF Railway

Table 2.20: BNSF Railway Shipping Rates for Gathered Train Services

Gathered Train Service Rate (per car)	**Texas Destinations**	
Points of Origin	**Ft Worth**	**Texas City**
Southwest IA (0080)	$3,675	$4,075
Southwestern NE (0210)	$3,575	$3,975
TX Panhandle North (0340)	$2,600	$3,000
TX Panhandle (0350)	$2,500	$2,900
TX Panhandle South (0351)	$2,800	$3,200
TX Gulf (0370)	$2,875	$2,475

Adapted from BNSF Railway

Table 2.21: BNSF Railway Shipping Rates for Unit Train Services

Unit Train Service Rate (per car)	**Texas**	
Points of Origin	**Ft Worth**	**Texas City**
Southwest IA (0080)	$3,175	$3,575
Southwestern NE (0210)	$3,075	$3,475
TX Panhandle North (0340)	$2,100	$2,500
TX Panhandle (0350)	$2,000	$2,400
TX Panhandle South (0351)	$2,300	$2,700
TX Gulf (0370)	$2,375	$1,975

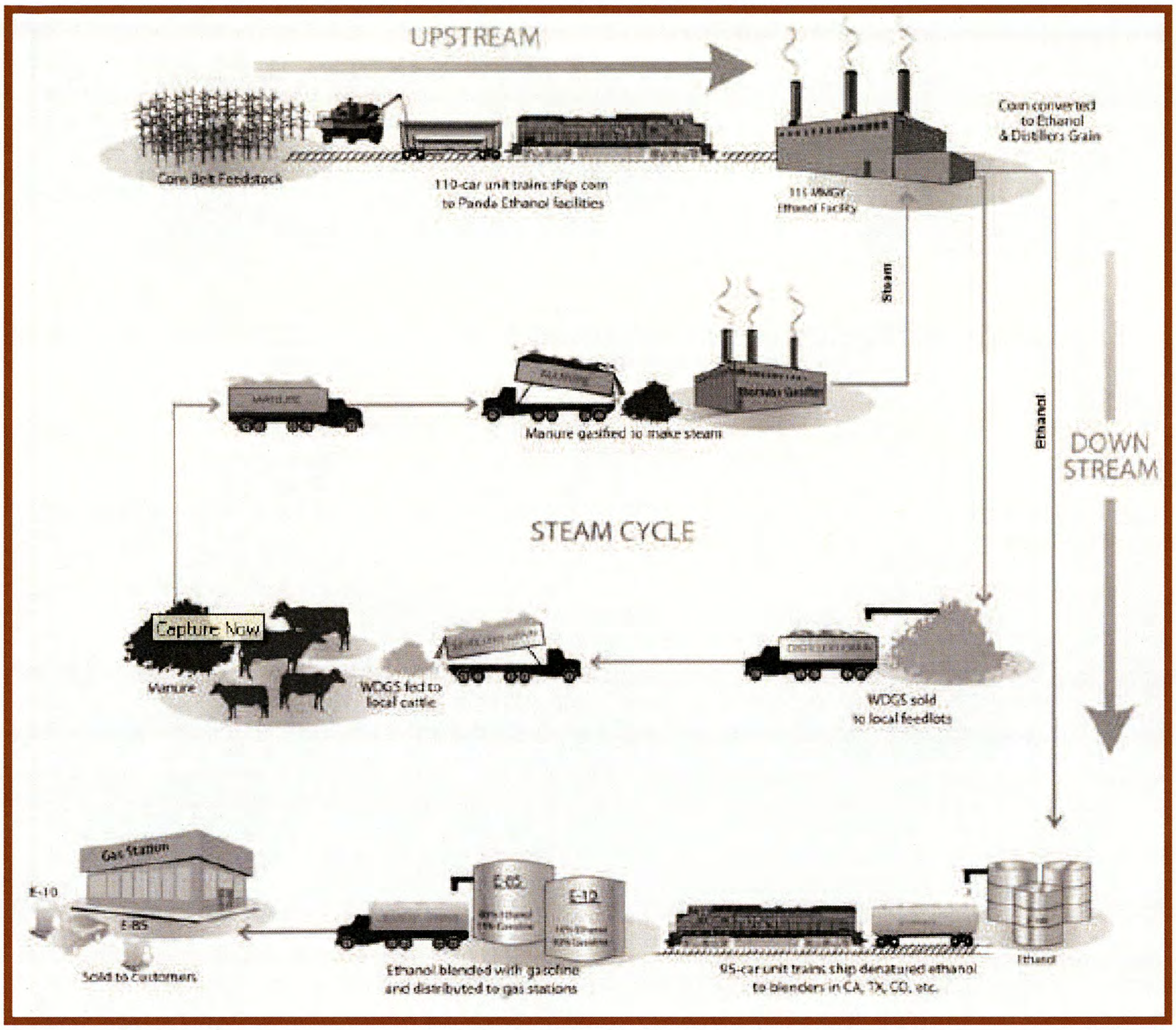
Adapted from: BNSF Railway

Tables 2.19 to 2.21 make clear that rail shipping rates (per car) are substantially lower for gathered and unit train services compared to the single carload service. However, destinations that can receive bulk shipments of ethanol or bio-diesel are limited to Fort Worth and Texas City.

Finally, it should be noted that ethanol is not blended with gasoline at oil refineries. Few refineries have rail access. Therefore, ethanol is blended at gasoline bulk storage terminals using splash injection techniques. Trucks loaded with gasoline enter onto loading racks and pass underneath an ethanol (or a bio-diesel) storage tank. The tanker trucks receive a dose of splash injection to attain a 90/10 gasoline mix. Other mix blends, however, also exist for both ethanol and bio-diesel. From there, the final product is distributed to dispensing stations for local consumption (Boske and Woodward, 2008).

2.5.1.2 Role of Texas's Transportation System in Ethanol Production

In their assessment of the Texas bio-fuel market, Panda Ethanol Inc. outlined a detailed business plan they planned to implement after the completion of their 115 MMY gallon ethanol production facility in Hereford, TX. The business plan included a supply chain of commodities arriving and departing to and from the facility, along with expected production levels of ethanol and its co-products and the expected quantities of bio resources required to meet these production levels. The company filed for bankruptcy in early 2009 before the completion of their facility. Their business plan is, however, used to illustrate how an ethanol production plant would use Texas's transportation network. Figure 2.58 illustrates the supply chain for the Panda Ethanol plant that was proposed in Hereford, Texas.



Source: Panda Ethanol Inc.

Figure 2.58: Depiction of a Supply Chain for Ethanol Production

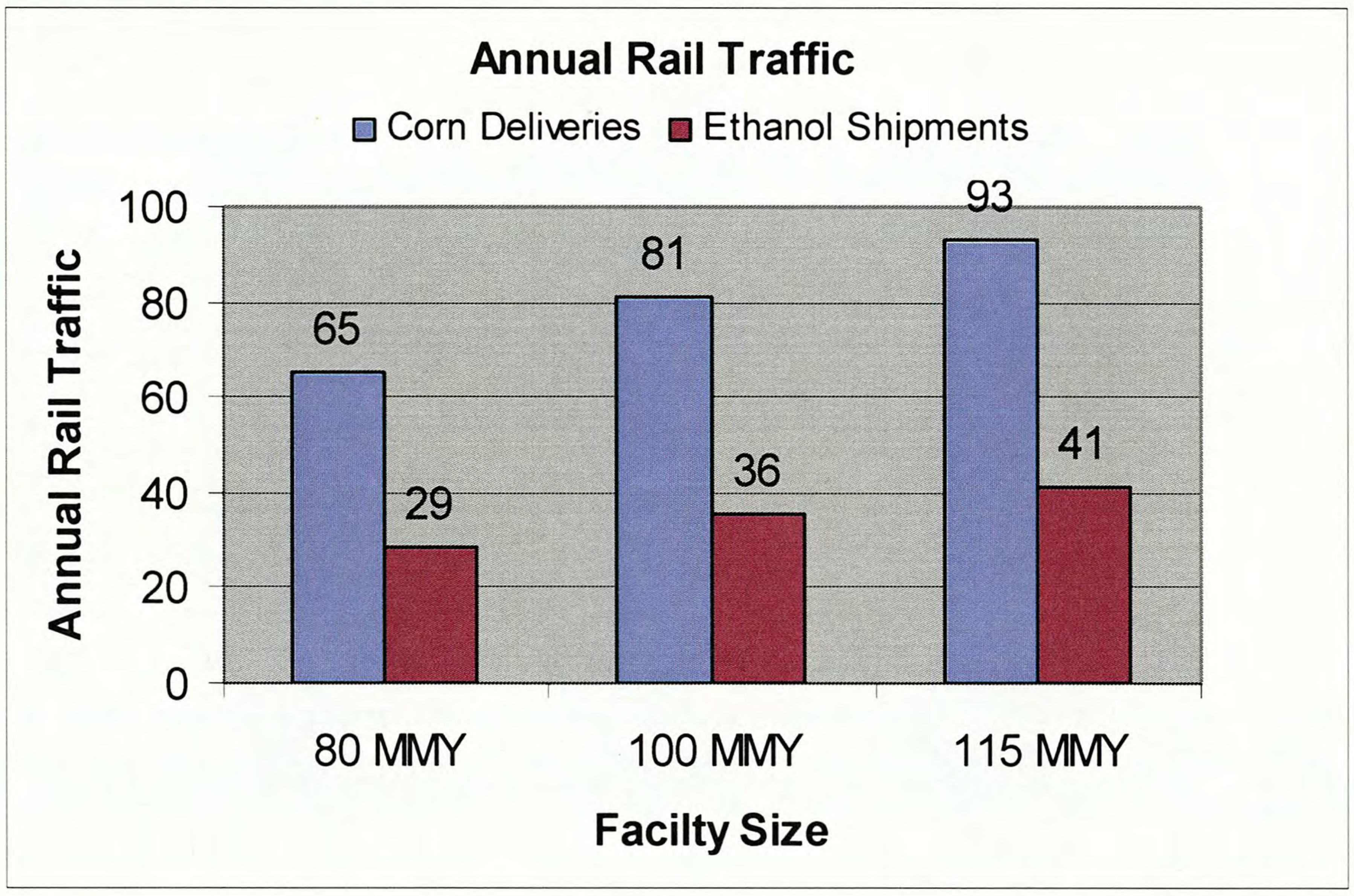
Figure 2.58 demonstrates how ethanol production requires the movement of various commodities to and from the facility. Based on data presented by Panda Ethanol, a facility that can produce 115 million gallons of ethanol per year will require the transportation of the following commodities:

- Annual deliveries of ***41 million bushels*** of corn to the facility
  - Weekly deliveries of 440,000 bushels of corn moved on 110-car unit trains to the facility
  - One bushel of corn produces 2.6–2.8 gallons of fully denatured ethanol and 18 lbs. of distiller grains.
- Weekly ***shipments of 2.8 million gallons*** of denatured ***ethanol*** moved on 95-car unit trains from facility to blenders
- ***1 billion pounds of manure*** per year transported from 21 feedlots within a 50-mile radius of the plant to the biomass gasification facility for energy production
  - Dry cow manure has the potential to produce from 2,500–6,000 BTU/lb of energy.

- ***312,000 tons of wet distiller grain per year*** moved back to feedlots
  - Distiller grains are a high protein animal feed byproduct that helps the ethanol industry recover 30–35% of their corn costs.

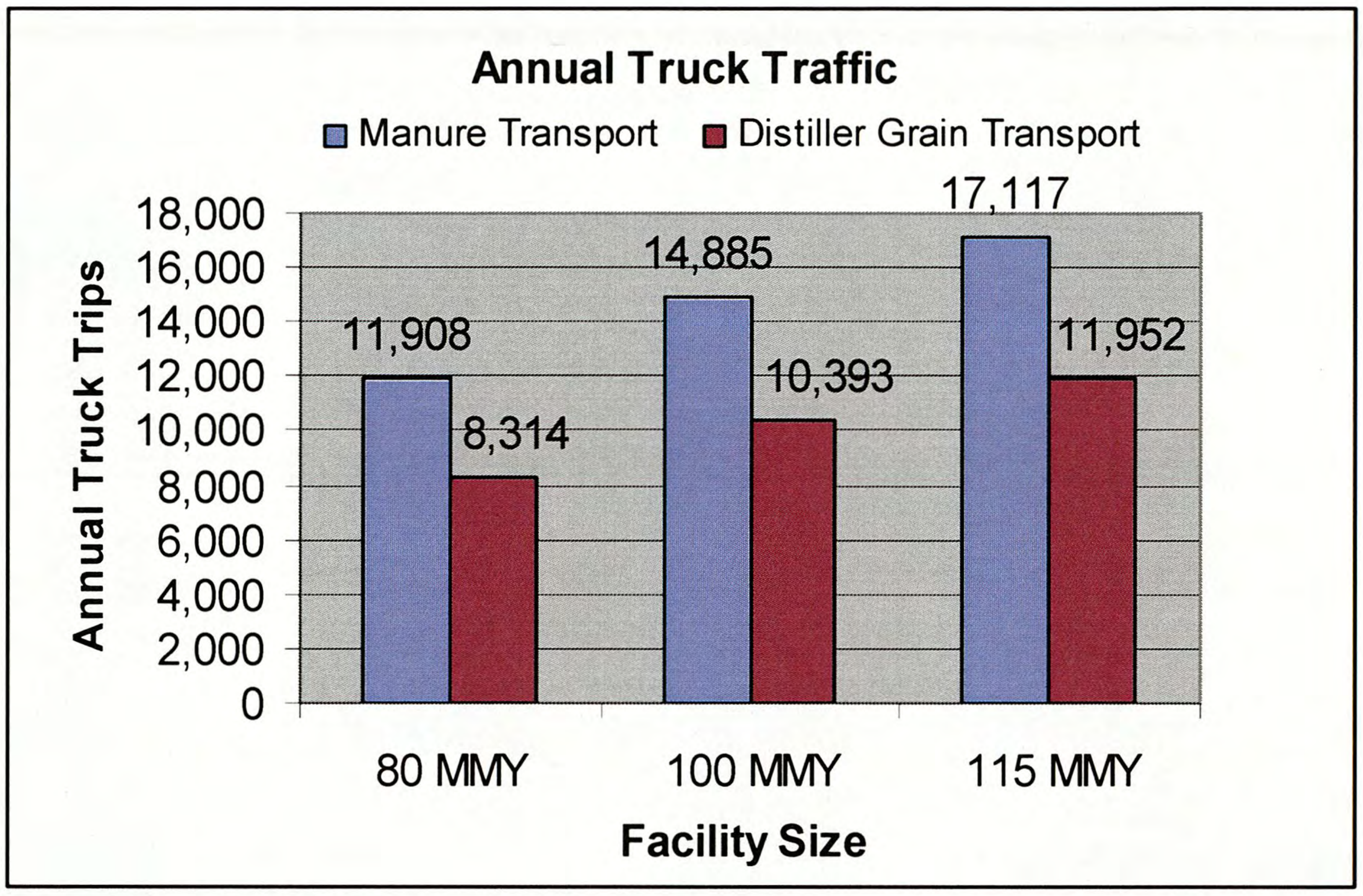
It is important to point out that because Texas is not a high producer of corn or soybean, most of the feedstock will be transported by rail from the Midwest. An analysis of Texas's ability to sustain an ethanol industry, conducted by Texas A&M, revealed that an 80 MMY gallon ethanol facility would consume 14% of the entire state's annual corn stock (Outlaw, 2003). Because Texas's agricultural sector does not have the means to sustain such a crop-intensive industry, ethanol plants in Texas will have to rely mainly on Midwestern corn. The denatured ethanol product also has to be transported by rail to blenders because ethanol is a highly corrosive liquid, and therefore cannot be piped through pipelines.

Based on these figures, annual rail activity and truck traffic associated with ethanol production can be estimated. Figures 2.59 and 2.60 present estimates of the traffic generated by the movement of various commodities necessary for the operation of an 80, 100, and 115 MMY gallon ethanol production facilities.



Note: corn deliveries based on 110-car unit trains; ethanol shipments based on 95-car unit trains.

Figure 2.59: Annual Rail Traffic Generated by Ethanol Plant



Based on Truck Weight Limits on FM Roads (GVW of 58,420 lbs.)

Figure 2.60: Annual Truck Trips Associated with Ethanol Plant

Deliveries of corn feedstock and the shipments of ethanol would occur on a weekly or a bi-weekly schedule to and from the facility. The delivery of cow manure and shipments of distiller grains would require almost daily trucking activity.

2.6 Concluding Remarks

This chapter documents the work that has been conducted on the development of energy supply chains for the major industries comprising the Texas energy sector: (a) natural gas, (b) oil, (c) coal, (d) wind, and (e) bio-fuels. Major activities within each energy industry that use Texas's transportation system were identified and statistics, such as traffic volume, road usage, and the average haul distance, were estimated. The supply chains developed in this chapter served as a foundation for measuring the transportation infrastructure impacts imposed by each industry (see Chapter 3).

Chapter 3. Impact on Texas's Road Infrastructure

This chapter discusses in detail the impact of the wind energy, natural gas, and crude oil energy industries on Texas's transportation system. The study team focused on the movement of the wind turbine components in evaluating the pavement damage characteristics associated with the wind energy industry. For the natural gas industry, the impact of the rig traffic, construction traffic, and saltwater traffic was assessed separately. The focus area for calculating the natural gas impacts was the Barnett Shale region in North Texas, one of the largest onshore natural gas reserves in the continental U.S. Finally, the focus area for evaluating the impact of the crude oil industry was the Permian Basin in West Texas. As with the natural gas case study, the study team assessed the impact of the construction and production traffic associated with the crude oil industry in the region. The following subsections discuss in detail the methodology, objectives, and results for each of the focus industries and regions.

3.1 Traffic Impacts Considered

A key objective of this study was to quantify the effect of traffic associated with the energy industry on Texas's transportation system. This section discusses the traffic impacts considered of Texas's wind energy, natural gas, and crude oil sectors.

3.1.1 Wind Energy Industry

The wind energy industry has seen an unprecedented growth over the last decade in Texas and the trend is expected to continue pending legislative policies that favor the growth and development of the renewable energy industry. Therefore, an understanding of the impact of the industry on Texas's transportation system is necessary. The movement of the wind turbine components often requires OS/OW permits as the individual components exceed regular size and weight allowances. The study team accessed TxDOT's OS/OW database to obtain relevant information on the truck configurations and weights that are used for mobilization of the wind turbine components. In addition to the movement of the wind turbine components, the installation of a wind turbine also involves preparing a pad site, which involves the movement of materials and equipment. Unfortunately, the study team could not obtain reliable information on the truck traffic involved in the movement of materials and equipment; therefore, the impact on the highway network imposed by this traffic could not be quantified.

3.1.2 Natural Gas Industry

For the natural gas sector, the study team focused on three different truck traffic generators. The drilling of a natural gas well requires specialized equipment such as the rotary drill, drill casing, and pipe—all of which require OS/OW permits. Again, the study team referred to the OS/OW database maintained by TxDOT to quantify the impact of the rig traffic on the highway infrastructure. In addition to the rig traffic, the impact of the construction and production traffic was also assessed. The construction traffic involves the use of bob tails to move equipment, rock-haulers bringing aggregates to the well site for building access roads, ready-mix concrete trucks, and tanker trucks associated with the transportation of the water and sand from hydraulic fracturing, and removal of backflow water. The production traffic is mostly saltwater trucks used to move the saltwater from the well site to the nearest injection well.

3.1.3 Crude Oil Industry

The study team focused on quantifying the impacts imposed by the construction and production truck traffic associated with the crude oil industry sector. The construction traffic consists primarily of tanker trucks for the movement of bulk sand, cement, water, mud, and other waste. It also includes flatbed trucks used for moving drilling and other construction equipment and rock haulers. The production traffic, on the other hand, comprises mostly tanker trucks that move the crude oil from the storage battery to the nearest pipeline breakout station.

3.2 Methodology

The following section provides a brief discussion on the distress mechanisms used in evaluating the pavement damage imposed by the truck traffic associated with different energy sectors on Texas's highway infrastructure. These distresses included rutting, longitudinal cracking, and alligator cracking. In addition, the study focused on evaluating the impact on the ride quality of these highway facilities and therefore the effect on roughness measures was also evaluated. The final subsection briefly explains a methodology that was used extensively in this study for assessment of the reduction in the service life of pavements due to trucking operations associated with the different energy industries.

3.2.1 Distresses

3.2.1.1 Rutting

Rutting is one of the most prominent distress mechanisms for flexible pavements. It results from the permanent deformation of the pavement and is directly related to the internal friction of the aggregate and the cohesion of the asphalt binder. The primary factors affecting rutting are mixture properties, temperature, number of load applications, loading frequency, and state of stress. The critical conditions for permanent deformation accumulation are elevated temperatures and lower load frequencies (i.e., slow moving traffic). These conditions decrease the viscosity of the binder and, consequently, the material deforms to the extent that traffic loads are carried predominantly by the aggregate structure (aggregate skeleton).

Rutting of bituminous mixes is a function of a variety of factors that include aggregate size, shape, surface texture, binder stiffness (e.g., asphalt binder grade), and the selection of aggregate gradation, asphalt content, and compaction effort. Rutting of asphalt mixes can result from shear flow due to a lack of confinement beyond the wheel path or may be due to densification of the material for poorly designed mixes.

3.2.1.2 Fatigue Cracking

Fatigue cracking occurs when the asphalt materials are subjected to repeated loads at stress levels lower than the tensile strength of the material. Consequently, hot mix asphalt (HMA), in accordance with the pavement lift thickness, should be designed to resist the maximum number of repetitive stresses and strains applied before significant cracking is observed. Fatigue cracking is considered a load-related issue, which is affected by external factors such as, underlying support, placement and compaction quality, age of the asphalt layer, and traffic volume. The mixture variables that have the most significant effect on the fatigue life of HMA mixtures are asphalt grade and content, and air void content (Rao et al., 1990).

Although the reason for fatigue cracking is often debated, it is generally agreed that fatigue cracking can be categorized into two groups based on the crack initiation mechanism—i.e., bottom-up and top-down cracking. Top-down cracking is thought to be the governing mechanism for longitudinal cracking and results from high radial tire pressures. The more traditional approach to modeling fatigue cracks relies on the bottom-up cracking mechanism, for which it is assumed that the cracks start at the bottom of the pavement structure where local tensile stresses are higher than the strength of the material. Due to repeated load cycles, the cracks propagate upward until they appear on the pavement surface and start to interconnect with longitudinal cracks, giving it the appearance of the back of an alligator. Thus, fundamentally both alligator and longitudinal cracks result from load-related fatigue in the material.

3.2.1.3 International Roughness Index

The International Roughness Index (IRI) is most commonly obtained from measuring the longitudinal road profile. It is calculated using a quarter-car vehicle math model (Sayers et al., 1986). Since its introduction in 1986, IRI has become the road roughness index most commonly used worldwide for evaluating and managing road systems.

The IRI was defined as a mathematical property of a two-dimensional road profile. As a profile-based statistic, the IRI had the advantage of being repeatable, reproducible, and stable with time. The slope of the IRI was chosen to be compatible with roughness measures in use. The slope is calculated as the average absolute (rectified) relative velocity of the suspension divided by vehicle speed to convert from rate (e.g., inch/s) to slope (inch/mi). The frequency content of the suspension movement rate is similar to the frequency content of the chassis vertical acceleration and also tire/road vertical loading. Thus, IRI is highly correlated with the overall ride vibration level and with the overall pavement loading vibration level. IRI is thus strongly correlated with ride quality and road loading.

3.2.2 Transfer Functions in MEPDG

The Mechanistic-Empirical Pavement Design Guide (MEPDG) uses transfer functions to relate pavement distresses to the fundamental properties of materials and their behavior under dynamic loading. The transfer functions thus capture the empirical aspects associated with design and analysis of pavement structures. The transfer functions used for distress predictions; need to be however, calibrated using project-specific data. The objective of this study was to evaluate the damage imposed by truck traffic associated with Texas's energy sectors from a rutting, cracking, and roughness perspective. Therefore, the transfer functions of interest are permanent deformation, cracking (alligator and longitudinal), and the roughness transfer functions. The following section elaborates on these four transfer functions.

3.2.2.1 Rutting Transfer Function

The rutting transfer function involves two separate empirical models that predict the plastic deformation in the asphalt and unbound layers, respectively. The empirical models/transfer function for permanent deformation in the asphalt layer is provided in Equation 1 (ARA, 2004):

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z \beta_{r1} 10^{k_1} T^{k_2 \beta_{r2}} N^{k_3 \beta_{r3}} \qquad \text{Eqn. 1}$$

$k_z = (C_1 + C_2 \times depth) \times 0.328196^{depth}$
$C_1 = -0.1039 \times H_{ac}^2 + 2.4868H_{ac} - 17.342$
$C_2 = 0.0172 \times H_{ac}^2 - 1.7331H_{ac} + 27.428$
Where,
H_{ac} = Total AC thickness (in)
ε_p = Plastic Strain (in/in)
ε_r = Resilient Strain (in/in)
T = Layer Temperature (°F)
N = Number of load repetitions

The plastic deformation in the subgrade is predicted by the transfer function provided in Equation 2 (ARA, 2004):

$$\delta_a(N) = \beta_{s_1} k_1 \varepsilon_v h \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad \text{Eqn. 2}$$

Where,
δ_a = Permanent deformation for the layer
N = Number of load repetitions
ε_v = Average vertical strain (in/in)
h = Thickness of the layer (in)
ε_0, β, ρ = Material properties
ε_r = Resilient strain (in/in)

It should be noted that the rutting transfer functions—as given in Equations 1 and 2—have an exponential form. If the rutting transfer functions are not calibrated the distress predictions from the model will be biased. Given that the relation between the predicted distress and the material properties is exponential in nature, the associated bias will be multiplicative. This implies that obtaining a ratio between the biased distress predictions will cancel out the individual biases in the numerator and the denominator.

3.2.2.2 Fatigue Cracking

The MEPDG uses different transfer functions to relate alligator and longitudinal cracking to material properties. As discussed earlier, alligator cracking is mostly modeled as if the crack starts at the bottom of the asphalt layer and propagates until it appears on the surface of the pavement. On the other hand, longitudinal cracking is believed to start at the pavement surface and propagate downward. The MEPDG provides separate transfer functions to capture the different mechanisms associated with fatigue cracking. The bottom-up cracking transfer function in the MEPDG is provided in Equation 3 (ARA, 2004):

$$FC_{bottom-up} = \left(\frac{6000}{1+e^{\left(C_1 \times C_1' + C_2 \times C_2' \log_{10}(Damage \times 100)\right)}}\right) \times \left(\frac{1}{60}\right) \qquad \text{Eqn. 3}$$

$C_2' = -2.40874 - 39.748 \times (1 + h_{ac})^{-2.856}$
$C_1' = -2 \times C_2'$

The top-down cracking transfer function in the MEPDG is modeled using Equation 4:

$$FC_{top-down} = \left(\frac{C_1}{1+e^{(C_1 - C_2 \times log_{10}(Damage))}}\right) \times 10.56 \qquad \text{Eqn. 4}$$

It is evident from Equations 3 and 4 that the percentage of the lane area that is cracked (alligator cracking) or the length of the fatigue crack (longitudinal cracking) is a function of the damage calculations. The calculation of damage caused by load-related fatigue in the material uses Miner's rule (El-Basyouny et al., 2005). However, to apply Miner's rule it is necessary to estimate the fatigue life of the mixture, which is done in the MEPDG with the following transfer function (ARA, 2004):

$$N_f = 0.00432 \times C \times \beta_{f_1} k_1 \left(\frac{1}{\varepsilon_t}\right)^{k_2 \beta_{f_2}} \left(\frac{1}{E}\right)^{k_3 \beta_{f_3}} \qquad \text{Eqn. 5}$$

Where,
N_f = Design life (in number of load cycles)
ε_t = Tensile strain (in/in)
E = Resilient modulus

Equation 5 suggests that the relation between the fatigue life of a pavement structure and the resilient modulus is exponential. Therefore, as discussed in the case of permanent deformation, the associated bias will be multiplicative, which implies obtaining a ratio of two biased distress predictions will cancel out the systemic differences.

3.2.2.3 IRI

The MEPDG uses a linear relation to relate the roughness scores with the visual distresses (see Equation 6).

$$IRI = 40Rut + 0.4FC + 0.008TC + 0.015(Site\ Factors) \qquad \text{Eqn. 6}$$

Where,
Rut = Rutting (in inches)
FC = Fatigue Cracking (% of lane area)
TC = Transverse Cracking (number of transverse cracks)

Equation 6 suggests that the roughness score is a function of other visual distresses including, rutting, fatigue cracking, and transverse cracking. If the roughness predictions are obtained from Equation 6 prior to calibration, the predictions will likely be biased. However, unlike the rutting or cracking transfer functions, the roughness equation is linear, which implies obtaining a difference between the predictions will likely cancel out the biases in the model.

3.2.3 Reductions in Service Life

A pavement structure is built to last a given number of years. At the end of the design life, the structure will reach a terminal distress value at which point it would require an intervention. Assuming that the pavement sections considered were built to reach a terminal distress value equal to that predicted by the MEPDG for the design traffic, the time it takes to reach that distress value due to the combined effect of the design and energy related traffic can be calculated. The difference in the time to reach the terminal distress value due to the design traffic, and due to the combined effect of the design and truck traffic associated with the energy sector, can help determine the reduction in service life (see Figure 3.1).

Figure 3.1: Reduction in Service Life

The reduction in the service life of the pavement sections were evaluated from a rutting perspective as the transfer function used for rut depth predictions is regarded the most mature and stable model in the MEPDG. The calculation of service life reduction helps pavement engineers and economists gauge the extent of the damage to Texas's highway infrastructure as reduced service lives imply shorter time intervals between maintenance cycles, resulting in increased maintenance expenses by the TxDOT districts.

3.3 Data Inputs

The MEPDG is a significant improvement over previous pavement design and analysis procedures. Prior to the MEPDG, most pavement design/analyses were based on empirical relationships, which were developed based on road tests conducted at test facilities. The MEPDG represents a significant improvement over these empirical design procedures in that it relates the visual distresses to the engineering properties of the material. However, using the mechanistic-empirical design procedures requires project-specific information regarding the materials, structure, climate, and traffic to properly characterize the particular pavement section. This implies that modeling a pavement section in the MEPDG and assessing the performance of the particular pavement section under dynamic loads require site-specific information. A certain number of pavement sections for which the climate, traffic, structure, and material design information are available thus needed to be identified to calculate the impacts of the energy sector on Texas's transportation system. The following subsections discuss the information available in existing databases and how these sources were used in meeting the objectives of this study.

3.3.1 Structural Design

TxDOT includes the design details of recently approved construction contracts in an intranet database, i.e., "Plans Online." This database provides detailed information on the pavement structure (see Figure 3.2). Information from the "Plans Online" database was used to obtain the structural design of the pavement sections evaluated in this study. It should be noted that the pavement structure varied on certain occasions within a given project. However, the information obtained from the database was particularly helpful as it provided the beginning and ending stations for each design used within a project. When modeling these pavement sections in MEPDG, every pavement section was evaluated on a case-by-case basis as structural differences would translate in differences in visual distresses.

3.3.2 Material Design

The "Plans Online" database was also used to obtain material information used in the construction contracts. As Figure 3.2 shows, the structural design of the pavement sections also provides the material design for each of the pavement layers. Figure 3.2 illustrates the material design of a composite pavement. The "Plans Online" database also provides information on the type of asphalt mix used—e.g., dense-graded, gap-graded, or open-graded. For the base and sub-base courses, the database provides information on the type of material—i.e., flexbase or asphalt base or stabilized base. However, in most cases the "Plans Online" database does not provide information on the subgrade and soil classification. If the location of a given pavement section is known, the soil classification or characteristics can be obtained from the Texas Soil Database maintained by Texas A&M University's Soil Characterization Laboratory (http://soildata.tamu.edu/). In some instances the material information included in the "Plans Online" database provided the TxDOT item number for the type of material used. The study team then referred to the TxDOT Specifications to obtain the target gradation, binder content, and other relevant information necessary to characterize the material in the MEPDG (TxDOT, 2004).

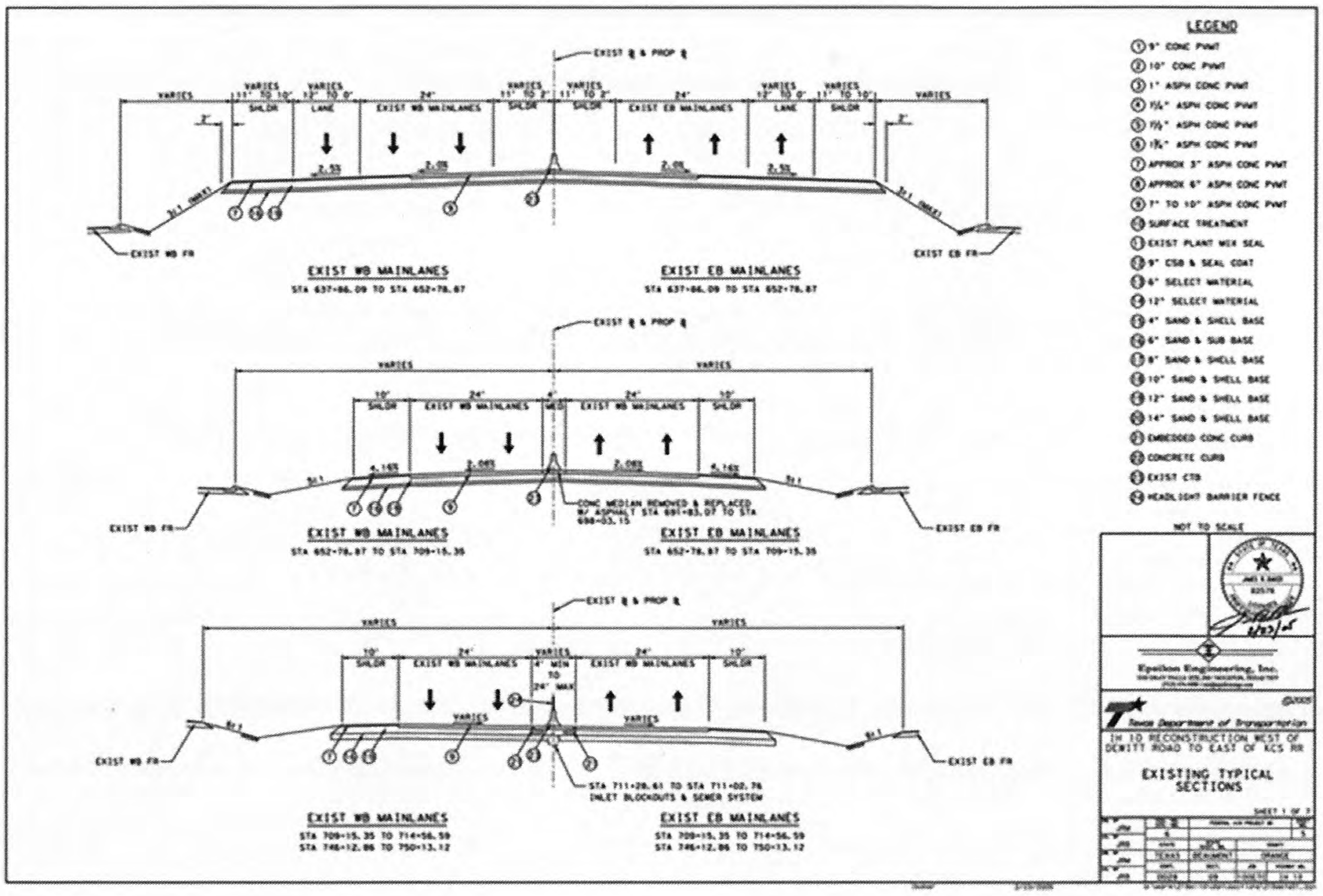


Figure 3.2: Structural Details of IH 10 in Orange County (CSJ 0028-09-100)

3.3.3 Climatic Information

Asphalt is characterized as a thermo-rheological material, which means its properties are expected to vary with temperature. This implies that the performance characteristics of a flexible pavement will change depending on the time of the day and the season. It is therefore important to obtain reliable climate information for the pavement sections included in the study.

The Enhanced Integrated Climatic Model (EICM) developed by the Federal Highway Administration (FHWA) can interpolate and provide climatic forecasts for any location if the GPS co-ordinates and the elevation are known (Larson et al., 1997). The study team obtained the GPS locations of the pavement sections from the Texas Cartographic Information Systems database. These GPS locations were then entered into the EICM model.

3.3.4 Traffic Information

As previously mentioned, this study evaluated the impact of the wind energy, natural gas, and crude oil sectors on Texas's highway infrastructure. It is important to note that assessing the damage imposed by the truck traffic associated with the energy sectors requires prior information on the damage imposed by the normal/design truck traffic. Thus, obtaining information about the truck traffic characteristics of the design traffic as well as the truck traffic associated with the energy sectors would be helpful. The following sub-sections discuss in detail the data sources that were referenced in obtaining the traffic information.

3.3.4.1 Design Traffic

The design traffic refers to the expected truck traffic volume that the pavement is designed for. TxDOT maintains network-level traffic volume information for its entire highway network in the Pavement Management Information System (PMIS) database. The 20-year cumulative standard axle count data included in PMIS was used to calculate the annual average daily design truck volume. To simplify the problem, the design truck type was assumed to consist of two standard 18 kip axles. Figure 3.3 illustrates the design truck counts obtained for a sample of the Interstate Highway sections evaluated in this study.

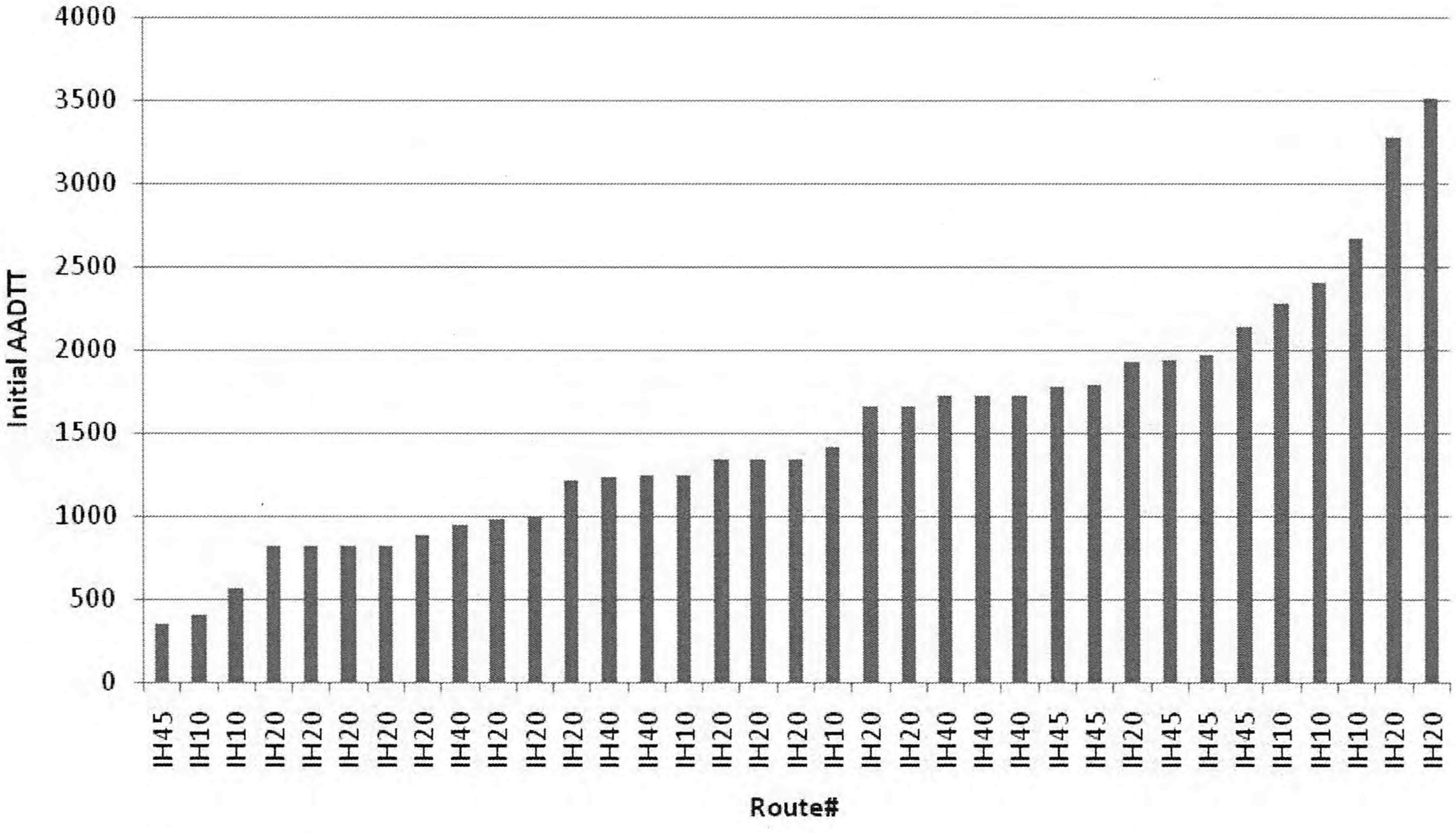


Figure 3.3: Design Traffic for IH Sections from Texas PMIS Database

In this context, it should be noted that the higher the design traffic volume, the higher the associated damage. A rational approach for evaluating the damage imposed by the truck traffic associated with the energy sector is to calculate the additional damage with respect to the damage imposed by the design traffic. Most pavement damage models are exponential, which implies that the calculation of damage should be in the form of a ratio where the total damage imposed by the design and energy sector traffic is normalized with the damage imposed due to the design traffic only. If this ratio exceeds 1, it would indicate the additional damage imposed by the truck traffic associated with the energy sector. However, in situations where the damage imposed by the design traffic is relatively high, the additional damage imposed by the energy sector would reduce and the ratio would be closer to 1. Thus, it is important to note that the additional damage imposed by the energy sector will be partly influenced by the design traffic volume.

3.3.4.2 Truck Traffic Associated with the Wind Energy Sector

As mentioned, this study focused on evaluating the impact of the truck traffic associated with mobilizing the wind turbine components. The transportation of the wind turbine components requires specialized vehicles, i.e., OS/OW vehicles. TxDOT maintains an OS/OW database wherein the details of the OS/OW permits are stored. The database includes information on the permitted route, the truck configuration, individual axle weights, and axle spacing. The information pertaining to the permitted route was used extensively in developing the trip characteristics of this OS/OW loads, including the average length of haul and facility usage as a percentage of the overall VMT (see Chapter 2). However, from a pavement damage perspective the axle weight and the truck configuration are of greater interest. Given that the wind related OS/OW traffic uses specialized vehicle configurations, eight virtual traffic classes were created to model the effect of these truck categories on the pavement structure. Table 3.1 shows the number of single, tandem, tridem, and quad axles for each of the virtual truck categories and also includes their relative distribution in the sample of wind related OS/OW truck traffic.

Table 3.1: OS/OW Traffic Characterization for the Wind Sector

Wind Truck Class	Single Axles (#)	Tandem Axles (#)	Tridem Axles (#)	Quad Axles (#)	Relative Proportion (%)
4	1	2	2	0	5.5
5	1	0	4	0	5.5
6	1	1	1	0	11.1
7	1	0	1	1	11.1
8	1	1	2	0	11.1
9	1	0	4	0	11.1
10	1	2	0	0	11.1
11	1	2	0	0	33.3

The axle weights obtained from the OS/OW database were used in developing axle spectra for the single, tandem, tridem, and quad axles for each of the wind truck classes.

It should be noted that the impact of the construction traffic associated with wind energy development was not evaluated in this study because of a lack of reliable information.

The AWEA provides quarterly reports on U.S. wind energy projects, including detailed information on the number of wind turbines that were installed between 2000 and 2009. According to the OS/OW database, the installation of one wind turbine generates nine OS/OW truck trips. These two data sources were used to estimate the total turbine-related truck traffic moving daily on the Texas highway network (see Figure 3.4). It should be noted that the wind turbine components are routed through different corridors to reach their destinations. Thus, evaluating the impact of this additional truck traffic requires determining the wind traffic that will traverse a particular pavement section. As mentioned, 97 records from the OS/OW database were extracted through random sampling and analyzed to visualize the routes used to move these OS/OW wind loads. Subsequently, the study team determined the percentage of wind traffic that would traverse each of the pavement sections by considering how many of the routes include the specific section. Having determined the proportion of the total number of trips that are routed through a given pavement section, determining the annual average daily turbine-related truck traffic traversing a particular pavement section is then possible.

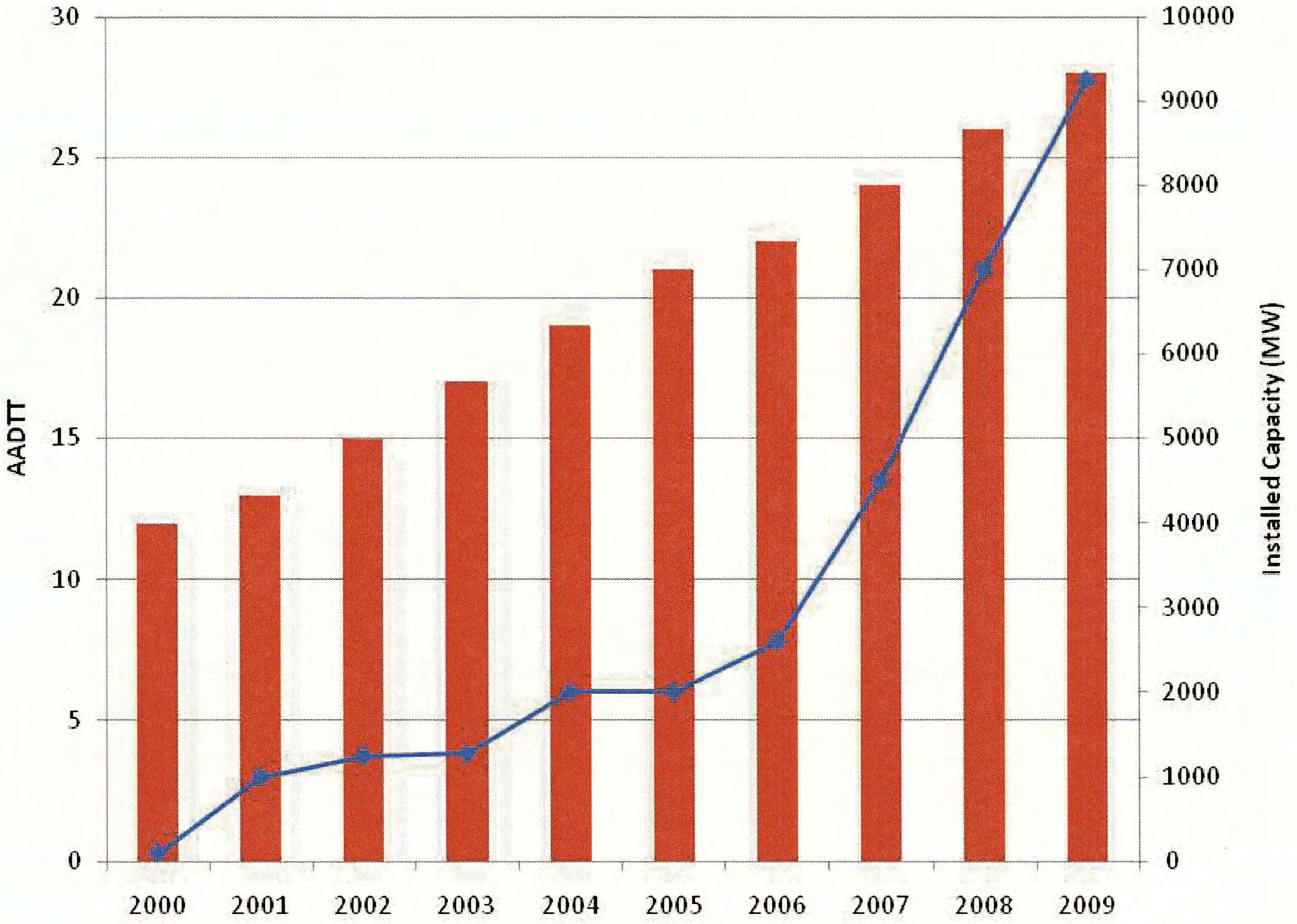


Figure 3.4: Average Daily Truck Traffic Generated by Movement of Wind Turbine Components

3.3.4.3 Truck Traffic Associated with the Barnett Shale Natural Gas Industry

The truck traffic associated with the natural gas development in the Barnett Shale can be broadly classified into three categories—the rig traffic, fraccing traffic, and the saltwater removal traffic. Each of these categories has unique characteristics.

The transportation of the rig is by far the heaviest load associated with drilling and putting a well into production. An estimated 20 OS/OW truck permits are required for mobilizing the drill rig and its auxiliaries—10 are required while rigging up and 10 when rigging down (Kuhn, 2006). The truck traffic associated with rig movement is however, a one-time event over the life of a well site. Thus, the damaging effects of the rig traffic are experienced only when a new natural gas site is developed. TxDOT maintains a database of OS/OW truck permits that are issued in a given year. An analysis of 50 permitted routes revealed that the average haul distance for moving the drill rig is about 33 miles. Also, the VMT is almost evenly distributed between the four major functional highway classes: Interstate Highways, US Highways, State Highways, and FM Roads. However, a slightly higher percentage of the VMT occurs on the lower classification roadway facilities in the Barnett Shale region, i.e., State Highways (28%) and FM Roads (27%) compared to Interstates (19%) and US Highways (23%). From a pavement damage point of view, the truck configuration and axle weights are of greater interest. Similar to the wind sector, special truck categories were established to characterize the rig traffic. Table 3.2 provides the number of single, tandem, tridem, and quad axles for each of these specialized truck categories and their relative distribution.

Table 3.2: Rig Traffic Characterization for the Natural Gas Industry

Wind Truck Class	Single Axles (#)	Tandem Axles (#)	Tridem Axles (#)	Quad Axles (#)	Relative Proportion (%)
4	2	0	0	0	1.3
5	3	0	0	0	68.3
6	4	0	0	0	10.8
7	5	0	0	0	0.3
8	1	1	1	0	1.3
9	1	0.95	0.10	0.95	5.3
10	1	0.48	1	0.76	6.3
11	1	1	2	0	6.3
12	1	2	2	0	0.5

Recent technological advancements have allowed for the commercial and profitable extraction of natural gas from the Barnett Shale geological formations. Specifically, a key innovation in drilling operations involves horizontal fracturing of the pervious shale strata that contain pockets of natural gas. This process is also referred to as *fraccing*. Fraccing involves the injection of fresh water mixed with a propping agent (i.e., very fine sand, also known as frac sand) at a very high pressure into the well to fracture the formation containing the gas. The process lasts about 14 days and includes the mobile rig set-up, fracturing activity, rig removal, and pad restoration (Barton, 2010). The fresh water is typically trucked to the pad site one tanker at a time, requiring approximately 685 loaded trucks per wellhead. After the fresh water is mixed with frac sand, the water is injected at very high pressure to fracture the shale. Roughly 25% of the water returns to the surface as backflow within the first 2 weeks. This water is collected and hauled off to a saltwater injection well. Removal of this backflow water requires approximately 214 loaded trucks. Note that the truck traffic associated with transporting the backflow water is not the same as the saltwater disposal traffic mentioned earlier. The backflow is a characteristic of the fraccing operation, while the saltwater disposal traffic is associated with natural gas production after the gas well is commissioned. In Texas, the permissible weight limit on a single axle is 18 kips and 31 kips on a tandem axle, which implies that the gross vehicle weight of the water tankers should be around 50 kips. However, loaded water tankers can move a payload of up to 80 kips when comprised of one single and a tandem axle (Schiller, ND). The fraccing of the well is the most traffic intensive phase of well development and needs to be repeated (i.e., re-fraccing of natural gas wells) every 5 years to maintain production levels. In addition, site preparation and the construction of access roads reportedly requires the movement of logging and earth moving equipment (Garrison, 2011). The total traffic volume associated with the construction activity has been estimated at 997 trucks. During a telephone conversation with TxDOT district staff, the study team learned that most of the building materials, such as aggregates and cement, are moved on rail except for the last 10 miles, when trucks are used to deliver the materials to the well site (Garrison, 2011). The study team assumed the same VMT distribution by functional class for the movement of materials and equipment as for saltwater removal. In other words, most of the hauling distances are on lower functional classes.

A study by Texerra, Inc. reported that, on average, a natural gas well in the Barnett Shale area requires 3.08 million gallons of water for hydraulic fracturing. Approximately 95% of that water emerges above ground as “production” water, saturated with salts and other chemicals, which must be properly disposed of in class II salt water disposal wells (Texerra, 2007). The saltwater disposal operation uses tanker trucks and, therefore, does not require special permits, which makes tracking their movement and the determination of the VMT associated with this activity challenging. Thus, the study team determined the shortest route from the natural gas well to the closest saltwater disposal well and calculated the average trip length and VMT by facility used. On average, the trip length was 9.4 miles; most of the VMT occurred on lower functional classes, including city streets (30.7%) and FM roads (24.8%). Each wellhead generates approximately 4,200 gallons of saltwater per day, which equates to roughly one truckload per day. The tanker trucks used for saltwater disposal are typically comprised of one steering axle and two tandem axles. These trucks are permitted to have a gross vehicular weight of 80 kips while loaded and around 35 kips when unloaded (Schiller, ND).

3.3.4.4 Truck Traffic Associated with the Permian Basin Crude Oil Industry

The truck traffic associated with the crude oil industry can be divided into two groups: the construction traffic and the production traffic. The construction traffic comprises the transportation of the rotary rig, material, and equipment. The following paragraphs discuss in detail the type of truck traffic associated with each of these two operations and their trip characteristics.

The construction traffic associated with an oil well site are the traffic associated with the four-step well development process of site preparation, rigging up, drilling, and rigging down. A rig site requires the preparation of the rotary rig, which consists of a base, a crown, and a mast along with the delivery of fluid tanks and other fluid services. In some cases, a work-over rig is required on an existing well site for sand cleanout operations, repairing liners and the casing of the well-hole, or sidetracking a well-hole to deepen or relocate the bottom of a well to a more productive zone (U.S. Department of Labor, ND).

A study conducted by TTI reported that the construction traffic associated with an oil well's development lasts about 35–40 days (Mason et al., 1982). Furthermore, the study showed that the ADTT was 27 trucks, resulting in a total two-way traffic of 1,054 trucks during the construction period, which is equivalent to 527 one-way truck visits. Flatbed trucks are used to move the rig to the site, while gravel trucks are required for the construction of the site access road. Tanker trucks are used for moving cement, sand, mud, and water to the site and waste water from the site.

The evaluation of the pavement damage due to the construction truck traffic requires information on the truck volume, truck classification, and detailed axle spectra for different axle groups and truck classes. Obtaining such detailed information is however, not only challenging but also time and resource consuming. The TTI report provided estimates of the truck traffic for each of the activities associated with a typical oil well development project (Mason et al., 1982). The study team estimated the average daily 18-kip axle repetitions for each stage of oil well development from the actual truck traffic reported (see Table 3.3). This may provide a conservative estimate because of the implicit assumption that the axle spectra of oil traffic is no different than that of typical truck combinations operating on the Texas highway system.

Table 3.3: 18-kip Repetitions for Construction Traffic Associated with Oil Well Development

Activity	Average Daily 18-kip Repetitions	Duration of the Activity (Days)	Cumulative 18-kip Repetitions
Access Road	49.67	3	149
Rigging Up	40.25	4	161
Drilling	11.80	20	236
Rigging Down	66.00	1	66
Completion	17.60	5	88

An estimated 700 18-kip axle repetitions are involved in the development of an oil well. Oil wells reportedly need to be re-serviced every 7.5 years to maintain production levels, which will result in another 700 18-kip axle repetitions on the adjoining highway infrastructure (Mason et al., 1982).

The production traffic originates due to the need for the transportation of crude oil from the tank batteries to the pipeline breakout facilities. The Permian Basin is an older geological formation and much of the oil today is obtained from secondary recovery. Therefore, the volumes of crude oil produced from today's wells are significantly lower. The production level in the Permian Basin is an estimated nine barrels per well per day, which implies that it will require one 6,000-gallon truck visit every 2 weeks. The study conducted by TTI in 1982 estimated that this would equate to about 1.5 18-kip axle repetition per day (Mason et al., 1982).

A critical component of the production traffic associated with the oil sector is the saltwater disposal traffic. An estimated nine barrels of saltwater are produced for every single barrel of crude oil production (Lilo et al., 2002). Contrary to natural gas extraction, where the saltwater is transported from the well site to the injection wells, most of the saltwater produced from oil wells is re-injected to maintain reservoir pressure and production levels rather than being transported to secondary injection wells (RRC, 2010).

3.3.5 Selection of Pavement Sections

3.3.5.1 Wind Energy

A sample of 97 permitted routes for the movement of wind turbine components was randomly selected from TxDOT's OS/OW database. These routes were individually plotted in Google Maps to obtain a graphical representation of the most widely used corridors by the wind energy sector. Next, the study team referred to the TxCIT database to obtain a list of projects that are on the routes used by the wind energy sector for moving wind turbine components. The TxCIT database was used because relevant information required to characterize a pavement section could be easily traced to other available databases. The TxCIT database provides a list of recent HMA projects along with their location and Control-Section-Job numbers (CSJ), which is used to reference other databases like the "Site Manager" and "Plans Online" databases to obtain structure and material related information.

This approach allowed the study team to identify a good sample of flexible pavement sections for the Interstate System, US Highways, and State Highways from the TxCIT database. As most of the turbine component traffic primarily uses these three types of highway facilities (see Chapter 2), the study team did not include any FM Road sections for evaluating the associated damage imposed by this truck traffic.

3.3.5.2 Natural Gas

For the natural gas sector, the study team adopted a similar approach as for the wind energy sector. The study team focused on the OS/OW permits that are required for the movement of rotary drill rigs in the Barnett Shale area. This approach helped the study team to identify a candidate list of pavement sections for evaluating the pavement damage associated with transporting the rotary drill rigs.

However, the truck traffic associated with hydraulic fraccing and saltwater removal does not require special permits and therefore the route choices of these trucking operations were difficult to obtain. As mentioned earlier, the study team used Vincenty's formula to match a natural gas well site to a saltwater disposal site based on the shortest path (Vincenty, 1975). Once the routes were identified, the study team used the same approach as for the wind energy sector to obtain the list of candidate pavement sections along the routes.

The traffic associated with hydraulic fraccing primarily originates from service companies that are located in the Barnett Shale region. The study team assumed—based on anecdotal information from the industry—that the trip characteristics of the saltwater and fraccing traffic are similar in terms of trip length and facility usage. Therefore, the same pavement sections were used to assess the pavement damage imposed by the saltwater and hydraulic fraccing traffic.

3.3.5.3 Crude Oil

The truck traffic associated with the crude oil sector comprised of two groups: construction and production traffic. The construction traffic involves the transportation of the drill rig, materials, and other equipment. The movement of the drill rig requires OS/OW permits, but the truck traffic involved in hauling aggregates and other equipment do not require special permits. A random sample of 50 routes used for transporting drill rigs was obtained from the OS/OW database. The specific routes were plotted in Google Maps and a list of pavement sections were identified on these routes using the same procedure as for the wind energy sector.

For the production traffic, the study team followed the same approach that was adopted for defining the trip characteristics of the saltwater truck traffic generated by the natural gas sector. The study team matched the tank batteries to the nearest pipeline breakout stations based on the shortest path algorithm. Next, these routes were plotted in Google Maps and a list of pavement sections were identified on these routes. These pavement sections were subsequently analyzed to assess the pavement damage due to the production truck traffic associated with the crude oil sector.

3.4 Analysis Results

3.4.1 Wind Energy Industry

3.4.1.1 Additional Damage Imposed by Movement of Wind Turbine Components

One of the focus areas of this research was the evaluation of the pavement damage imposed by the movement of wind turbine components in terms of rutting, fatigue cracking, and roughness measures. As previously mentioned, the MEPDG uses transfer functions to relate fundamental pavement responses to distresses. In the case of rutting, longitudinal cracking, and alligator cracking, these transfer functions have an exponential form. To determine the extent of the damage caused by the wind turbine traffic, these transfer functions need to be calibrated for local conditions so that the predicted distresses reflect trends that are characteristic of the material and construction practices in that region. However, the calibration process requires significant resources and project-specific data, which is often difficult to obtain as it requires laboratory testing of in-situ materials. Currently, the MEPDG uses bias correction coefficients in the transfer functions that are calibrated to national conditions. These transfer functions thus reflect national averages rather than for a particular geographical location. Using the transfer functions in the MEPDG without calibrating to local conditions implies that the distress predictions will be systematically biased. To account for the bias in the predictions, the additional damage due to the movement of the wind-related trucks was calculated as a ratio of the damage due to the cumulative effect of the wind and design traffic relative to the effect of the design traffic only. Calculating a ratio will result in the bias term in the numerator as well as in the denominator canceling each other out. Therefore, if the additional damage due to the wind turbine traffic is negligible, the damage ratio will be approximately equal to one. The damage parameter for rutting, longitudinal cracking, and alligator cracking is given in Equation 7.

$$DP = \frac{Damage\ due\ to\ the\ Wind\ Traffic + Design\ Traffic}{Damage\ due\ to\ Design\ Traffic} \qquad \text{Eqn. 7}$$

where, DP = Damage Parameter for a particular distress mechanism

Figure 3.5 provides the damage parameter for US Highway sections from a rutting perspective. Figure 3.5 makes clear that the additional damage imposed by the movement of the wind components on US Highways is about 5%. For Interstate and State Highways, the damage was 1% and 8%, respectively (see Appendix A2). Similar trends were observed with respect to the other two distress mechanisms, i.e., longitudinal and alligator cracking.

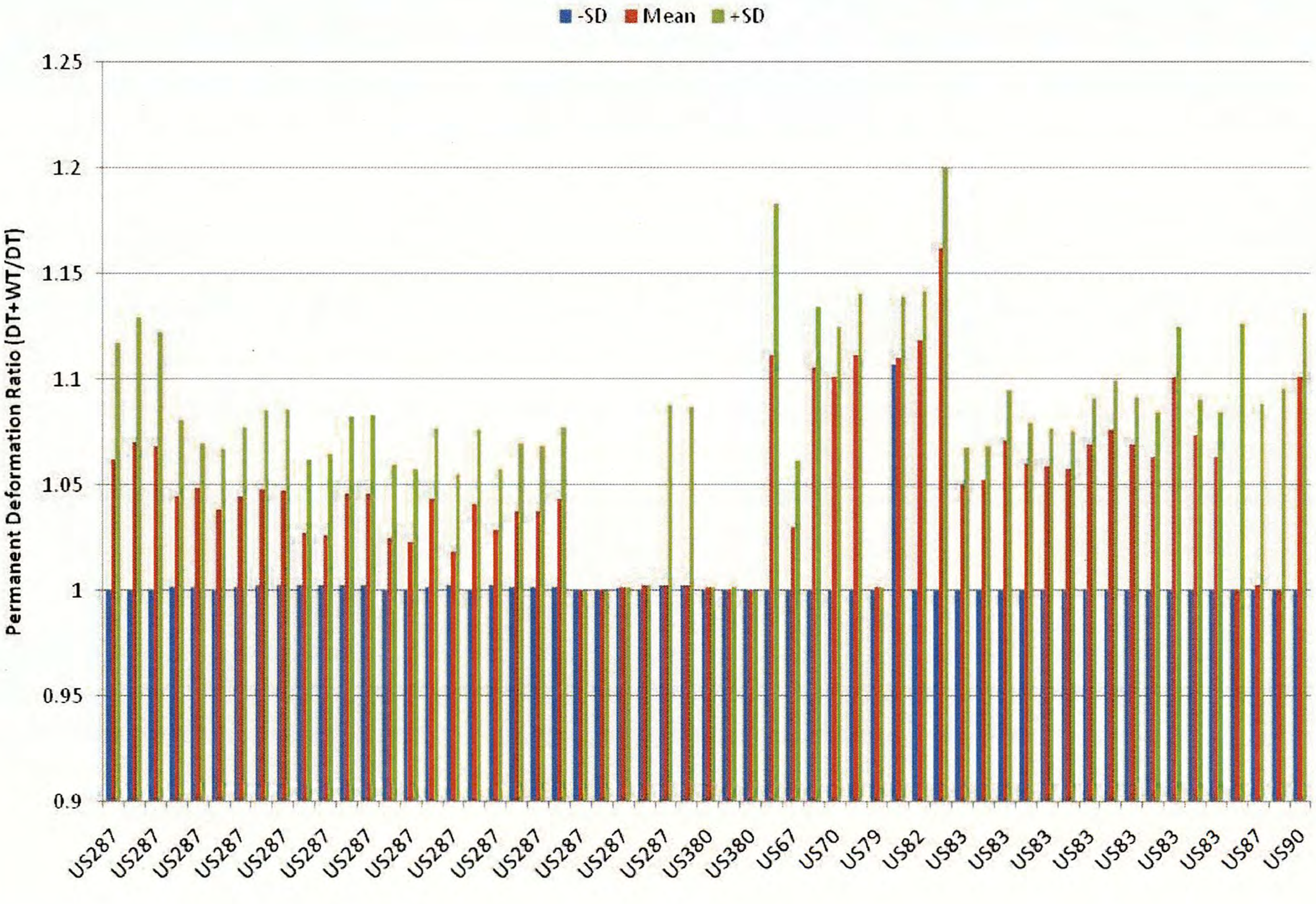


Figure 3.5: Damage Parameter for Rutting—US Highway Sections at the End of 20 Years

The damage parameters calculated for Interstate Highway sections from an alligator cracking perspective are illustrated in Figure 3.6.

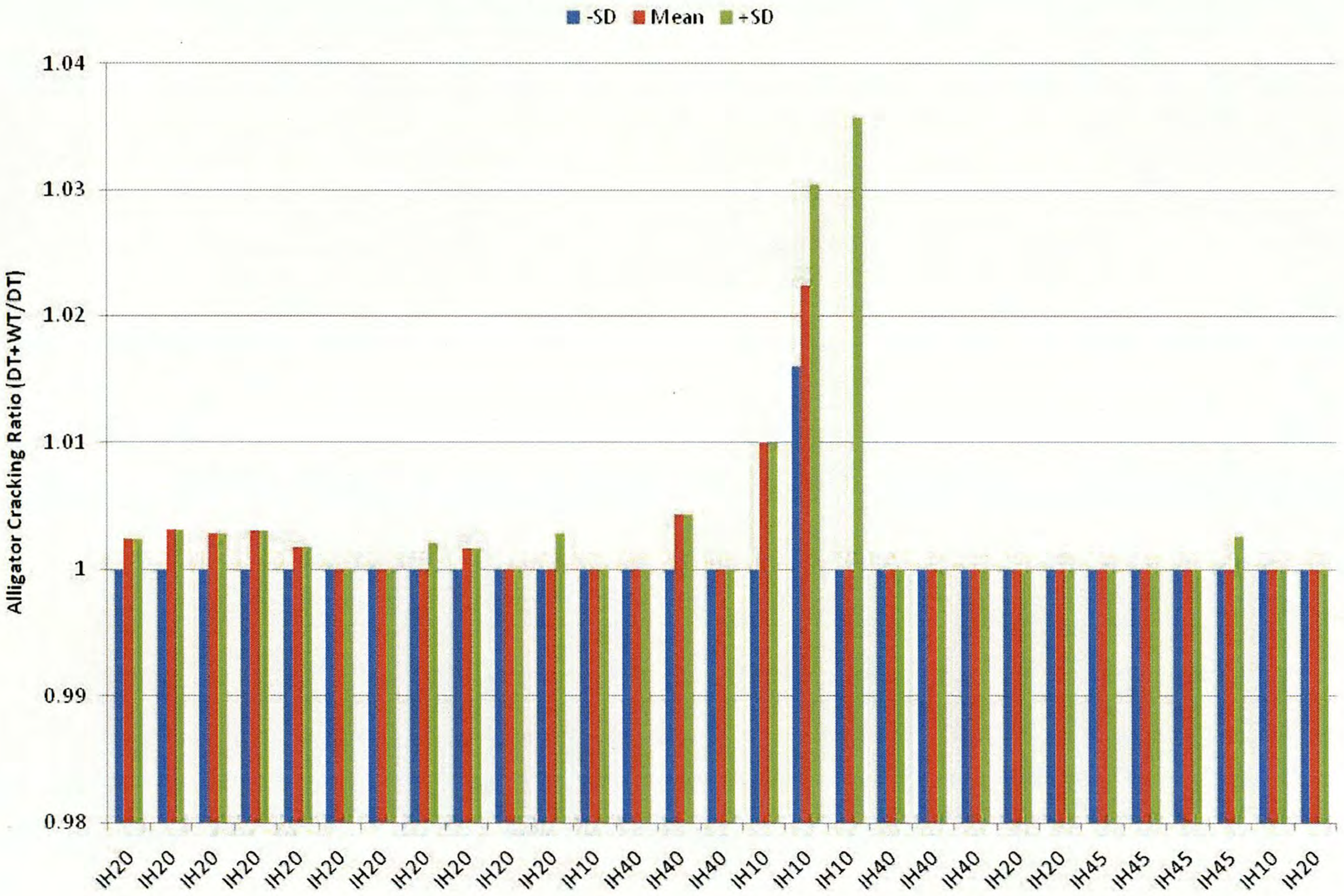


Figure 3.6: Damage Parameter for Alligator Cracking—IH Sections at the End of 20 Years

In general, the researchers observed that the additional damage imposed by the movement of wind turbine components is less than 1% for Interstate Highway sections over a 20-year service life irrespective of the distress mechanism. However, the lower functional road classes, such as US and State Highways, saw higher values of the damage parameters.

The higher damage parameters can be attributed to two factors. Firstly, the higher functional classes, e.g., Interstate Highways, are designed to carry higher daily truck traffic volumes compared to the lower functional classes. This design difference results in greater relative damage imposed by the design traffic with respect to the damage caused by the wind traffic; therefore, the net damage ratio is lower. Second, the higher functional classes are designed to carry higher traffic volumes and therefore their structural capacity is much higher than that of the lower classifications. The additional wind turbine truck traffic thus has a very low impact on the pavement structure of the higher functional classes as compared to the lower ones. On the other hand, most wind turbine components are hauled a significant distance over Interstate Highways relative to US and State Highways. Thus, the pavement structure of the US and State Highways may also limit the distances over which the wind-related truck traffic can be moved on these lower functional classes without imposing substantial damage to Texas's highway network.

In the case of the roughness estimates, the additional damage due to the movement of wind turbines was assessed differently. As mentioned earlier, the roughness transfer function is additive and is defined as the sum of the other distress types, including the ones measured above and transverse cracking. Therefore, the approach adapted constituted calculating the difference between the roughness predicted due to the combined effect of the wind turbine and design traffic and that calculated due to the effect of the design traffic only. As the transfer function is additive, calculating the difference between the two roughness scores will cancel the bias in the predictions. The damage parameter from a roughness standpoint is defined in Equation 8.

$$DP = (IRI\ due\ to\ Wind + Design\ Traffic) - (IRI\ due\ to\ Design\ Traffic) \qquad \text{Eqn. 8}$$

where,
DP = Damage Parameter for a particular Distress Mechanism

Figure 3.7 presents the damage parameter for US sections from a roughness perspective.

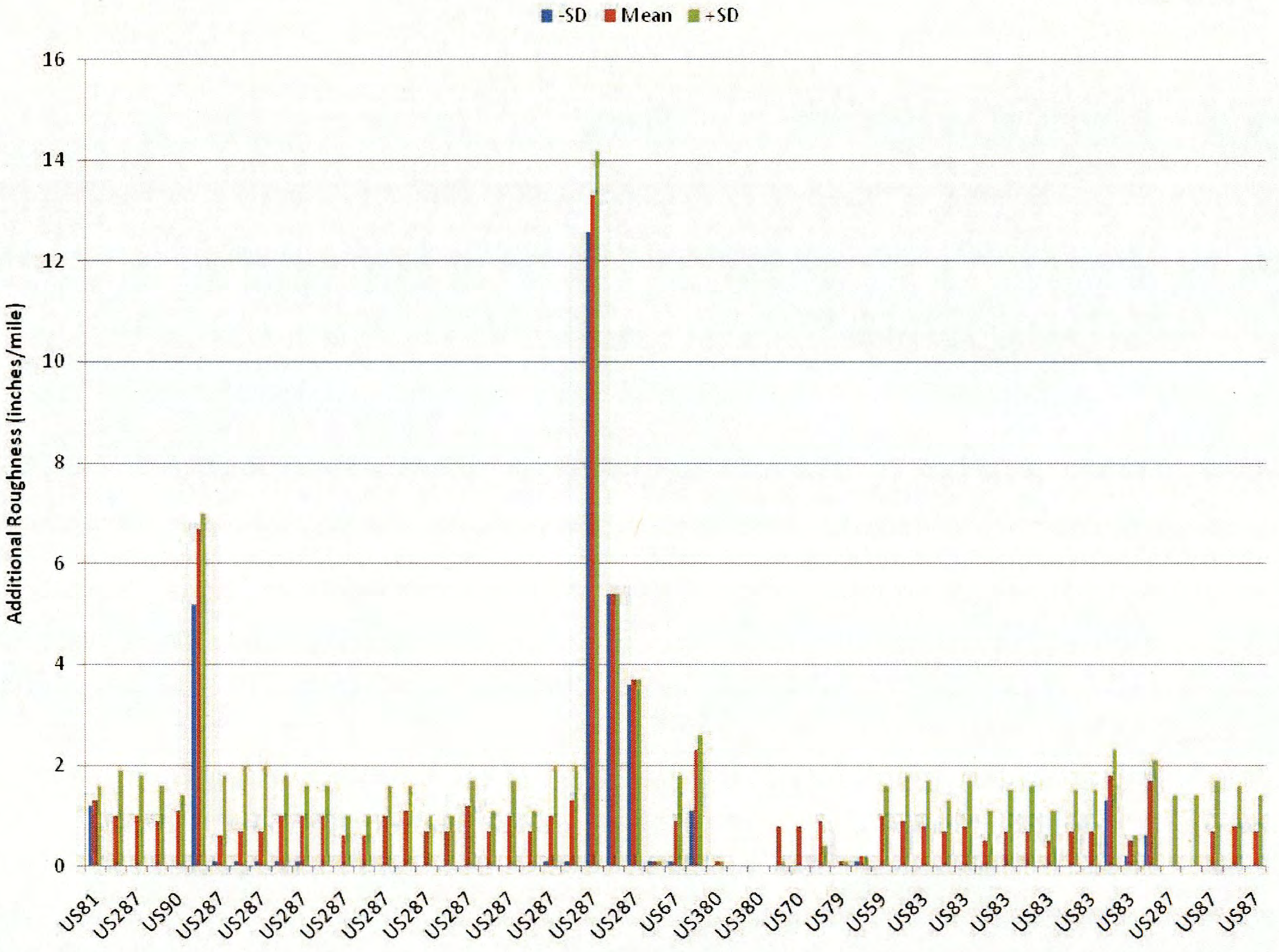


Figure 3.7: Damage Parameter for Roughness for US Sections at the End of 20 Years

Table 3.4 provides the damage parameters calculated for each of the three distress mechanisms and the roughness scores by the functional highway classes.

Table 3.4: Damage Parameters for Different Functional Classes and Distress Mechanisms at the End of a 20-year Analysis Period

		One Standard Deviation Lower than Expected Traffic	Expected Traffic	One Standard Deviation Higher than Expected Traffic
Longitudinal Cracking (%)	IH	0.1	0.3	0.4
	US	0.2	2.3	4.4
	SH	32	58	144
Alligator Cracking (%)	IH	0.1	0.2	0.4
	US	0.1	4.1	4.4
	SH	1.0	4.1	7.4
Rutting (%)	IH	0.2	0.4	0.7
	US	0.3	4.8	8.1
	SH	1.7	7.6	11.8
Roughness (inches/mile)	IH	0.1	0.2	0.3
	US	0.6	1.2	1.8
	SH	0.6	1.3	1.9

The results presented in Table 3.4 show that the damage parameters start increasing—in general—when moving from higher to lower functional road classes.

As estimated in Chapter 2, the VMT incurred by the wind turbine truck traffic occurs mostly on the higher functional highway classifications. To estimate the overall impact of the OS/OW wind turbine truck traffic associated with wind energy developments in Texas, the individual functional class damage parameters can be weighed by the proportion of the total VMT that is traversed on the given functional class. Table 3.5 provides the overall impact scores associated with OS/OW wind truck traffic on the Texas highway network with respect to each of the three distress mechanisms— rutting, longitudinal cracking, and alligator cracking—as well as roughness.

Table 3.5: Overall Impact on Texas Highway Infrastructure due to Wind Turbine Traffic

Distress Type	Impact on IH	Impact on US Highway	Impact on SH	Overall Impact
Longitudinal Cracking	0.3%	2.3%	58%	+11.4%
Alligator Cracking	0.2%	4.1%	4.1%	+2.1%
Rutting	0.4%	4.8%	7.6%	+3.0%
Roughness	0.2 in/mile	1.2 in/mile	1.3 in/mile	+0.7 in/mile

The data presented in Table 3.5 indicates that the damaging effects of the OS/OW wind truck traffic are more serious from a longitudinal cracking perspective than from an alligator cracking or rutting perspective. The results also indicate that the traffic's effect on the roughness measure, and hence the ride quality on these roads, is minor.

3.4.1.2 Impact on Service Life of Pavements

The previous section discussed in detail the additional damage imposed by the movement of the wind turbine components on Texas's highway infrastructure. This section addresses the reduction in service life due to the truck traffic resulting from the transportation of wind turbine components on Texas's highway infrastructure.

The reduction in pavement service life was calculated using the methodology described in Section 3.2.3. The procedure assumes that a pavement is designed to last a certain number of years given the design traffic. At the end of this period, it would reach a terminal distress value, which will require some kind of intervention. However, when a pavement is subjected to the design as well as OS/OW traffic resulting from developments in the wind energy industry, the time to reach the terminal distress value will be shortened. The difference in the service lives under these two scenarios is used to calculate the service life reduction due to the wind energy industry.

The reduction in the service life of the pavement sections were evaluated from a rutting perspective. Figure 3.8 illustrates the reduction in service life for the US Highway sections due to the movement of wind turbine components.

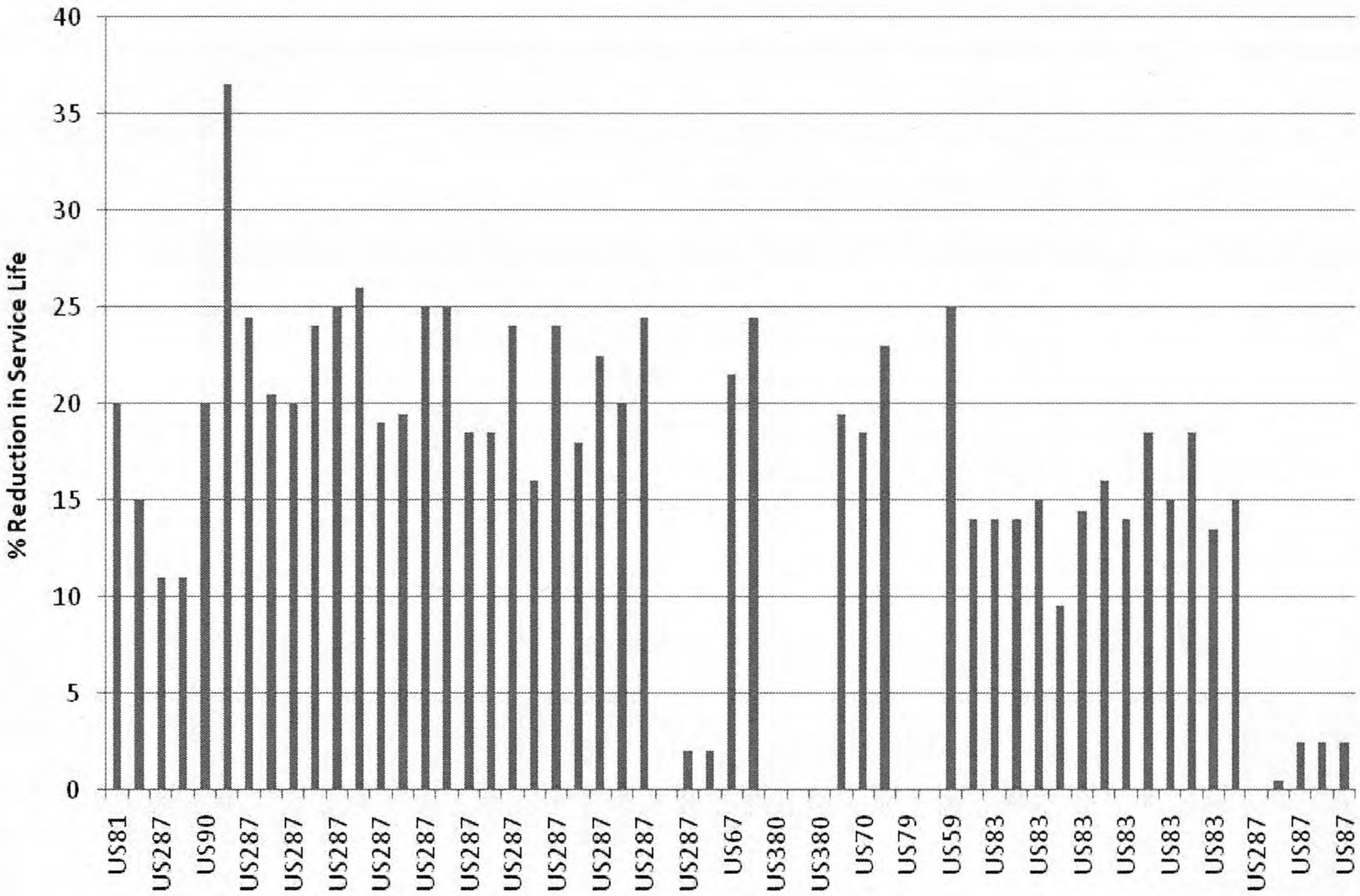


Figure 3.8: Reduction in Service Life of US Highway Sections due to Wind Turbine Truck Traffic

On average, the reduction in the service life of pavements due to the movement of wind turbine components on Interstate, US, and State Highways were 1.9%, 15.2%, and 20.2%, respectively. A weighted average service life reduction was calculated based on the VMT proportion traversed on each functional highway classification. Thus, the overall reduction in the service life of pavements due to the wind turbine truck traffic was estimated at 9.1%.

3.4.2 Natural Gas Sector (Barnett Shale Play)

3.4.2.1 Additional Damage Imposed by Natural Gas Development

The additional pavement damage associated with natural gas development was calculated separately for each of the three operations, i.e., mobilization of the drill rig, saltwater removal, and fraccing and pad-site preparation. This calculation was chosen because of the differences in truck types used, hauling distance, and duration of the activity. The damage imposed by these operations was also evaluated in terms of the four primary distress mechanisms mentioned earlier. From a distress perspective, the additional damage imposed was evaluated as the ratio between the predicted distress imposed by the truck traffic involved in one of the three operations and the design traffic and the distress predicted for the design traffic.

The mobilization of the rig occurs once during the entire service life (about 20 years) of a natural gas well. About 20 trucks are required to mobilize and de-mobilize the rig per well site. To ensure a rig traffic volume of one truck/day over a 20-year service life, the pavement damage imposed by the development of 365 well sites were estimated[7]. The approach thus yields an average damage index for specific road sections over a 20-year analysis period due to the development of 365 gas wells. By calculating the additional damage over a 20-year analysis period, any timing concerns as to when to calculate the damage ratios (i.e., early or later in the analysis period) are addressed. The timing concern stems from the fact that the transfer functions that relate the behavior of the material under dynamic traffic loading to visual distresses are non-linear. Figure 3.9 presents the damage ratio that was calculated for rig movements on Interstate Highway sections from a rutting perspective.

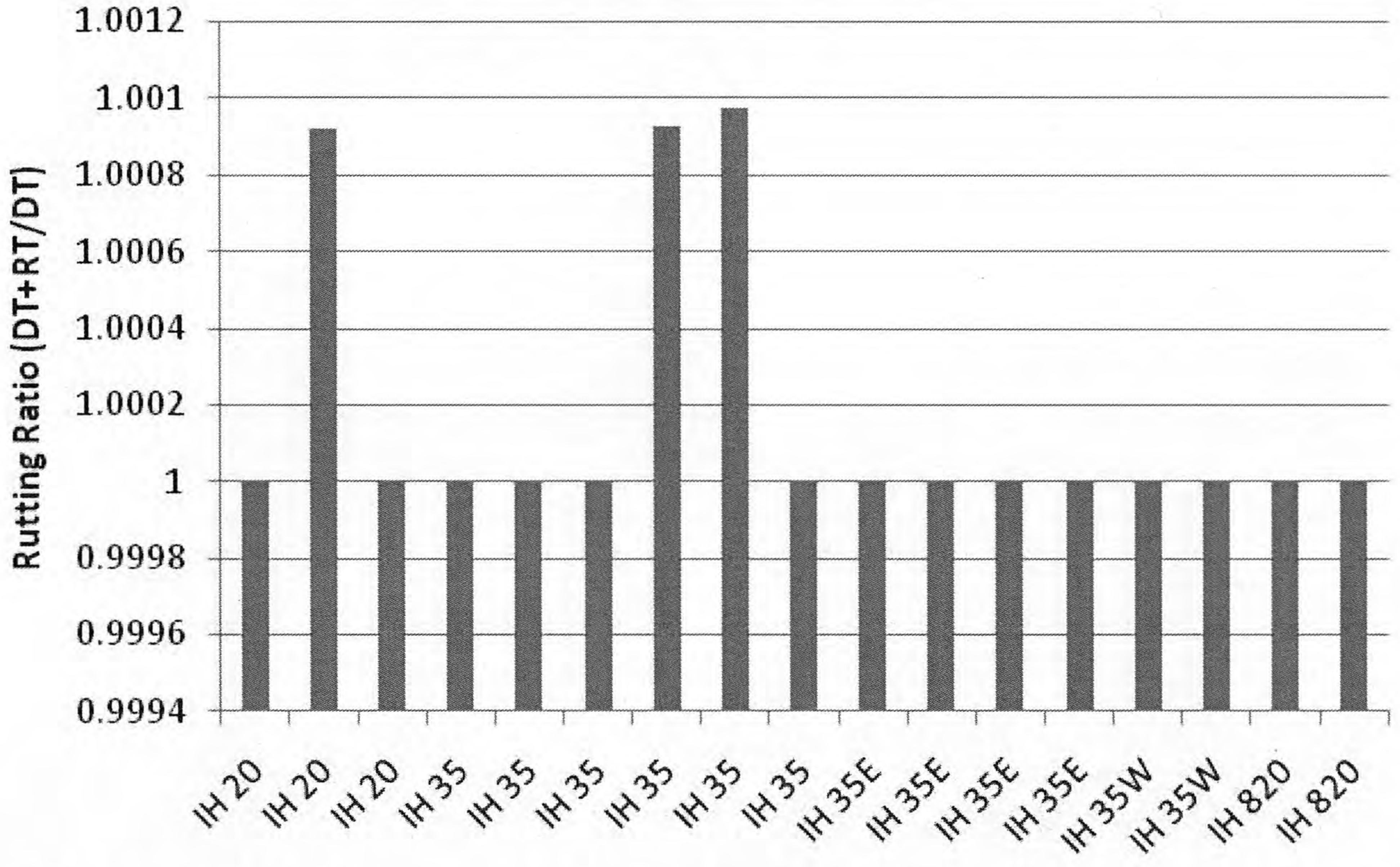


Figure 3.9: Ratio of the Permanent Deformation of IH Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-year Analysis Period)

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[7] A total of 4,145 drilling permits were issued for the fiscal year 2008 in the Barnett Shale area according to information provided by the RRC.

In the Barnett Shale region, a typical well/pad site has 3 to 4 wellheads, but a well site in a rural location may have as many as 8 to 10 wellheads. However, well/pad sites in the Barnett Shale region are typically concentrated in a smaller geographic area. The equipment and material needed for the development of a specific well site (i.e., installation of the wellheads) typically traverse the same truck corridor. Also, the saltwater traffic will typically use the same route for all the wellheads at a specific site once they enter production. However, the corridors/routes used for these two types of operations may or may not be the same and, to some extent, depend on the location of the saltwater tank farms. The study team considered each of these activities independently of each other. A scenario where the truck traffic destined for a specific site use the same corridor/route was therefore not considered. The pavement damage imposed by the construction and saltwater traffic was calculated for 10 wellheads within a radius of 10 miles from the well site separately. Figures 3.10 and 3.11 present the damage ratios computed for the construction and saltwater traffic from a rutting perspective.

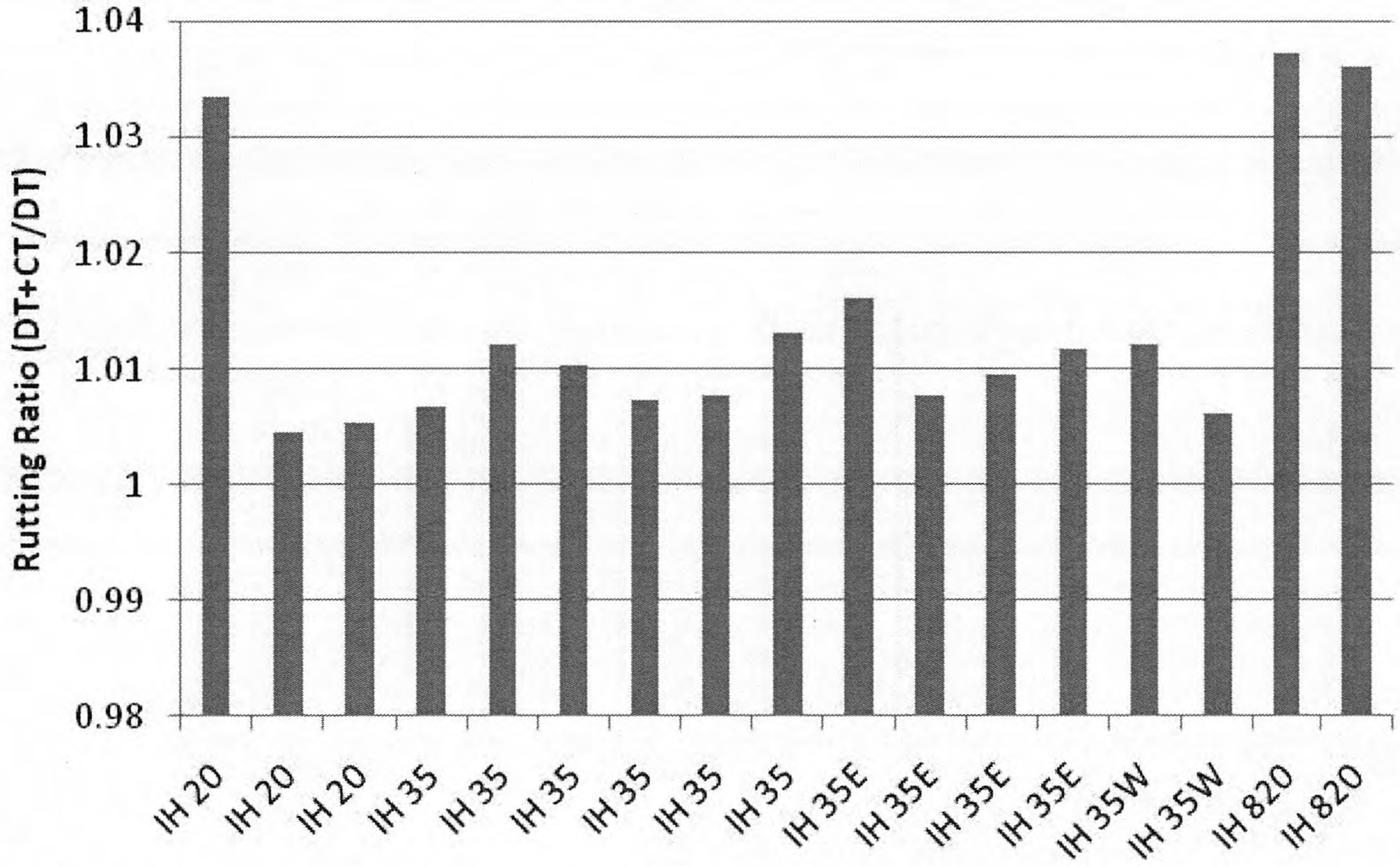

Figure 3.10: Ratio of the Permanent Deformation of IH Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-year Analysis Period)

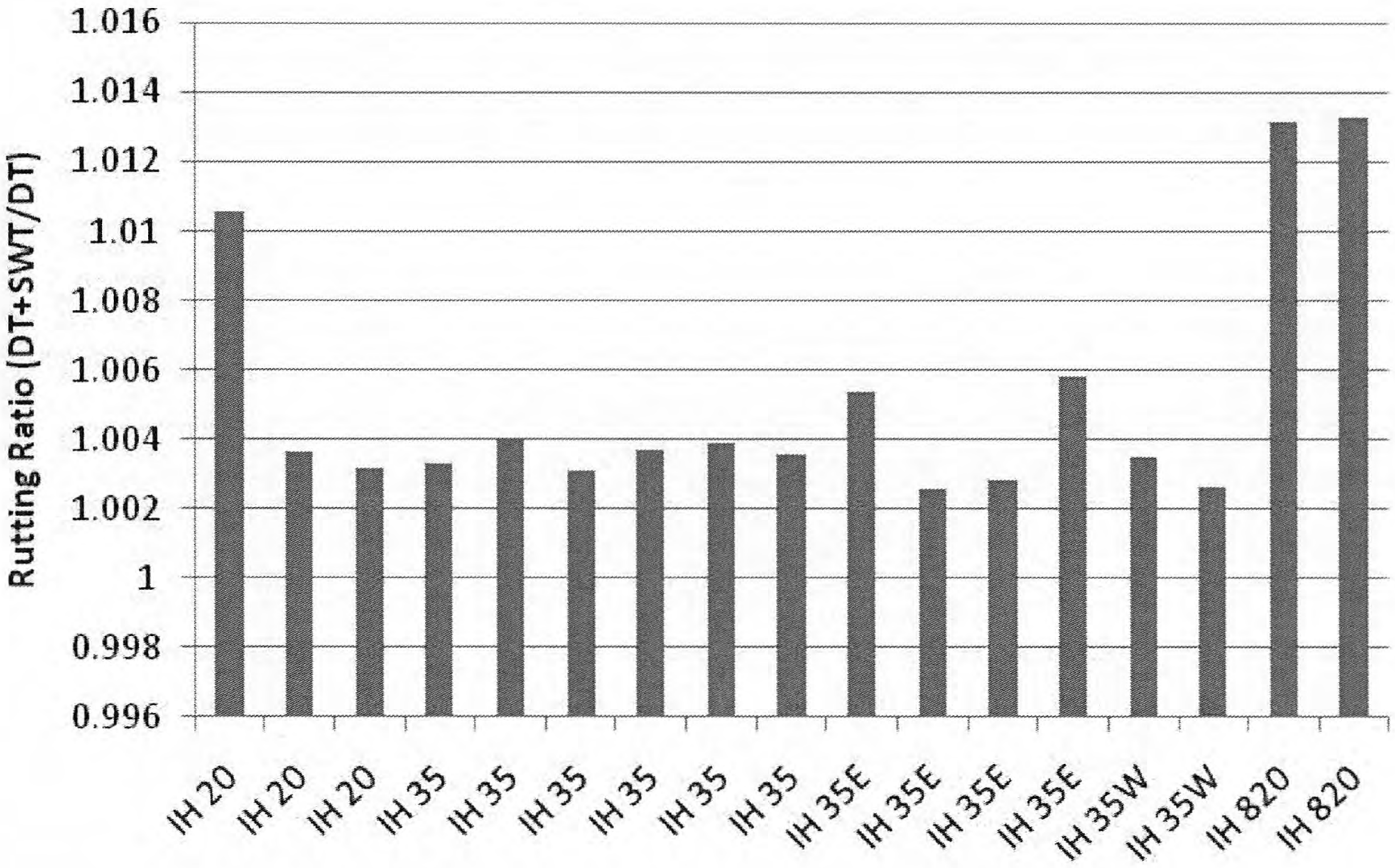

Figure 3.11: Ratio of the Permanent Deformation of IH Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-year Analysis Period)

Similar ratios for the pavement damage imposed by the rig, construction, and saltwater traffic were calculated for US Highways, State Highways, and FM Roads from a roughness, longitudinal cracking, and alligator cracking perspective (see Appendix A2).

However, to the average road user pavement roughness may be the most noticeable as it impacts ride quality. In addition, it also potentially increases vehicle delay, fuel consumption, and maintenance costs. The evaluation of the damage imposed by the trucking operations associated with natural gas development on the roughness measure differs from the approach used to estimate the other distress mechanisms in that a difference rather than a ratio was calculated between the roughness scores. The increase in the roughness measure imposed by trucks involved in natural gas development is presented in Figures 3.12 and 3.13.

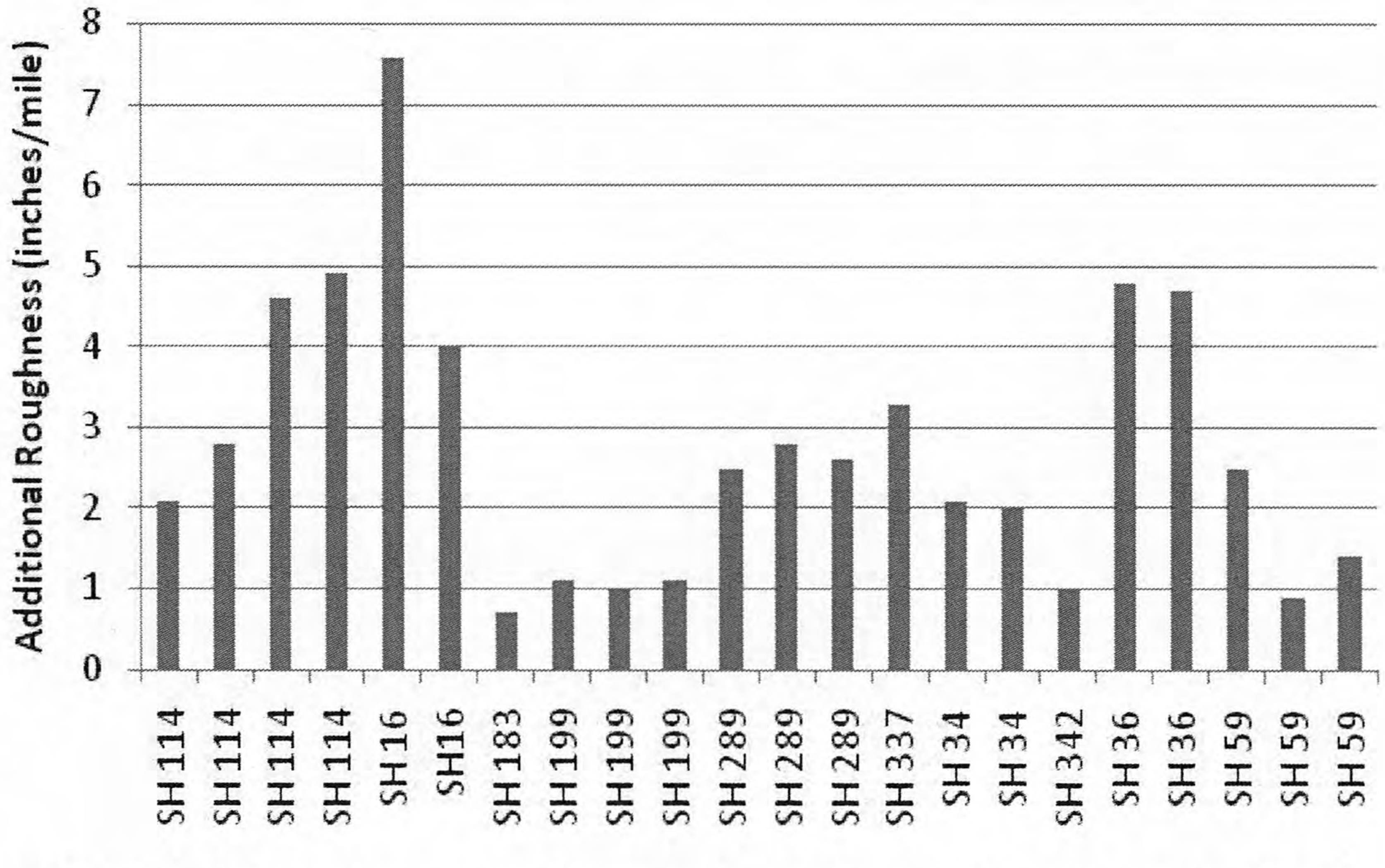

Figure 3.12: Additional Roughness on SH Sections due to Construction Traffic in the Barnett Shale Region (for 10 Wellheads over a 20-year Analysis Period)

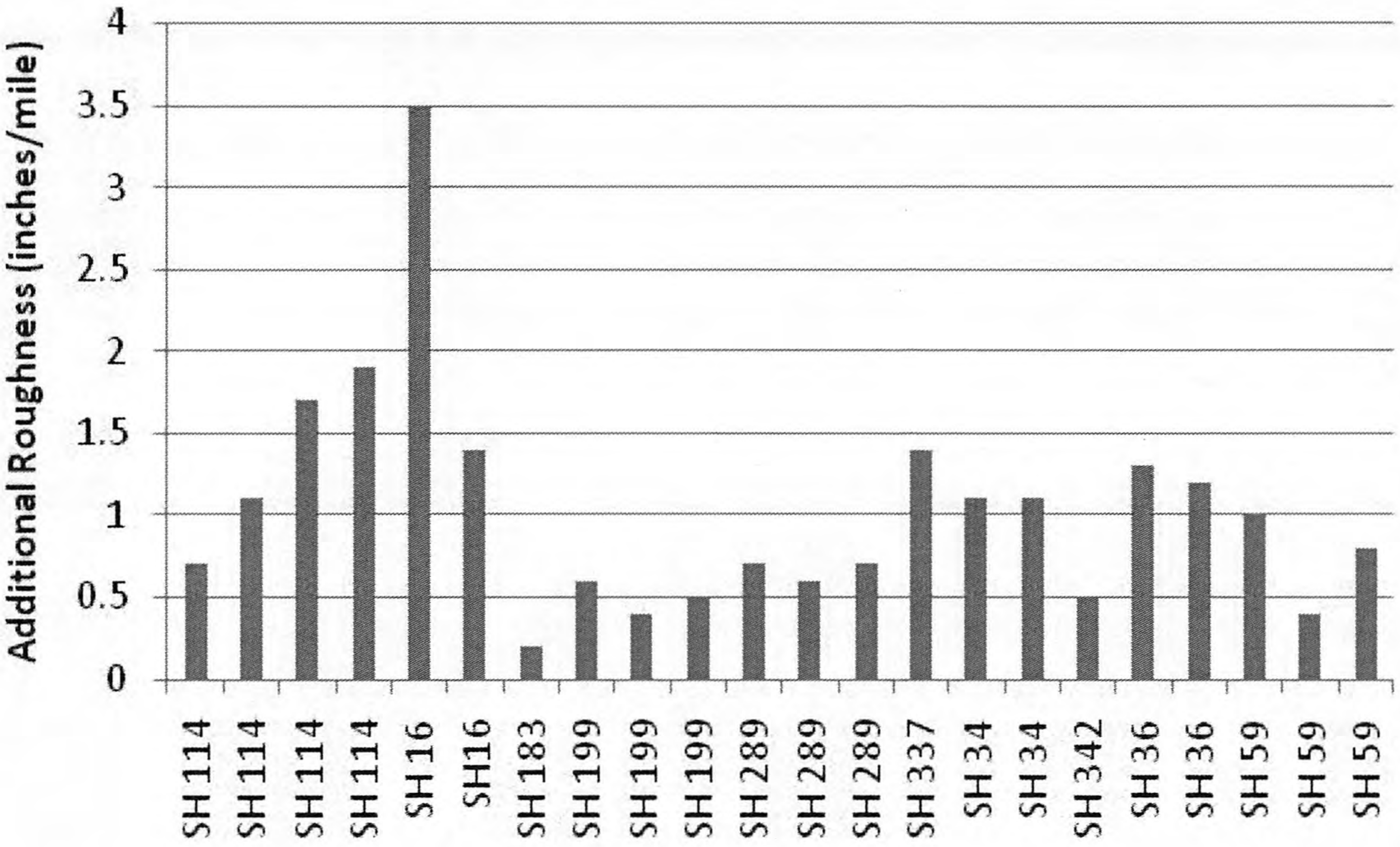

Figure 3.13: Additional Roughness on SH Sections due to Saltwater Traffic in the Barnett Shale Region (for 10 Wellheads over a 20-year Analysis Period)

In general, the results indicate that the pavement damage imposed by the construction traffic associated with natural gas development is most severe, followed by the damage imposed by the saltwater disposal traffic and the rig traffic. This result can be partly attributed to the large number of trucks involved in the fraccing of a gas well and partly to the fact that a large percentage of these trucks have high axle weights. According to the Asphalt Institute's fourth power law, the damage on the pavement structure due to one pass of an axle varies as the fourth power of its weight (Kinder et al., 1988). In the case of the saltwater disposal truck traffic, the volumes are not that high relative to the construction traffic, but the long-lasting duration of this activity eventually has a serious bearing on the pavement structure (see Appendix A2). The rig traffic has the least impact on the pavement structure due to the specialized nature of the truck configurations that are used to move the rig components.

The calculations and figures presented above show the damage contributions by the different trucking activities imposed on each of the four functional classes—IH, US, SH and FM roads. However, the overall impact on the road network varies largely by activity and is a function of the VMT traversed on each of the highway functional classes. A weighted average of the individual damage factors by the VMT traversed on each of the functional highway classes was thus calculated. Table 3.6 provides the detailed estimates of the overall impact imposed by each trucking activity associated with natural gas development.

Table 3.6: Overall Impact of Natural Gas Development in the Barnett Shale Region on Texas's Highway Infrastructure

Type of Traffic	Distress Type	Impact on IH	Impact on US Highway	Impact on SH	Impact on FM Roads	Overall Impact
Rig Traffic (for 365 well sites)	Longitudinal Cracking	0.1%	1.0%	2.2%	7.9%	+2.8%
	Alligator Cracking	0.4%	0.8%	2.1%	5.7%	+2.2%
	Permanent Deformation	0.02%	0.25%	1.5%	4.8%	+1.6%
	Roughness	0.0 in/mile	0.1 in/mile	0.2 in/mile	1.0 in/mile	+0.3 in/mile
Construction Traffic (for 10 wellhead installations)	Longitudinal Cracking	1.4%	14.5%	70.8%	293%	+93.9%
	Alligator Cracking	1.2%	13.3%	42.1%	84.8%	+35.1%
	Permanent Deformation	1.4%	9.0%	14.1%	27.8%	+13.2%
	Roughness	0.4 in/mile	2.0 in/mile	2.8 in/mile	4.9 in/mile	+2.6 in/mile
Saltwater Traffic (for 10 wellheads)	Longitudinal Cracking	0.6%	6.2%	30.0%	124%	+40%
	Alligator Cracking	0.6%	5.9%	15.6%	36.6%	+14.6%
	Permanent Deformation	0.5%	3.7%	5.8%	14.0%	+6.0%
	Roughness	0.2 in/mile	0.8 in/mile	1.0 in/mile	2.5 in/mile	+1.1 in/mile

The results presented in Table 3.6 provide evidence that the construction traffic associated with natural gas development imposes significant damage to the highway assets in the Barnett Shale region. The impact is even more serious for the lower classifications of highways, such as the FM roads. Finally, it should be noted that both the saltwater and construction traffic have an average haul distance of around 10 miles, which implies that the effect of this traffic is confined to the Barnett Shale region.

3.4.2.2 Reduction in Service Life due to Damage Imposed by Natural Gas Development

The previous section discussed the expected increase in the visual distresses of flexible pavements in the Barnett Shale region imposed by the trucking operations involved in natural gas well developments. The increased damage imposed to the pavement structure as a result of the truck traffic associated with the natural gas industry is expected to translate to a proportionate decrease in the service life of pavements. The difference in the time required to reach the terminal distress value due to the design traffic and due to the combined effect of the design and natural gas traffic was used to calculate the reduction in the service life of the pavement sections.

The reduction in the service life of the pavement sections was evaluated from a rutting perspective. Figure 3.14 illustrates the reduction in service life of the US Highway sections that are impacted by saltwater disposal traffic.

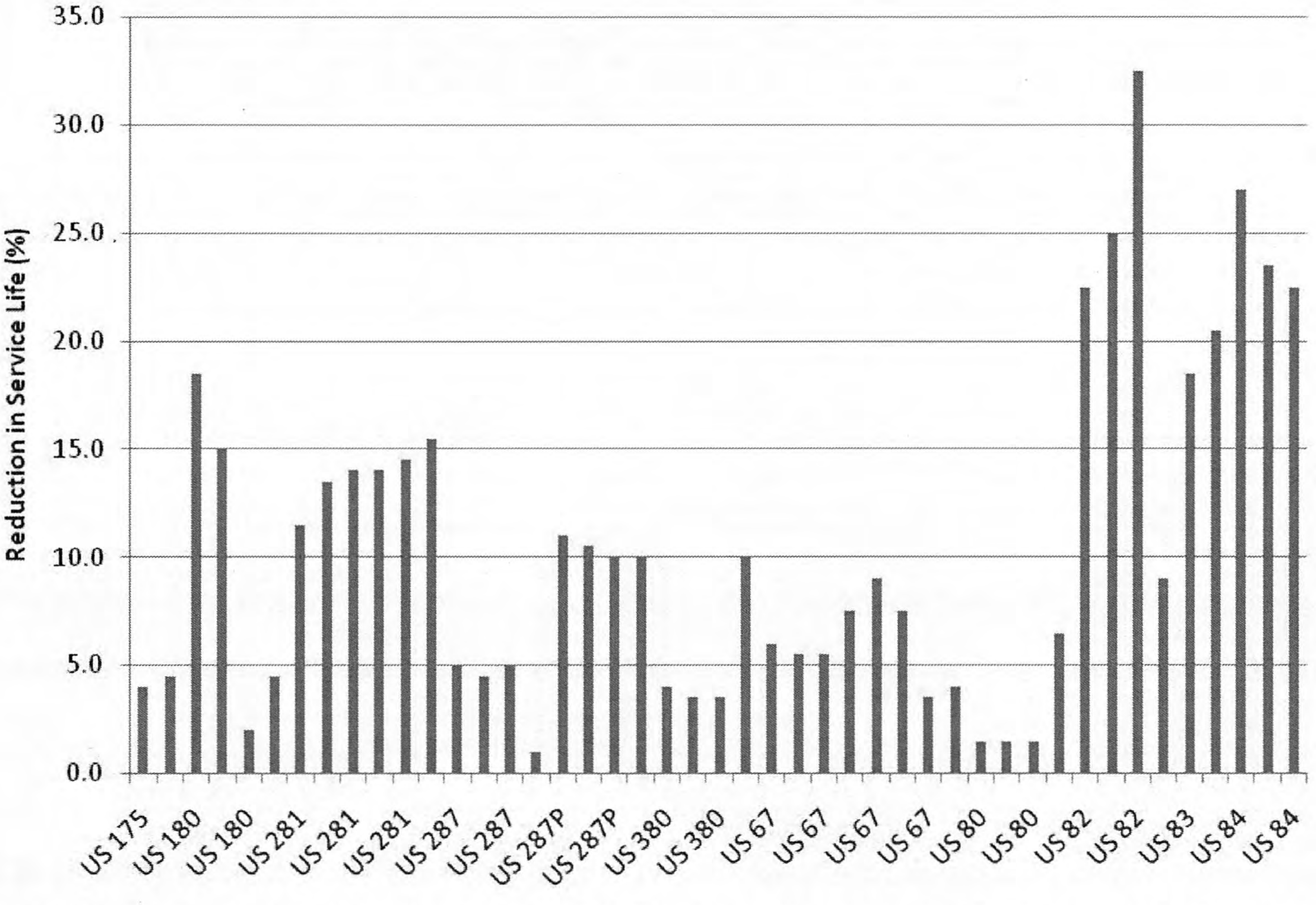

Figure 3.14: Reduction in Service Life of US Highway Sections in the Barnett Shale Region due to Saltwater Disposal Traffic

As mentioned previously, differences in the characteristics and haul distances of the truck traffic associated with each of the natural gas well development activities (i.e., rig movement, construction traffic, and saltwater disposal traffic) require an estimate of the overall impact on the service life of the pavements imposed as a result of the different operations. A weighted average of the service life reduction associated with each activity by the VMT proportion traversed on each functional highway classification was calculated; Table 3.7 lists the results.

Table 3.7: The Impact on the Service Life of Highways in the Barnett Shale Region due to Natural Gas Development (Rutting Perspective)

Traffic Type	**Impact on IH**	**Impact on US Highway**	**Impact on SH**	**Impact on FM Roads**	**Overall Impact**
Rig Traffic (365 well sites)	-0.7%	-1.4%	-4.8%	-15.5%	-5.6%
Construction Traffic (10 wellheads)	-3.7%	-24.4%	-35.6%	-52.9%	-29.5%
Saltwater Traffic (10 wellheads	-1.3%	-10.4%	-16.5%	-34.3%	-15.7%

The results provided in Table 3.7 demonstrate that the construction traffic associated with developing 10 natural gas wellheads can cause up to a 30% reduction in the service life of the highway infrastructure used, if all the truck traffic uses the same truck corridor/route. It should also be noted that the pavement damage imposed by the three activities—i.e., rig movement, construction, and saltwater disposal—was considered independently, which is a conservative scenario as in some cases the same corridor/route will serve the trucks associated with more than one of these activities.

3.4.3 Crude Oil Sector (Permian Basin)

The cumulative 18-kip axle repetitions associated with the construction truck traffic involved in oil well development were reported as 700 in a TTI study conducted in 1982 (Mason et al., 1982). However, the construction traffic typically visits an oil field once every 7.5 years when the well needs to be re-serviced to maintain production levels. In this study, an analysis period of 20 years was selected, which implies that the construction traffic will recur between two and three times to re-service a specific oil well. The cumulative 18-kip axle repetitions over an analysis period of 20 years would thus equate to about 1867 (e.g., 700×20÷7.5). The latter equates to less than one 18-kip axle per day per well. The pavement damage imposed by 16 oil wells operating in the region where the pavement section is located was therefore estimated. This resulted in a daily 18-kip axle repetition of four over a 20-year analysis period attributable to the construction truck traffic associated with crude oil development in the Permian Basin region. Similarly, the damage estimates for the production truck traffic was also estimated for 16 oil wells operating in the region[8]. The study conducted by TTI in 1982 concluded that the production truck traffic in the Permian Basin per well was equal to 1.5 18-kip axle repetitions per day. Thus, for 16 oil wells, the production traffic would require 24 18-kip axle repetitions daily.

3.4.3.1 Damage Estimates for Construction Traffic Associated with the Crude Oil Sector

The damage parameter as defined in Equation 1 was estimated for three different distress mechanisms—rutting, longitudinal cracking, and alligator cracking. Because the pavement structures of the higher classifications of highways are designed for higher truck traffic volumes, it is not surprising that the additional damage imposed by the trucking operations associated with the crude oil industry are minimal in the case of the Interstate System and severe in the case of the FM Roads. Figures 3.15.a and 3.15.b present the damage ratios calculated for the construction traffic from a rutting perspective for Interstate Highways and FM Roads, respectively.

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[8] A total of 2,723 oil wells were completed in the Permian Basin during the fiscal year 2009–10, according to well count statistics provided by the RRC.

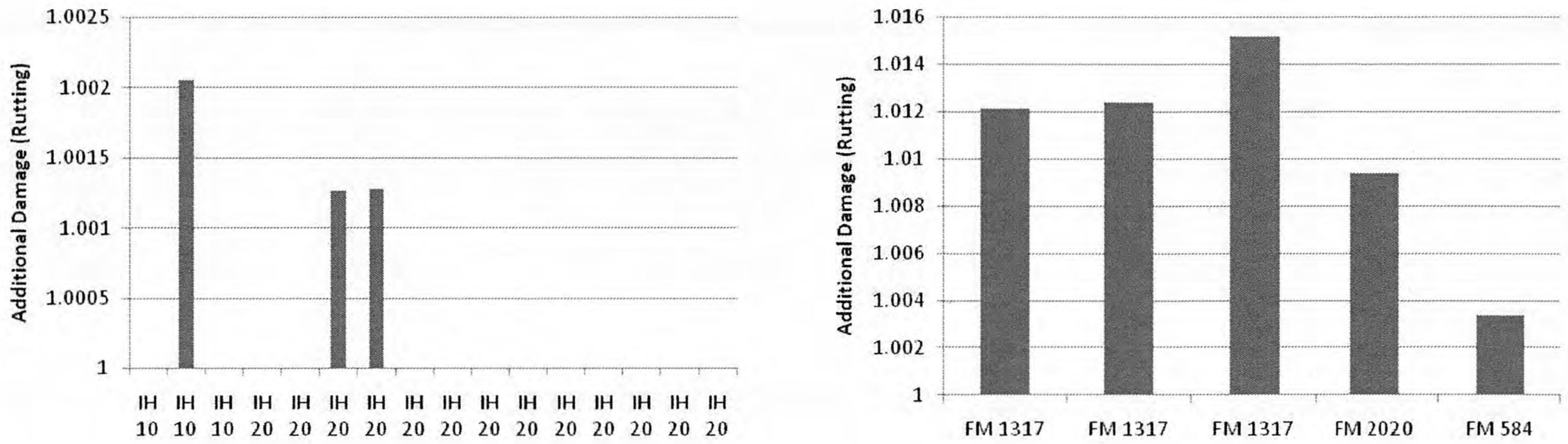

Figure 3.15: Ratio of Rut Depths on (a) IH (left) and (b) FM (right) Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-year Analysis Period)

Similar trends were observed for the additional damage estimates from the cracking and roughness perspectives. An overall damage estimate for the construction truck traffic associated with the crude oil industry in the Permian Basin was calculated by weighing the individual damage estimates for the different facility types by their respective proportion of the total VMT traversed. The damage estimates for the construction traffic with respect to the three distress mechanisms and roughness are summarized in Table 3.8.

Table 3.8: Additional Damage due to the Construction Traffic Associated with Crude Oil Development in the Permian Basin on Texas's Highway Infrastructure

Distress Type	**Impact on IH**	**Impact on US Highway**	**Impact on SH**	**Impact on FM Roads**	**Overall Impact**
Longitudinal Cracking	0.1%	1.3%	1.4%	7.8%	2.8%
Alligator Cracking	0.1%	3.4%	2.8%	9.2%	4.2%
Rutting	0.0%	0.3%	0.4%	1.1%	0.5%
Roughness	0.1 in/mile	0.1 in/mile	0.1 in/mile	0.3 in/mile	0.1 in/mile

The results presented in Table 3.8 indicate that the construction traffic associated with crude oil development has little to no impact on the Interstate system, US, and State Highways. Although the additional damage imposed by the construction truck traffic on the FM Roads is relatively higher than on the other functional classes, the overall impact on Texas's highway infrastructure is minimal. Finally, it is important to note that the impact of the construction traffic on the roughness measures is negligible and thus it is expected it will be hardly noticeable to the average road user's ride quality.

3.4.3.2 Damage Estimates for Production Traffic Associated with the Crude Oil Sector

The impact of the production traffic on Texas's highway infrastructure was assessed using the approach described previously (i.e., the same approach used for calculating the damage imposed by the wind energy and natural gas sectors). The results showed that the truck traffic associated with the transportation of crude oil from the tank batteries to the pipeline breakout stations has a far more serious impact on Texas's highway assets than the construction traffic.

This result can be attributed to the higher truck volumes and the prolonged duration of the exposure to the higher truck levels. Figures 3.16.a and 3.16.b illustrate the damage ratios from an alligator cracking perspective for pavement sections on the Interstate System and FM Roads impacted by oil production traffic (see Appendix A2).

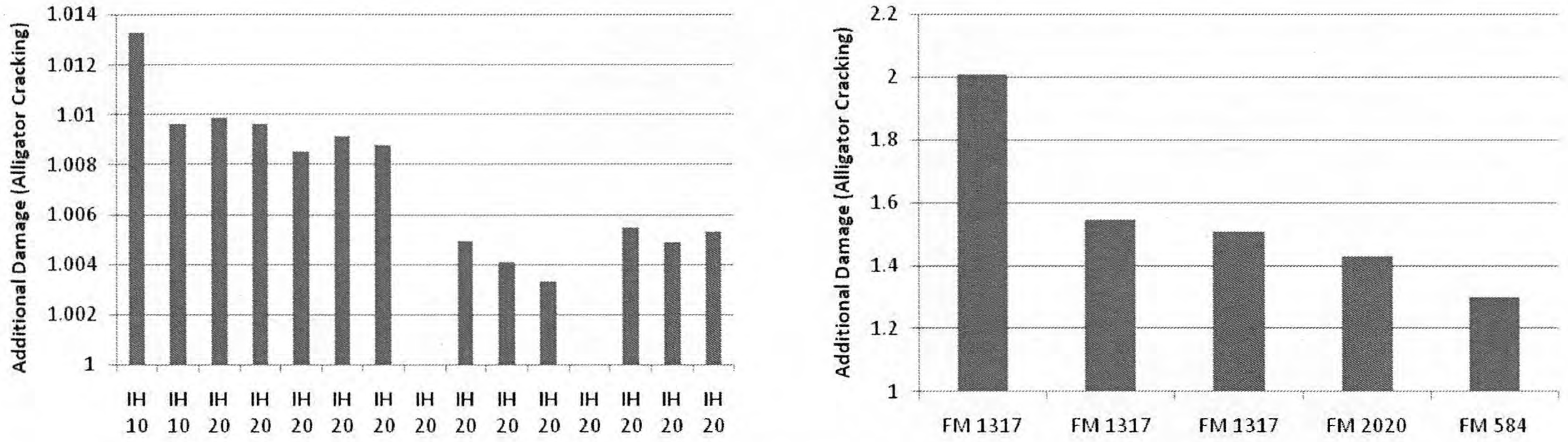

Figure 3.16: Ratio of Rut Depths on (a) IH (left) and (b) FM (right) Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-year Analysis Period)

The additional damage imposed by the production truck traffic with respect to the different distress mechanisms and the roughness measures are summarized in Table 3.9. Table 3.9 also illustrate the overall damage estimate for the production traffic, which was calculated by weighing the individual damage estimates for the different facility types by their respective proportion of the total VMT traversed.

Table 3.9: Additional Damage due to the Production Traffic Associated with Crude Oil Development in the Permian Basin on Texas's Highway Infrastructure

Distress Type	**Impact on IH**	**Impact on US Highway**	**Impact on SH**	**Impact on FM Roads**	**Overall Impact**
Longitudinal Cracking	1.0%	10.2%	16.6%	46.0%	21.7%
Alligator Cracking	0.7%	11.4%	15.4%	56.0%	24.3%
Rutting	0.3%	1.7%	2.0%	5.2%	2.7%
Roughness	0.2 in/mile	0.3 in/mile	0.5 in/mile	1.5 in/mile	0.7 in/mile

The results presented in Table 3.9 indicate that the impact of the production truck traffic on Texas's highway system is substantially higher than that of the construction traffic. High truck traffic volumes, the prolonged exposure to high truck volumes, and a relatively high percentage of the overall production VMT being traversed on the lower functional classes of highways are considered the reasons for this finding. It is also reasonable to expect that the highway network serving the construction and production traffic will be the same, specifically the final link that provides access to the specific oil field. A lack of route information for the construction and production traffic, however, prevented the calculation of the joint impact imposed by the two activities. The construction and production traffic impacts were thus considered separately. However, this scenario might be conservative, as in some cases the same corridor/route will serve the trucks associated with both these activities.

3.4.3.3 Reduction in Service Life due to Damage Imposed by Crude Oil Development

The additional damage imposed by truck traffic associated with the crude oil industry will accelerate the failure of pavement structures in the Permian Basin region. The service life reductions were calculated as the difference in the time duration to reach the terminal distress value under the combined influence of the design and the crude oil traffic and that due to the design traffic only.

The reduction in pavement service life was evaluated from a rutting perspective. Figures 3.17.a and 3.17.b illustrate the reduction in service life for the Interstate Highway and FM pavement sections due to the production traffic.

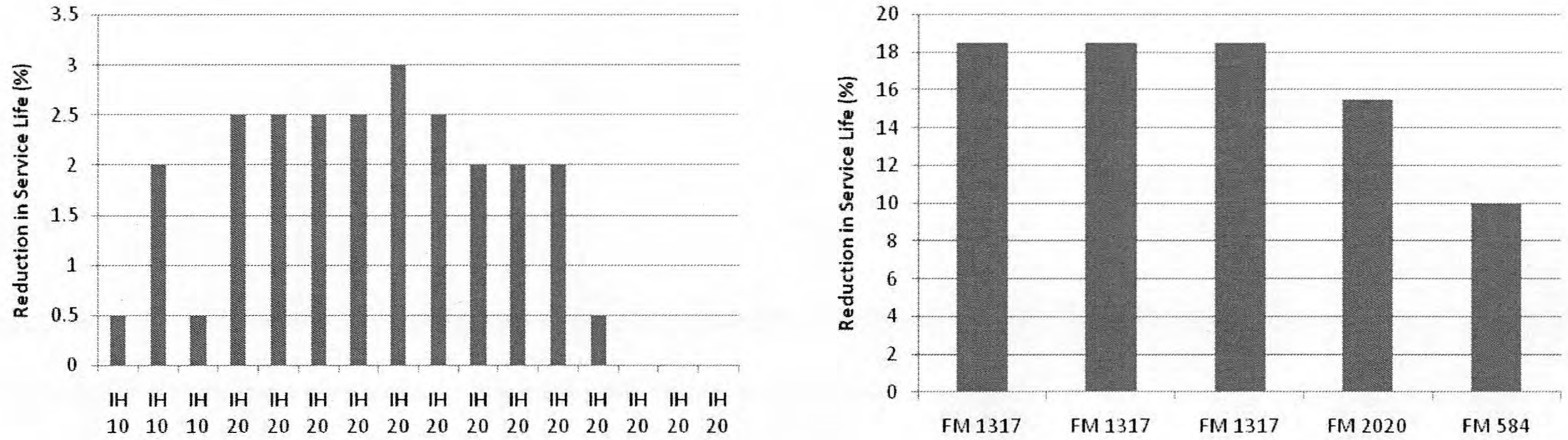

Figure 3.17: Reduction in Service Life of (a) IH (left) and (b) FM (right) Sections in the Permian Basin Region due to Production Traffic

The reduction in the service life of pavements attributable to the construction and production traffic, respectively, was estimated for the different functional classes of highways. A weighted average of the service life reduction associated with each activity by the VMT proportion traversed on each functional highway classification was also calculated. The results are summarized in Table 3.10.

Table 3.10: The Impact on the Service Life of Highways in the Permian Basin Region due to the Crude Oil Sector (Rutting Perspective)

Traffic Type	Impact on IH	Impact on US Highway	Impact on SH	Impact on FM Roads	Overall Impact
Construction Traffic (16 wells)	1.1%	1.5%	1.3%	3.1%	1.8%
Production Traffic (16 wells)	1.6%	5.4%	6.8%	16.2%	8.6%

It is worth noting that the production traffic associated with 16 oil wells imposes a 9% reduction in the service life of pavements in the Permian Basin region while the impact of the construction traffic is comparably lower. It is also important to note that the extent of the damage will vary for the two activities because of the differences in the average length of haul. Furthermore, because the impact on the service life of pavements has been evaluated separately for the construction and production traffic, these results should be regarded a conservative estimate. In situations where the trucking corridors/routes of the two activities overlap, service life reductions higher than those reported in this research study can result.

3.5 Concluding Remarks

This study presents a methodology for estimating damage to the Texas highway infrastructure due to developments in the energy sector. The procedure entails the usage of the recently developed MEPDG and its embedded transfer functions for estimating pavement damage with respect to three primary distress mechanisms, i.e., rutting, longitudinal cracking, and alligator cracking. In addition, the extent of damage on the pavement structure from a roughness perspective was also estimated as part of this analysis.

The study focused on evaluating the damage associated with truck traffic associated with wind energy, natural gas and crude oil energy sectors. The natural gas sector was seen to have the most serious impact on Texas's highway infrastructure of the three energy sectors that was concentrated upon. The particular finding was attributed to high truck volumes and heavy axle weights—both of are detrimental for the pavement structure.

In case of the crude oil energy sector, the impact of the production traffic associated with transportation of the crude oil from the tank batteries to the pipeline breakout station was more serious than the construction traffic. This particular observation was primarily attributed to the nature of the operation—while the construction traffic lasts for about 30–35 days, the production traffic lasts over the service life of the well.

In the case of the wind energy sector, the study team focused on evaluating the pavement damage associated with movement of the wind turbine components. The wind turbine components primarily traverse on the higher classifications of highways; therefore, the associated damage was relatively lower as compared to other energy sectors. However, contrary to truck traffic associated with crude oil and natural gas sectors, the average length of haul for the wind energy industry is relatively much higher. This implies the pavement damage associated with the wind energy sector will be system-wide, while that for natural gas or crude oil is mostly confined within a region. In addition, it should be also noted that the pavement damage associated with construction of pad sites necessary for erection of the wind turbines was not included in this study due to unavailability of reliable information on the construction traffic characteristics.

Chapter 4. Concluding Remarks

Texas's energy sector has a critical impact—historically and currently—on both the state economy and Texas's transportation system. The state's various transportation modes, including rail, highways, pipelines, and ports, form a system that supports the energy sector in a number of ways. Examples include (a) the movement of various components during the construction and implementation of the energy source (e.g., wind turbines and solar farms), (b) the provision of enabling infrastructure (e.g., transmission lines), and (c) the movement of the intermediate and final products in some energy supply chains (e.g., low sulfur mid-west coal by Class 1 unit trains to the major coal burning plants in Texas). It was thus critical that TxDOT develop a better understanding of how the energy sector uses Texas's transportation system, as well as quantify the impacts on Texas's highway infrastructure to ensure adequate maintenance funding. The research team thus developed supply chains for Texas's major energy industries: natural gas, oil, coal, wind, and bio-fuels. These supply chains were subsequently used to estimate the impacts of Texas's wind, natural gas, and oil industries on Texas's highway infrastructure. The major findings of this research are briefly summarized in this chapter.

4.1 Impact of the Wind Energy Industry

The research team estimated the damage to Texas's highway infrastructure due to the movement of wind turbine components. The research team used the recently developed MEPDG and its embedded transfer functions for estimating pavement damage with respect to three primary distress mechanisms: rutting, longitudinal cracking, and alligator cracking. In addition, the impact on the pavement structure from a roughness perspective was also estimated as part of this analysis. The truck volumes associated with transporting wind turbine components was obtained from estimates provided by the AWEA. TxDOT's OS/OW database helped the research team identify the major corridors for the movement of wind turbine trucks. The pavement damage was assessed on IH, U.S., and State Highway sections that were located along these major corridors.

The results, in general, show that the wind truck traffic imposes greater damage to the pavement structure when moving from higher to lower functional roadway classes, primarily because the lower classes of highways, especially State Highways, were not designed to carry high volumes or heavy loads. The estimated additional damage due to the transportation of wind turbine components on IH and US Highway sections is about 0.3 and 4% respectively, irrespective of the distress mechanism. On State Highways, however, the movement of the wind trucks will result in a 58% increase in longitudinal cracking, which implies that it will reduce the service life of the pavement by 37%. Finally, the impact on the roughness scores was minimal for all three types of functional classes, which implies that the movement of wind turbine components does not impact the overall ride quality of these roads.

In terms of the overall impact of the OS/OW wind truck traffic, the researchers observed that the additional damage imposed was 2 and 3% for alligator cracking and rutting, respectively. However, from a longitudinal cracking perspective, the additional damage imposed was almost 11% higher relative to the damage imposed by the design traffic. As far as the roughness measure was concerned, the OS/OW wind truck traffic contributed an additional 0.7 inches/mile over a 20-year analysis period, which would hardly impact the ride quality and be hardly noticeable to the average road user. Finally, the additional damage imposed by the truck traffic associated with wind turbine component movements will result in a reduction in the service life of the pavements. Assuming that the pavements were constructed to reach their terminal distress values at the end of the analysis period, given the design traffic, the time to reach the same terminal distress value was calculated due to the combined effect of the design traffic and the wind turbine truck traffic. The results of this research study suggest that the reduction in the service life of the highway infrastructure due to the movement of wind turbine components amounts to about 9%.

It has been speculated that at some point the Texas wind energy market will be saturated and the number of windmill components moving within the state borders will greatly reduce. This research study, however, has shown that Texas's ports serve as major entry points for overseas windmill components arriving by sea and destined for Texas's neighboring states. Also, Texas is strategically located in the U.S. and traversed by two major trade corridors (i.e., the IH-35 NAFTA corridor and the Ports-to-Plains corridor) that facilitate the movement of windmill components to neighboring states. For these reasons, it is argued that Texas's transportation system will continue to play a key role in facilitating the growth of the wind industry, by facilitating the movement of wind traffic across state borders up into the Great Plains.

4.2 Impact of the Natural Gas Industry (Barnett Shale Play)

Natural gas development in the Barnett Shale region of Texas has been a major contributor to the economic prosperity of the region. However, from a highway infrastructure perspective, it has resulted in increased maintenance costs for TxDOT's Fort Worth and Dallas districts. Developing a natural gas well results in a significant increase in truck traffic due to the movement of materials and equipment, building the pad site and access roads, the drilling and fraccing operations, and finally saltwater disposal from the site. The traffic associated with each of these activities differs in terms of the average haul distance, duration of the operation, truck volumes, axle configuration, and axle weights. Thus, the traffic associated with natural gas development was categorized as (1) traffic associated with the mobilization of the drill rig and accessories; (2) construction traffic, including rock haulers, transportation of frac sand, water, and backflow water from the wells; and (3) the saltwater disposal traffic.

The movement of the drill rig is a one-time event in the service life of a gas well. Truck traffic associated with the fraccing of the well, on the other hand, occurs every 5 years to maintain the production level of the well. Finally, the saltwater disposal traffic is a routine operation, as the saltwater must be transported from the well site to the nearest injection tank farm over the life of the well.

The associated damage imposed by each of these trucking operations was evaluated using the MEPDG with respect to three primary distress mechanisms: rutting, longitudinal cracking, and alligator cracking. Pavement roughness was also evaluated. The results indicated that construction traffic has the most serious impact in terms of the damage imposed on the pavement structure irrespective of the distress mechanism used. The rig traffic appears to have a negligible impact on the pavement structure, while the saltwater traffic has some impact on the pavement structure. The overall impact of the rig traffic, construction traffic, and saltwater traffic from a rutting perspective is about 1.6%, 13%, and 6%, respectively, in additional damage. It was observed that the construction traffic's damaging impacts is partly attributable to high axle weights and volumes over a very short time period.

The additional damage imposed by the truck traffic associated with natural gas development will also result in a reduction in the service life of the pavements. Assuming that the pavements were constructed to reach their terminal distress values at the end of the analysis period, given the design traffic, the time to reach the same terminal distress value was calculated due to the combined effect of the design traffic and the natural gas traffic. Under the premise that the trucking corridors used by the rig traffic, the construction traffic, and the saltwater disposal traffic are mutually exclusive, it was found that the overall reduction in the pavement service life due to each of these three activities were 5.6%, 29%, and 16%, respectively.

Finally, it has to be noted that other traffic generating activities associated with the natural gas industry may impact the transportation system in ways that were not estimated. For example, seismic exploration conducted by vibe buggies and thumper trucks may impact the roadway infrastructure and the underlying pipeline network. Also pipeline construction to move the natural gas from the gas well to consumption centers may require digging up parts of state owned rights-of-way and potential truck trips can be generated by the movement of natural gas itself. However, only about 5% of all natural gas produced in the U.S. is moved by truck. These activities are, however, difficult to quantify as no real measurable parameters are collected that can be analyzed. Therefore, to conclude, it is important to mention that many other activities in the natural gas energy supply chain may potentially impact Texas's transportation system. The data available, however, allowed only for the quantification of the impacts of the construction traffic and salt water disposal traffic.

4.3 Impact of the Crude Oil Industry (Permian Basin)

Texas's transportation system is very important in the procurement and distribution of crude oil. Texas's transportation system facilitates three major activities in the crude oil supply chain: 1) well development, 2) oil production, and 3) petrol gasoline distribution. These three activities have different transportation impacts.

The construction phase of an oil well development involves building access roads to the site, rigging up, drilling, rigging down, and well completion. The entire operation involves numerous truck trips to and from the well site to bring materials and the equipment necessary for constructing the oil well. The mobilization of the rotary rig requires OS/OW permits while all the remaining loads are transported on conventional combination trucks. It was observed that the VMT of the construction traffic was more or less evenly distributed among US Highways, State Highways, and FM Roads with a slightly lower utilization of the Interstate System.

The production traffic associated with crude oil development is mostly responsible for the transportation of the oil from the tank batteries located near the well site to the pipeline breakout stations. In the case of the production traffic, the Interstate System represents 5% of the total VMT while Access Roads, County Roads, and FM Roads account for almost 50% of the total VMT.

The results from this research study indicate that the construction traffic has little to no impact on Texas's highway infrastructure. The additional damage imposed by the truck traffic involved with the construction activities range between 0.5% and 4%, depending on the distress mechanism considered. The additional damage will translate into a reduction in the service lives of the facilities that are in use, but the estimates provided in this study indicate that the construction traffic will reduce the expected service life of the highway facilities in the Permian Basin region by about 1.8%.

On the other hand, the production traffic has a far more serious effect on Texas's road infrastructure. The additional damage due to the production truck traffic is 24% and 3% from a fatigue cracking and rutting perspective, respectively. The impact on the service life of highway facilities in the region is also naturally more serious in the case of the production truck traffic than the construction traffic. It was estimated that the additional damage can reduce the service life of pavement structures by almost 9%. The unrelenting nature of the operation and a higher utilization of the lower functional road classes for hauling the crude oil to the breakout stations are the primary reasons for the reduction in the pavement service lives.

It should also be noted that the additional damage and the reduction in service life of pavement structures due to the construction and production truck traffic has been estimated separately. In other words, an overlap between the corridors used for the two different operations has not been considered. However, in reality this might very well be the situation, especially for the last leg in the supply chain as access to the oil well might be provided by one or two different roads. Thus, the estimates provided in this study are conservative and could be much more severe if there is an overlap between the corridors used by the truck traffic associated with these two different operations.

Finally, the impacts of the gasoline distribution traffic on Texas's highway infrastructure were not estimated, because of a lack of reliable data. Gasoline distribution traffic is, however, largely a function of the population size and density in a region. Major urban population centers in Texas, such as Houston, San Antonio, El Paso, and the Dallas-Fort Worth area, thus generate substantial distribution traffic, which will theoretically impact the highway networks in these urban areas.

4.4 Concluding Remarks

Texas's energy sector is undeniably a major contributor to the economic prosperity of the state and it can be argued that growth in the energy sector has tempered the economic contraction of the state's economy in the recent 2008 recession. This research study has showed that Texas's transportation system plays a very important role in serving and facilitating Texas's energy sector. The continued impact of the sector on Texas's highway infrastructure and the transportation system's continued ability to serve the industry is, however, in question at current funding levels and given how funding is allocated to transportation. Adequate funding sources to maintain the current road infrastructure is required to ensure that Texas's transportation system will continue to facilitate and serve the energy sector in the future.

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Appendix A1: GPS Coordinates of Pavement Sections

Control-Section-Job Number	County	Highway	Latitude	Longitude	Elevation (ft)
Wind Energy					
0002-11-053	CULBERSON	IH 10	31.04	-104.89	4281 ft
0003-06-083	REEVES	IH 20	31.23	-103.89	3192 ft
0003-07-047	REEVES	IH 20	31.39	-103.62	2710 ft
0004-04-079	WARD	IH 20	31.52	-103.15	2608 ft
0004-07-111	ECTOR	IH 20	31.81	-102.43	2936 ft
0005-06-107	HOWARD	IH 20	32.29	-101.34	2425 ft
0007-06-073	EASTLAND	IH 20	32.47	-98.63	1394 ft
0028-14-099	ORANGE	IH 10	30.12	-93.75	10 ft
0090-02-050	OLDHAM	IH 40	35.19	-102.97	3862 ft
0090-03-054	OLDHAM	IH 40	35.26	-102.76	4213 ft
0090-04-062	OLDHAM	IH 40	35.24	-102.40	4006 ft
0141-01-045	CROCKETT	IH 10	30.70	-101.12	2500 ft
0141-09-067	KIMBLE	IH 10	30.52	-99.80	1729 ft
0166-01-045	NAVARRO	IH 45	31.90	-96.38	400 ft
0271-02-052	AUSTIN	IH 10	29.76	-96.19	197 ft
0271-04-081	WALLER	IH 10	29.78	-95.95	164 ft
0275-01-144	POTTER	IH 40	35.19	-101.84	3668 ft
0275-05-040	GRAY	IH 40	35.19	-101.07	3261 ft
0495-02-057	VAN ZANDT	IH 20	32.59	-95.88	509 ft
0495-07-065	GREGG	IH 20	32.43	-94.94	371 ft
0500-01-130	GALVESTON	IH 45	29.33	-94.94	3 ft
0500-03-518	HARRIS	IH 45	29.59	-95.19	33 ft
0675-03-063	LEON	IH 45	31.41	-96.04	354 ft
0675-08-090	MONTGOMERY	IH 45	30.28	-95.46	161 ft
0675-08-094	MONTGOMERY	IH 45	30.51	-95.49	299 ft
2121-01-067	EL PASO	IH 10	31.84	-106.57	3799 ft
2374-03-068	DALLAS	IH 20	32.64	-96.82	627 ft
2374-03-070	DALLAS	IH 20	32.64	-96.83	627 ft
0263-04-027	FISHER	SH 70	32.85	-100.45	1975 ft
0328-04-039	ATASCOSA	SH 97	28.93	-98.52	413 ft
0362-04-032	PALO PINTO	SH 16	33.00	-98.40	1165 ft
0402-05-002	HARRISON	LP 390	32.52	-94.39	420 ft
0598-01-074	HARRIS	SH 288	29.60	-95.39	56 ft
0598-01-075	HARRIS	SH 288	29.67	-95.38	49 ft
2552-01-047	EL PASO	LP 375	31.90	-106.44	4052 ft
2642-01-038	GREGG	LP 281	32.51	-94.79	348 ft
2839-02-013	PALO PINTO	SH 337	32.94	-98.26	971 ft

Control-Section-Job Number	**County**	**Highway**	**Latitude**	**Longitude**	**Elevation (ft)**
0013-05-053	MONTAGUE	US 81	33.53	-97.83	1066 ft
0013-10-073	TARRANT	BU 287P	32.88	-97.38	774 ft
0028-03-097	LIBERTY	US 90	30.04	-94.90	75 ft
0032-04-023	COTTLE	US 83	33.93	-100.33	1860 ft
0043-01-062	CHILDRESS	US 287	34.42	-100.19	1821 ft
0043-04-072	HARDEMAN	US 287	34.29	-99.72	1581 ft
0043-05-101	WILBARGER	US 287	34.25	-99.48	1430 ft
0043-08-071	WICHITA	US 287	33.99	-98.82	1063 ft
0077-06-079	TOM GREEN	US 67	31.43	-100.51	1926 ft
0132-03-029	KING	US 82	33.63	-100.35	1749 ft
0134-08-039	WISE	US 380	33.24	-97.51	906 ft
0134-09-060	DENTON	US 380	33.25	-97.39	774 ft
0146-06-020	FOARD	US 70	33.98	-99.61	1401 ft
0206-01-043	ANDERSON	US 79	31.88	-95.46	328 ft
0224-02-040	CLAY	US 287	33.63	-98.01	1050 ft
0945-04-025	CASS	FM 249	33.11	-94.18	249 ft
0030-09-040	WHEELER	US 83	35.23	-100.25	2303 ft
0042-04-037	ARMSTRONG	US 287	35.07	-101.25	3297 ft
0042-05-029	ARMSTRONG	US 287	35.03	-101.19	3156 ft
0066-04-067	MOORE	US 287	35.87	-101.97	3658 ft
Barnett Shale Natural Gas					
1333-04-004	YOUNG	FM 1191	33.00	-98.45	1106 ft
1356-01-023	COOKE	FM 1201	33.69	-97.19	850 ft
0718-01-050	DENTON	FM 156	33.10	-97.29	607 ft
0718-01-058	DENTON	FM 156	32.99	-97.33	722 ft
0747-06-011	ELLIS	FM 157	32.32	-97.02	574 ft
1603-03-028	TARRANT	FM 1709	32.93	-97.25	692 ft
0774-04-012	ERATH	FM 219	32.10	-98.35	1529 ft
0134-03-028	YOUNG	US 380	33.11	-98.59	1043 ft
0128-02-013	BROWN	FM 3064	31.68	-98.98	1365 ft
0782-01-031	COOKE	FM 3164	33.61	-97.02	758 ft
0823-02-017	COOKE	FM 373	33.64	-97.38	1017 ft
0385-01-018	PALO PINTO	FM 4	32.57	-98.20	961 ft
0816-03-015	DENTON	FM 455	33.39	-96.95	692 ft
0008-09-030	PARKER	FM 5	32.68	-97.61	781 ft
0313-07-015	PARKER	FM 51	32.70	-97.77	1138 ft
0596-02-033	ELLIS	FM 66	32.31	-97.01	528 ft
1048-02-028	ELLIS	FM 660	32.53	-96.66	443 ft
1179-02-030	PARKER	FM 920	33.00	-97.86	1201 ft
1048-01-020	ELLIS	FM 983	32.49	-96.75	509 ft
0007-06-073	EASTLAND	IH 20	32.47	-98.63	1394 ft

Control-Section-Job Number	County	Highway	Latitude	Longitude	Elevation (ft)
2374-03-068	DALLAS	IH 20	32.64	-96.82	627 ft
2374-03-070	DALLAS	IH 20	32.64	-96.83	627 ft
0014-07-092	HILL	IH 35	31.84	-97.09	604 ft
0014-24-049	HILL	IH 35	31.96	-97.12	574 ft
0048-08-040	ELLIS	IH 35E	32.22	-96.89	528 ft
0048-09-028	HILL	IH 35E	32.06	-97.09	676 ft
0196-02-101	DENTON	IH 35E	33.00	-96.95	449 ft
0014-16-257	TARRANT	IH 35W	32.89	-97.32	669 ft
0092-02-110	DALLAS	IH 45	32.56	-96.66	390 ft
0092-04-067	ELLIS	IH 45	32.33	-96.62	522 ft
0008-14-105	TARRANT	IH 820	32.84	-97.31	627 ft
0353-04-090	DALLAS	SH 114	32.92	-97.02	541 ft
0444-01-029	YOUNG	SH 114	33.37	-98.75	1181 ft
0444-01-030	YOUNG	SH 114	33.26	-98.50	1293 ft
0362-04-032	PALO PINTO	SH 16	33.00	-98.40	1165 ft
0134-03-028	YOUNG	US 380	33.11	-98.59	1043 ft
0094-03-093	DALLAS	SH 183	32.84	-97.03	512 ft
0171-05-085	TARRANT	SH 199	32.76	-97.34	518 ft
0091-01-039	GRAYSON	SH 289	33.46	-96.74	728 ft
0091-01-041	GRAYSON	SH 289	33.52	-96.71	850 ft
2839-02-013	PALO PINTO	SH 337	32.94	-98.26	971 ft
0173-01-043	ELLIS	SH 34	32.33	-96.63	535 ft
0048-01-057	DALLAS	SH 342	32.58	-96.76	469 ft
0182-01-012	EASTLAND	SH 36	32.10	-98.96	1631 ft
0239-05-027	MONTAGUE	SH 59	33.53	-97.89	955 ft
0197-02-097	DALLAS	US 175	32.72	-96.69	443 ft
0008-02-067	PARKER	US 180	32.80	-97.99	889 ft
0011-05-042	SHACKELFORD	US 180	32.72	-99.30	1401 ft
0249-08-039	PALO PINTO	US 281	32.83	-98.11	948 ft
0251-01-050	HAMILTON	US 281	31.98	-98.03	1007 ft
0172-05-104	ELLIS	US 287	32.38	-96.81	551 ft
0224-02-040	CLAY	US 287	33.63	-98.01	1050 ft
0013-10-073	TARRANT	BU 287P	32.88	-97.38	774 ft
0134-03-028	YOUNG	US 380	33.11	-98.59	1043 ft
0134-08-039	WISE	US 380	33.24	-97.51	906 ft
0134-09-060	DENTON	US 380	33.25	-97.39	774 ft
0054-06-083	BROWN	US 67	31.73	-98.98	1332 ft
0054-06-087	BROWN	US 67	31.74	-98.96	1385 ft
0261-02-064	DALLAS	US 67	32.59	-96.95	814 ft
0047-02-127	GRAYSON	US 69	33.74	-96.54	705 ft
0095-02-071	DALLAS	US 80	32.79	-96.60	499 ft

Control-Section-Job Number	County	Highway	Latitude	Longitude	Elevation (ft)
0013-05-053	MONTAGUE	US 81	33.53	-97.83	1066 ft
0045-01-052	COOKE	US 82	33.64	-97.13	787 ft
0156-06-046	BAYLOR	US 82	33.61	-99.25	1302 ft
0033-05-081	JONES	US 83	32.74	-99.90	1726 ft
0054-01-019	TAYLOR	US 84	32.22	-99.76	2008 ft
Permian Basin Crude Oil					
1344-01-011	LYNN	FM 1317	33.28	-101.91	3225 ft
1870-01-027	ECTOR	FM 2020	31.84	-102.51	2972 ft
2574-01-043	TOM GREEN	RM 584	31.44	-100.44	1837 ft
0141-01-045	CROCKETT	IH 10	30.70	-101.12	2500 ft
0141-09-067	KIMBLE	IH 10	30.52	-99.80	1729 ft
0002-11-053	CULBERSON	IH 10	31.04	-104.89	4281 ft
0003-06-083	REEVES	IH 20	31.23	-103.89	3192 ft
0003-07-047	REEVES	IH 20	31.39	-103.62	2710 ft
0004-04-079	WARD	IH 20	31.52	-103.15	2608 ft
0004-07-111	ECTOR	IH 20	31.81	-102.43	2936 ft
0005-06-107	HOWARD	IH 20	32.29	-101.34	2425 ft
0006-02-100	NOLAN	IH 20	32.43	-100.56	2388 ft
0140-16-006	CROCKETT	LP 466	30.71	-101.21	2349 ft
0439-04-017	HALE	SH 194	34.28	-101.91	3507 ft
2224-01-061	ECTOR	SH 302	31.82	-102.41	2910 ft
0263-04-027	FISHER	SH 70	32.85	-100.45	1975 ft
0227-07-034	TERRY	US 62	33.18	-102.27	3314 ft
0077-06-079	TOM GREEN	US 67	31.43	-100.51	1926 ft
0075-01-020	BREWSTER	US 67	30.59	-103.33	3576 ft
0020-08-039	PRESIDIO	US 67	30.28	-103.80	5115 ft
0131-06-049	DICKENS	US 82	33.68	-101.04	2976 ft
0132-03-029	KING	US 82	33.63	-100.35	1749 ft
0380-01-064	LUBBOCK	US 82	33.57	-101.92	3238 ft
0052-05-037	LAMB	US 84	33.94	-102.36	3579 ft
0053-01-106	LUBBOCK	US 84	33.52	-101.77	3146 ft
0068-04-031	DAWSON	US 87	32.75	-101.95	2986 ft

Appendix A2: Pavement Damage Estimates due to Wind, Natural Gas, and Crude Oil Energy Developments

Additional Damage Imposed due to the Movement of the Wind Turbine Components

Interstate Highway Sections

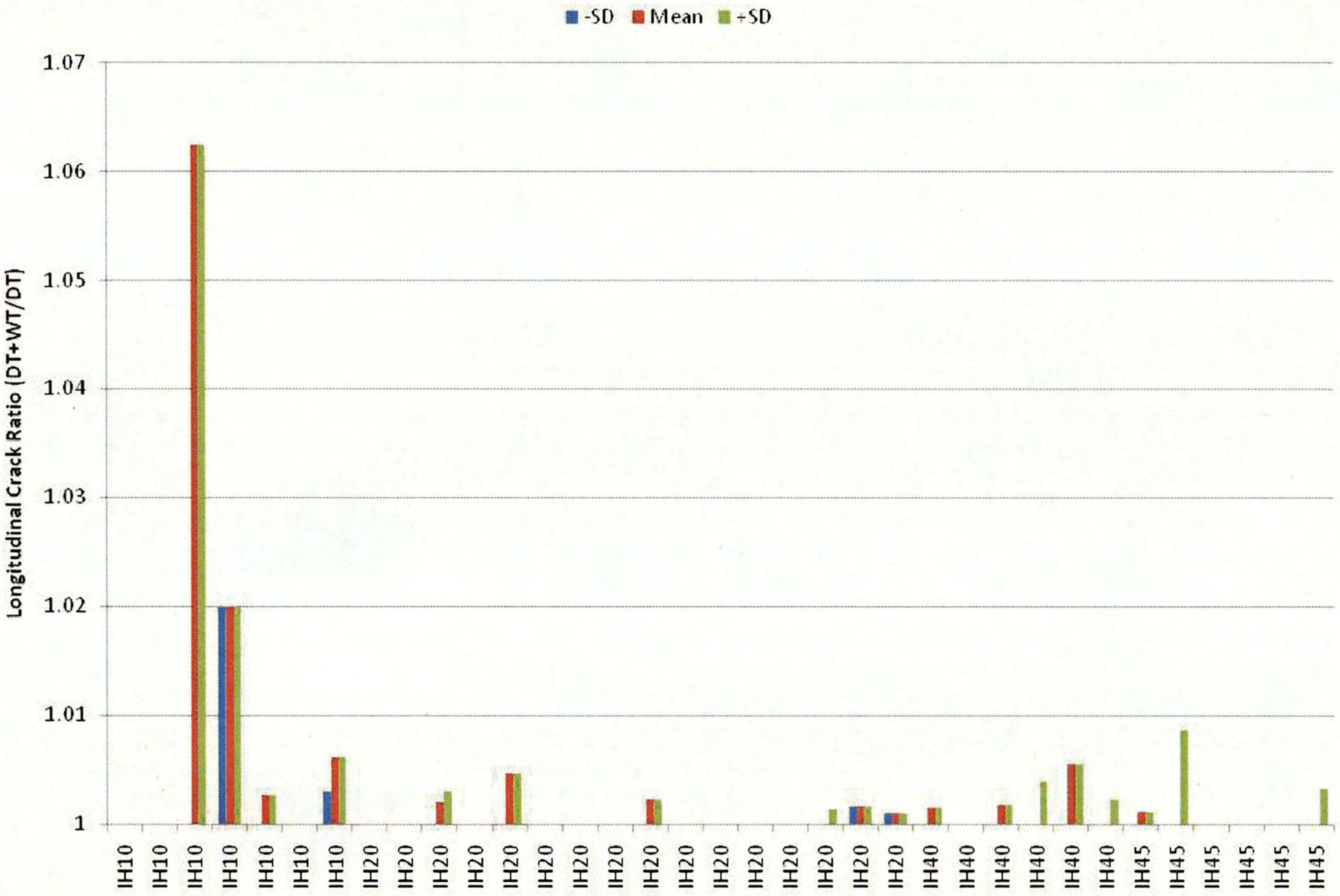


Figure A2.1: Ratio of Longitudinal Cracks on IH Sections at the End of a 20-Year Analysis Period

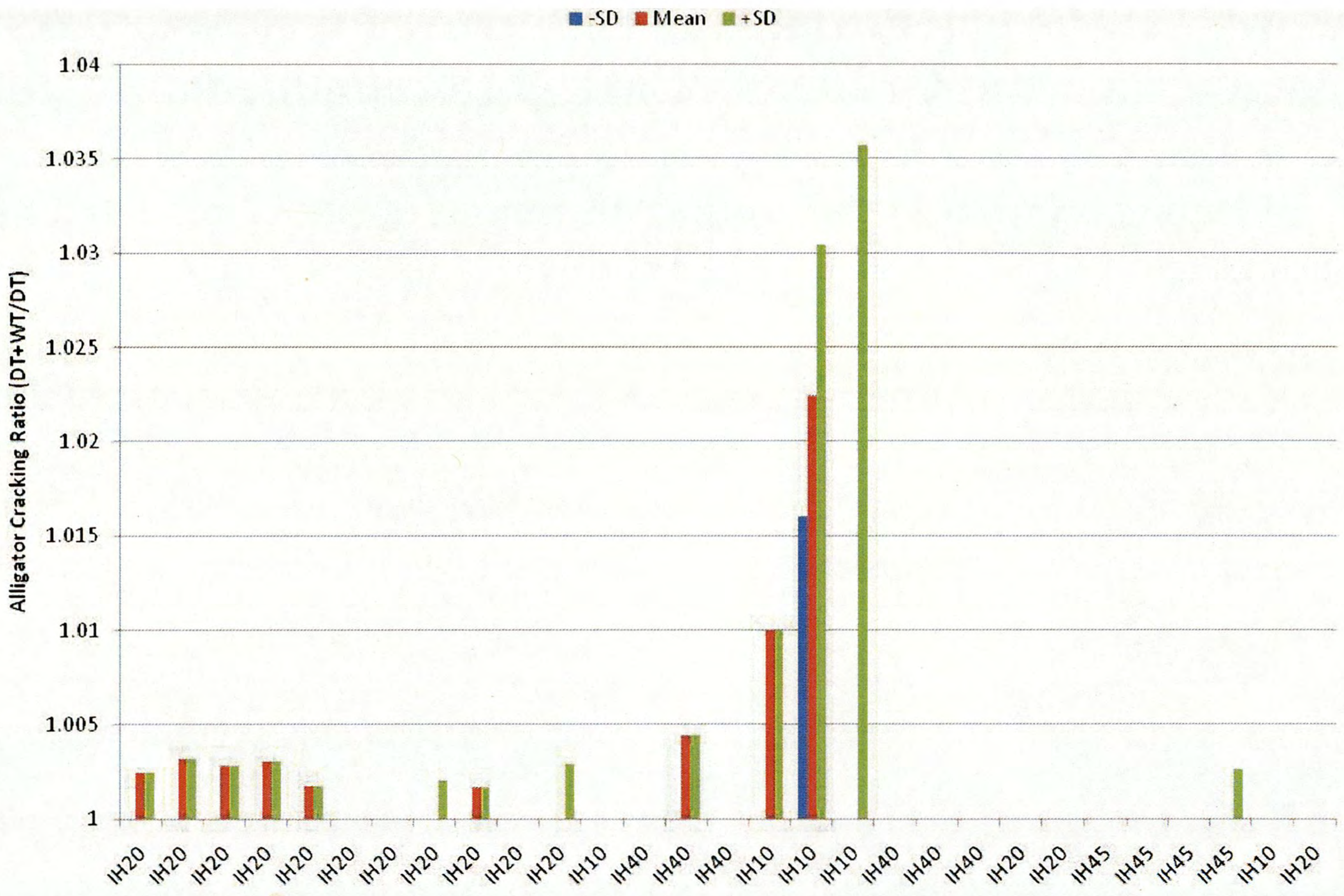


Figure A2.2: Ratio of Alligator Cracks on IH Sections at the End of a 20-Year Analysis Period

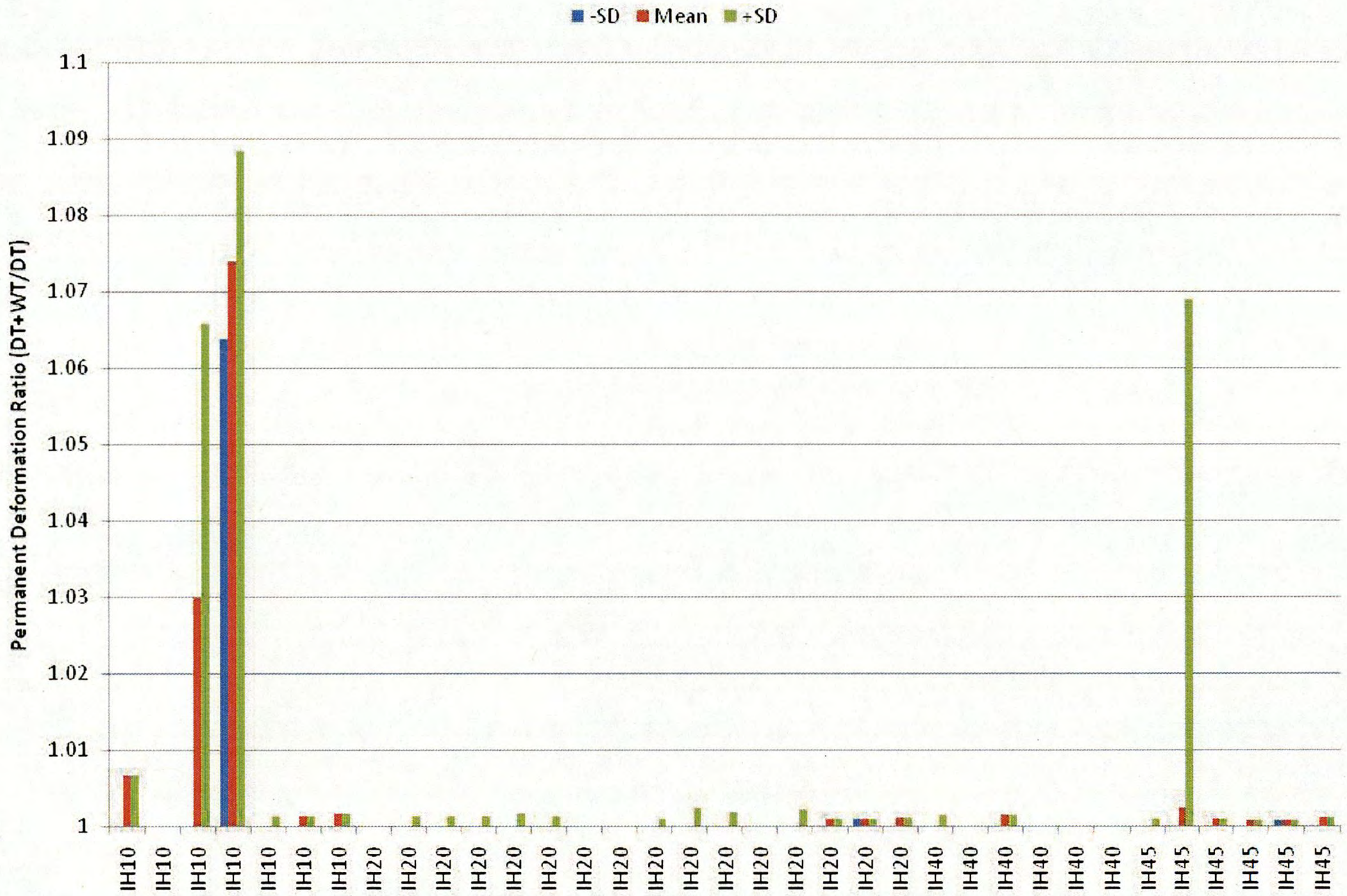


Figure A2.3: Ratio of Rut Depths on IH Sections at the End of a 20-Year Analysis Period

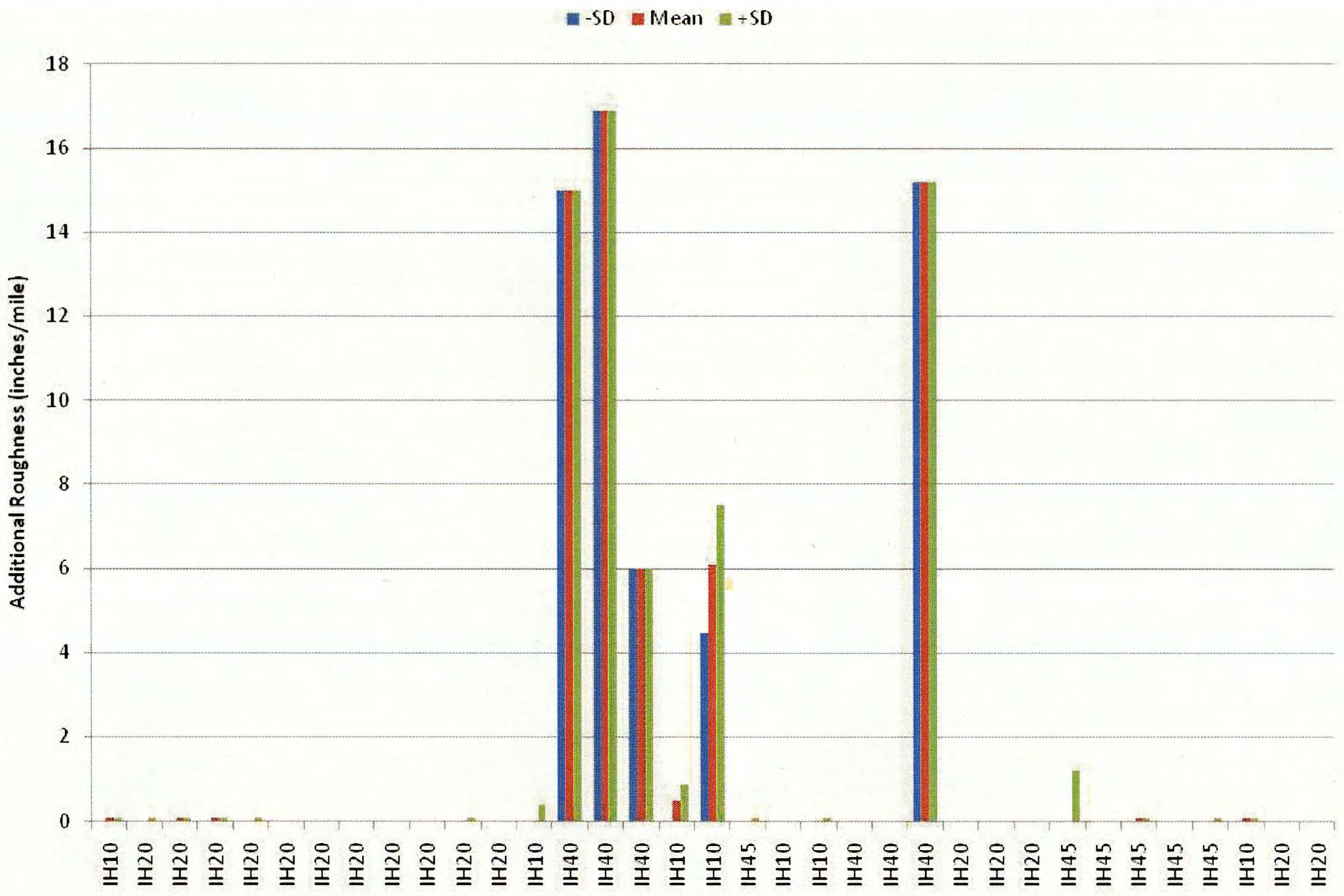


Figure A2.4: Ratio of the IRI on IH Sections at the End of a 20-Year Analysis Period

US Highway Sections

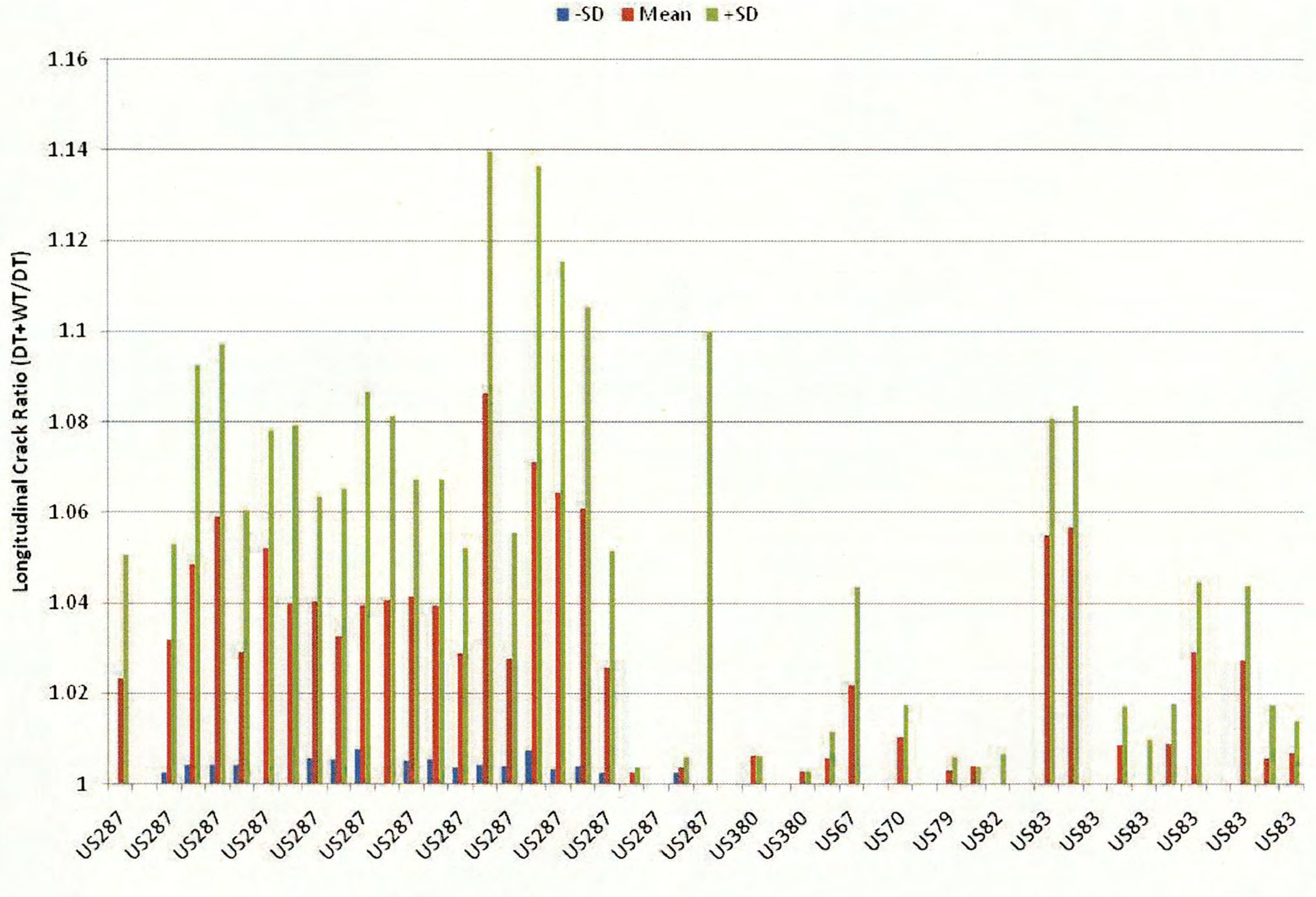


Figure A2.5: Ratio of Longitudinal Cracks on US Highway Sections at the End of a 20-Year Analysis Period

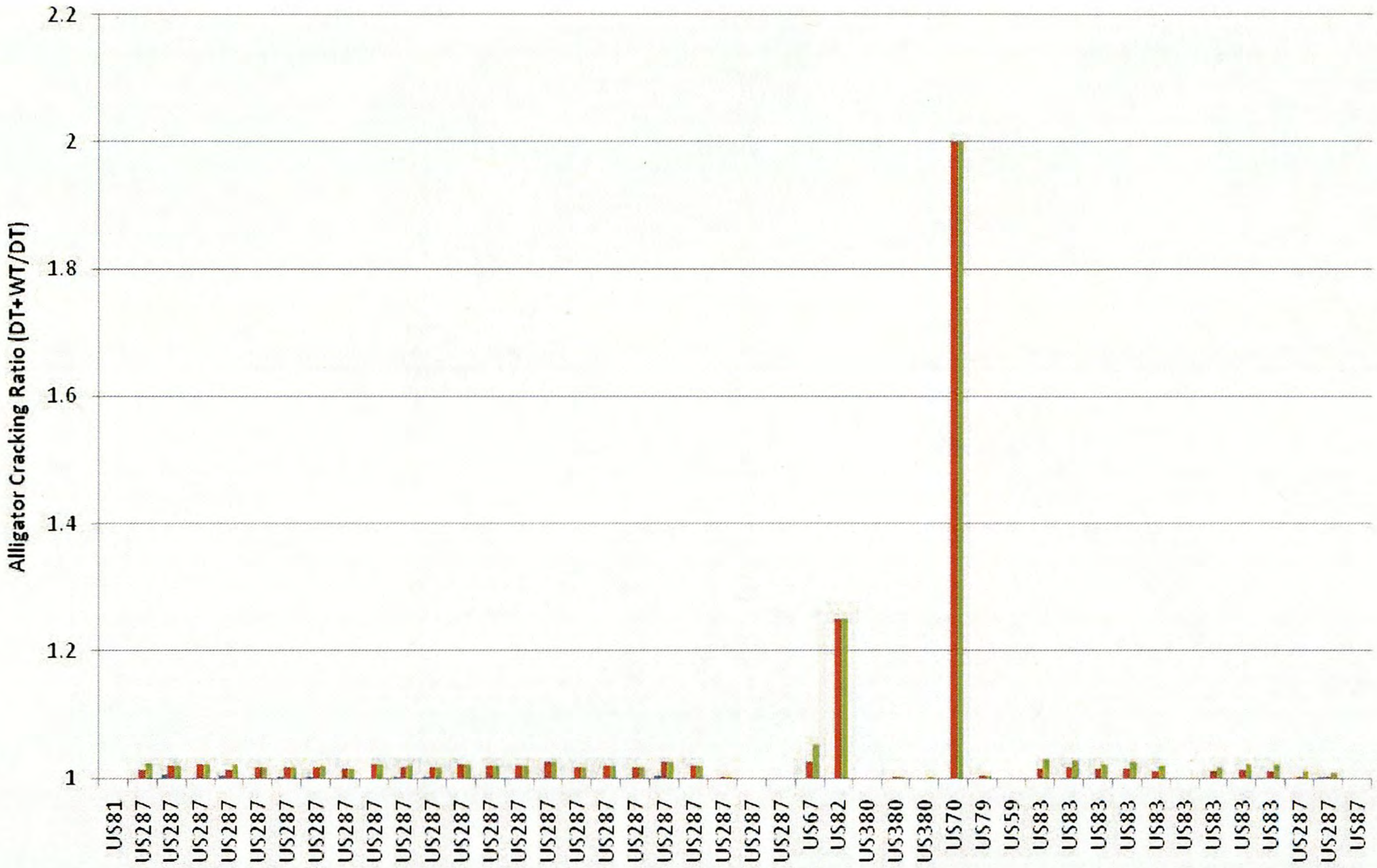


Figure A2.6: Ratio of Alligator Cracks on US Highway Sections at the End of a 20-Year Analysis Period

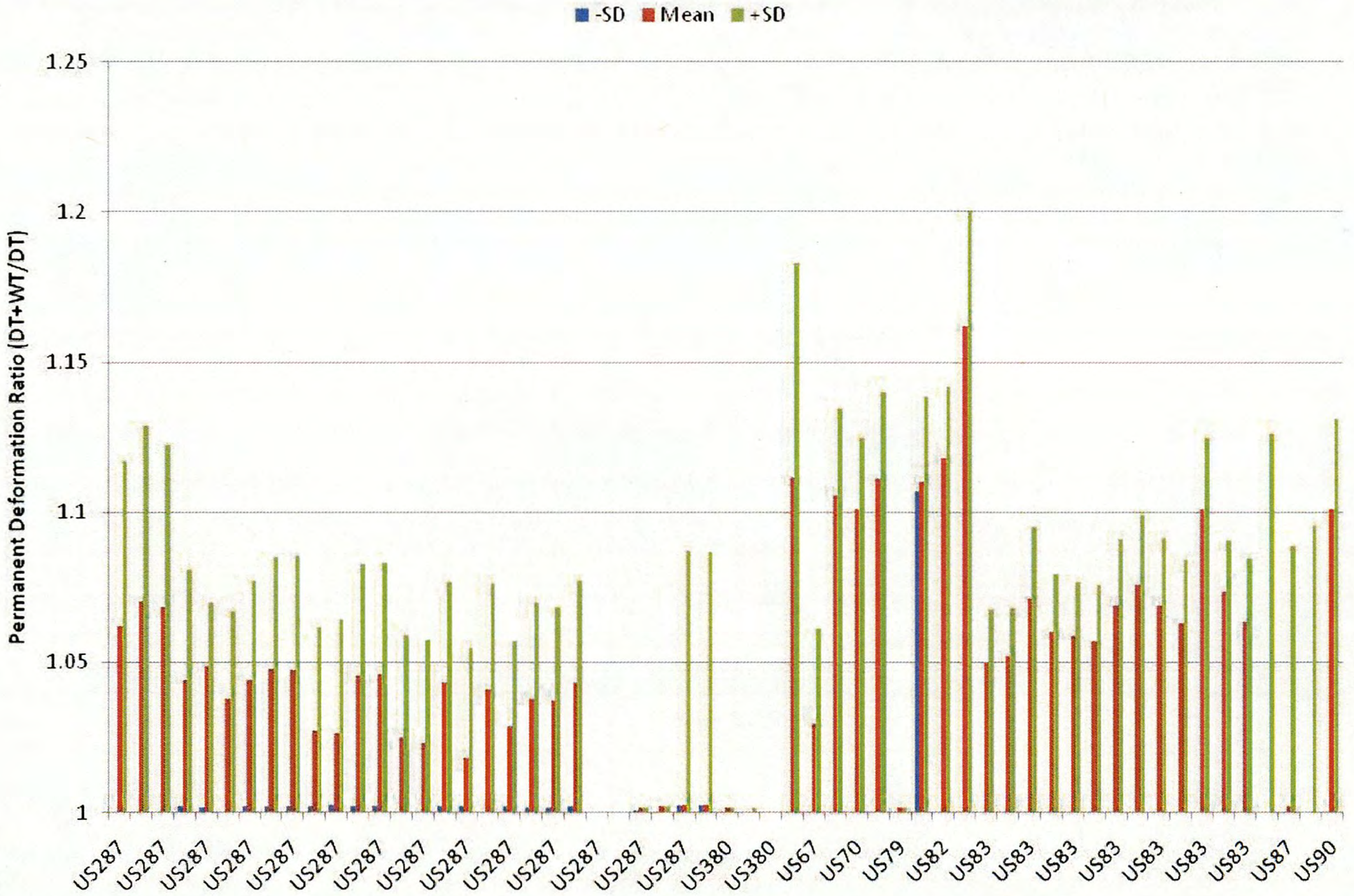


Figure A2.7: Ratio of Rut Depths on US Highway Sections at the End of a 20-Year Analysis Period

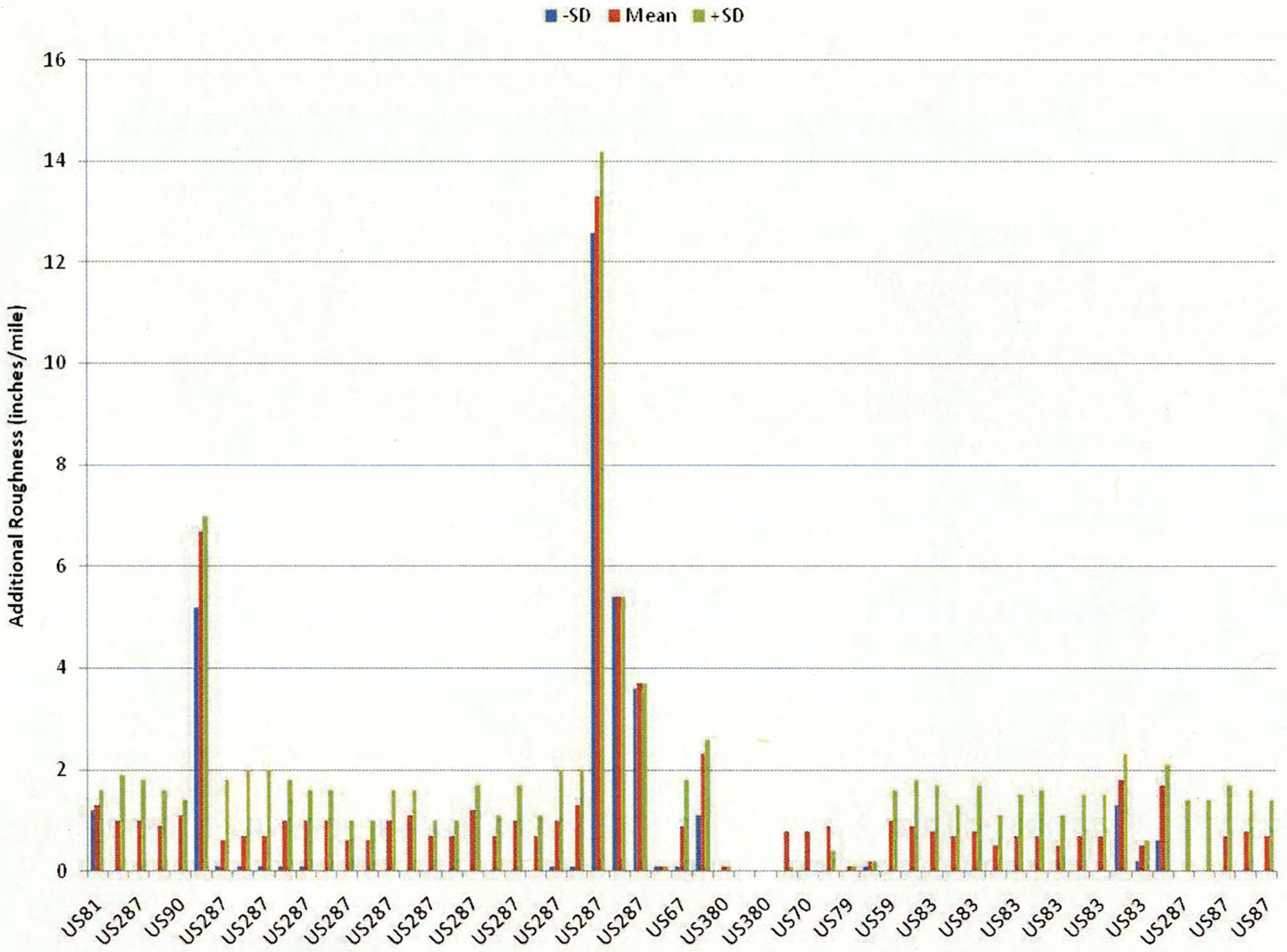


Figure A2.8: Ratio of the IRI on US Highway Sections at the End of a 20-Year Analysis Period

State Highway Sections

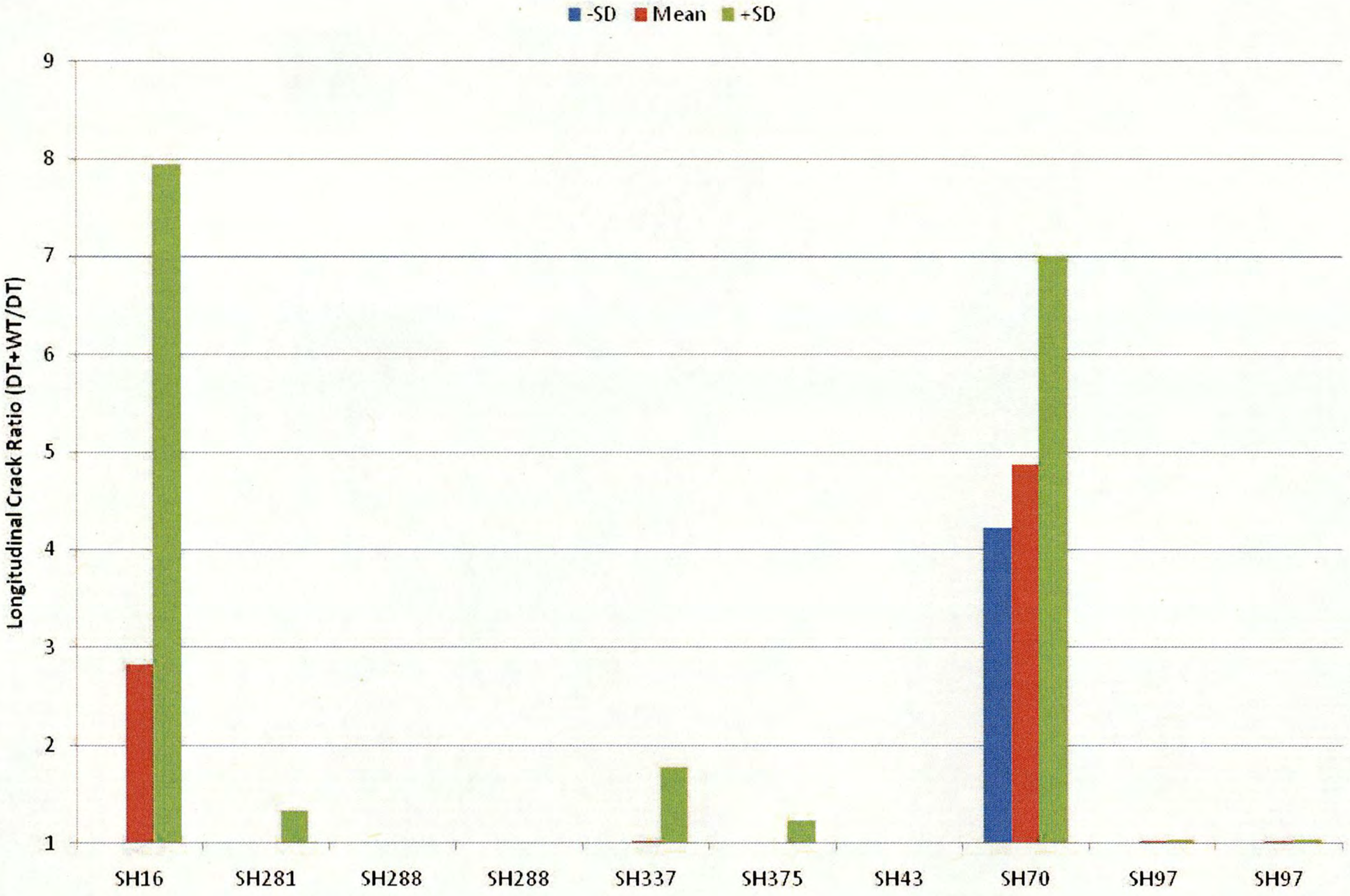


Figure A2.9: Ratio of Longitudinal Cracks on State Highway Sections at the End of a 20-Year Analysis Period

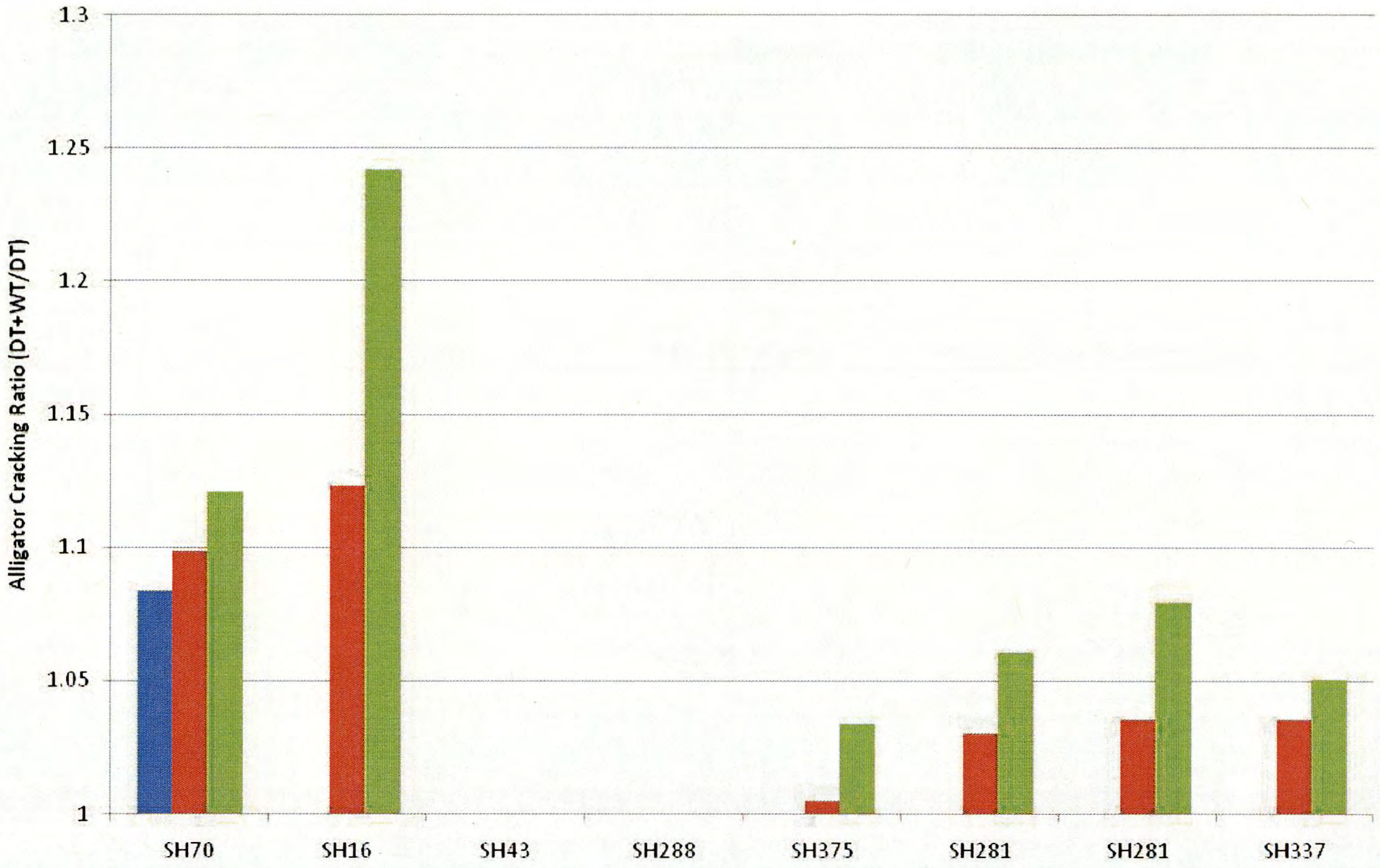


Figure A2.10: Ratio of Alligator Cracks on State Highway Sections at the End of a 20-Year Analysis Period

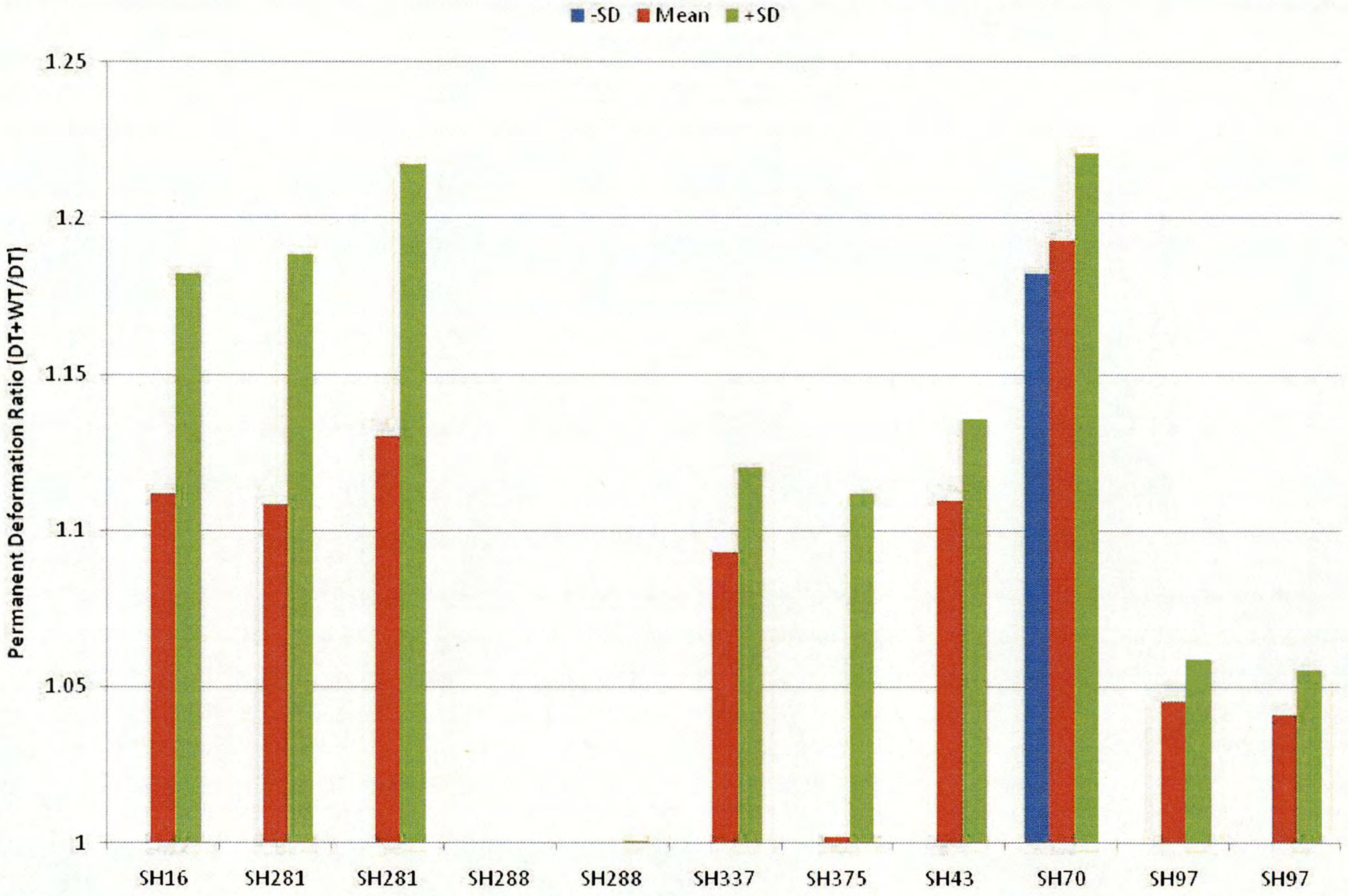


Figure A2.11: Ratio of Rut Depths on State Highway Sections at the End of a 20-Year Analysis Period

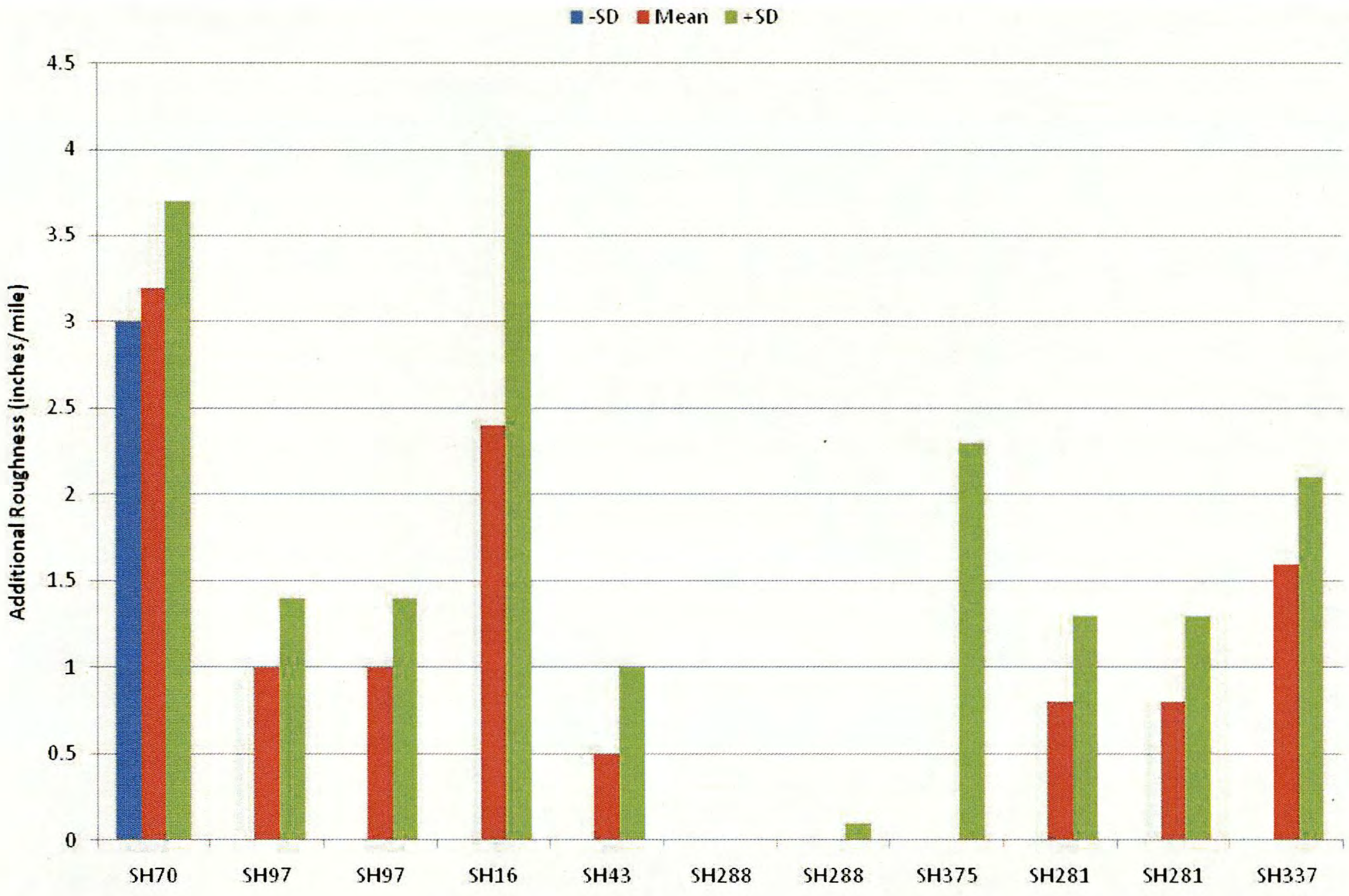


Figure A2.12: Ratio of the IRI on State Highway Sections at the End of a 20-Year Analysis Period

Additional Damage Imposed by the Natural Gas Development in the Barnett Shale Region

Interstate Highway Sections

Due to Rig Traffic

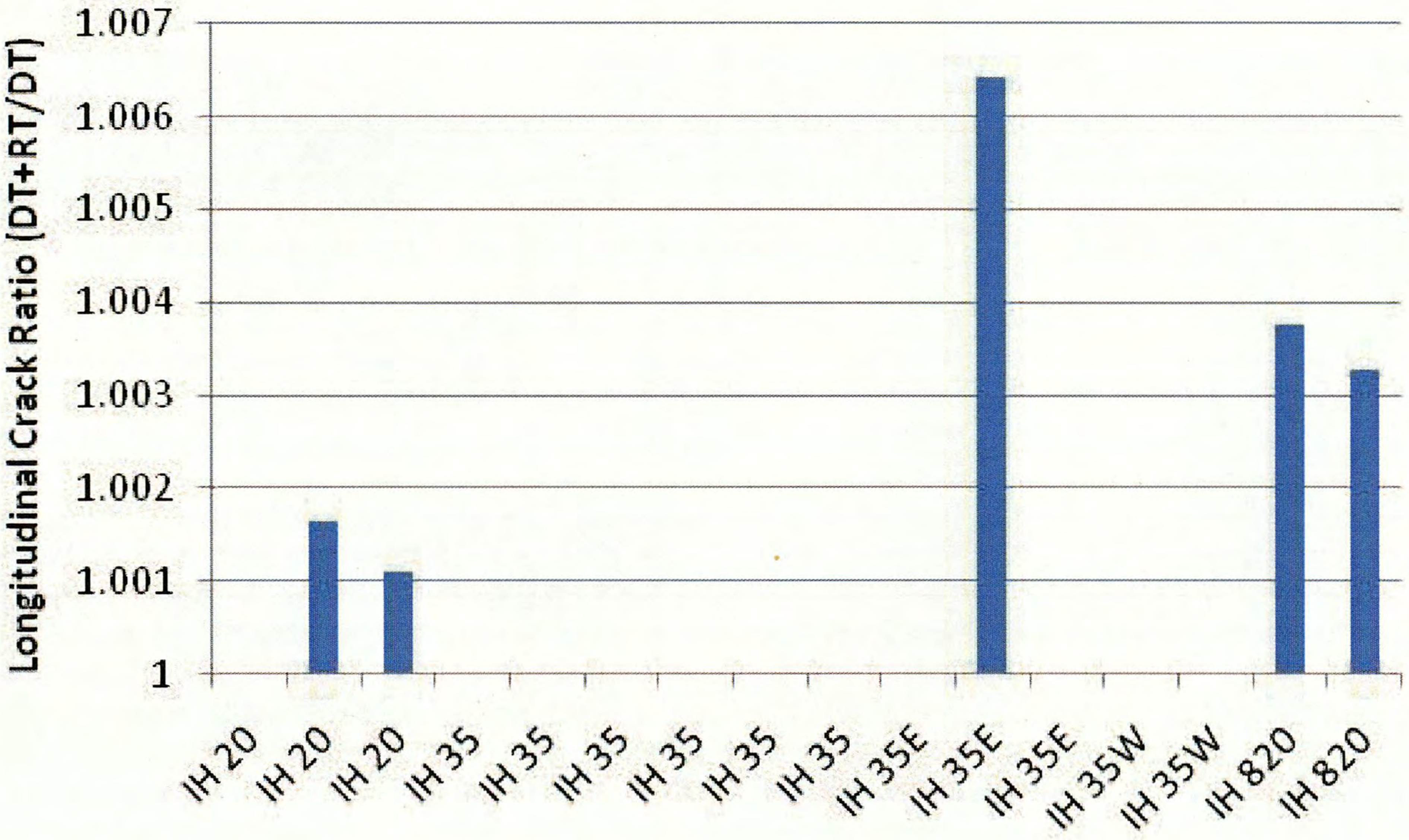


Figure A2.13: Ratio of Longitudinal Cracks on IH Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

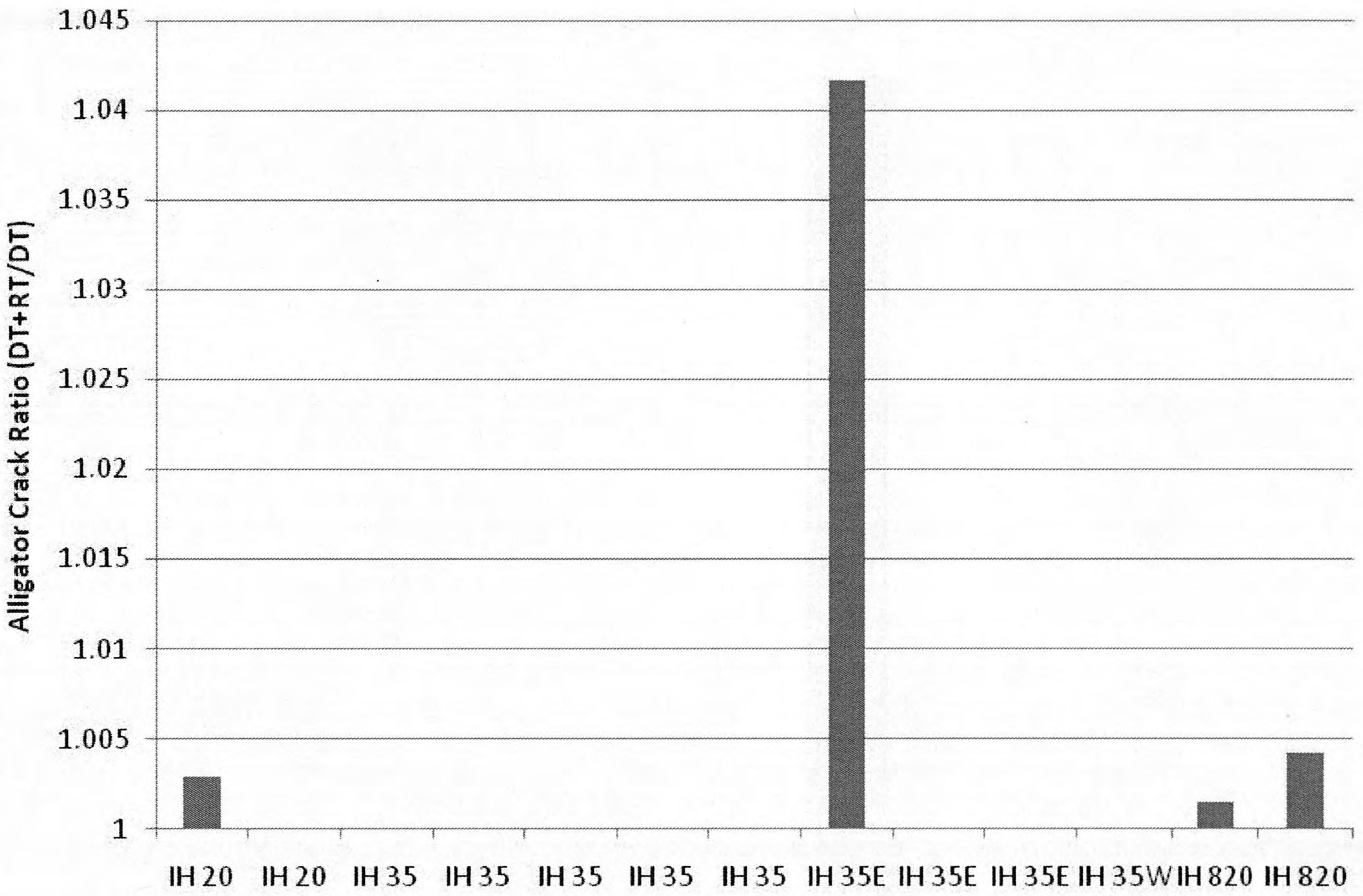


Figure A2.14: Ratio of Alligator Cracks on IH Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

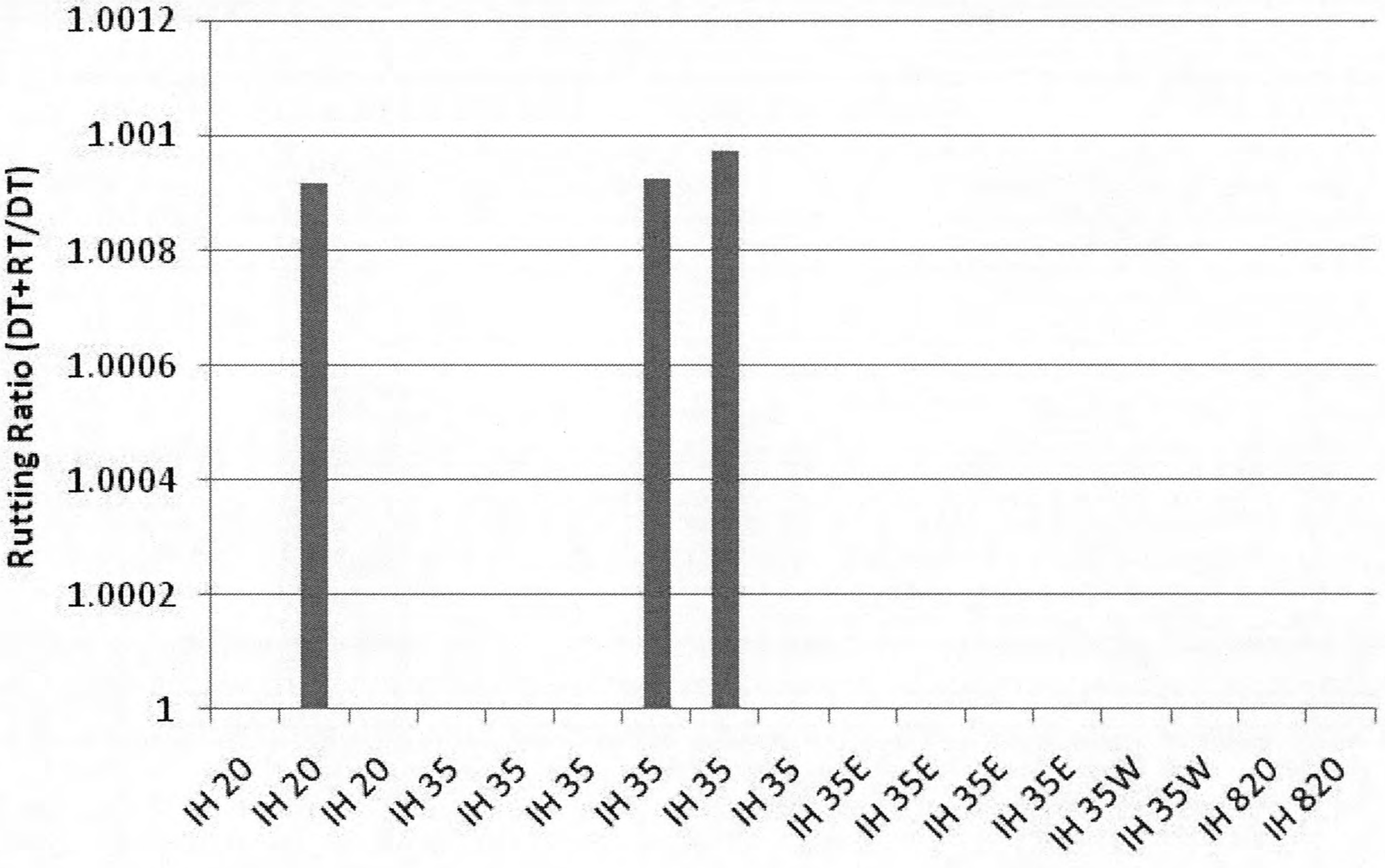


Figure A2.15: Ratio of Rut Depths on IH Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

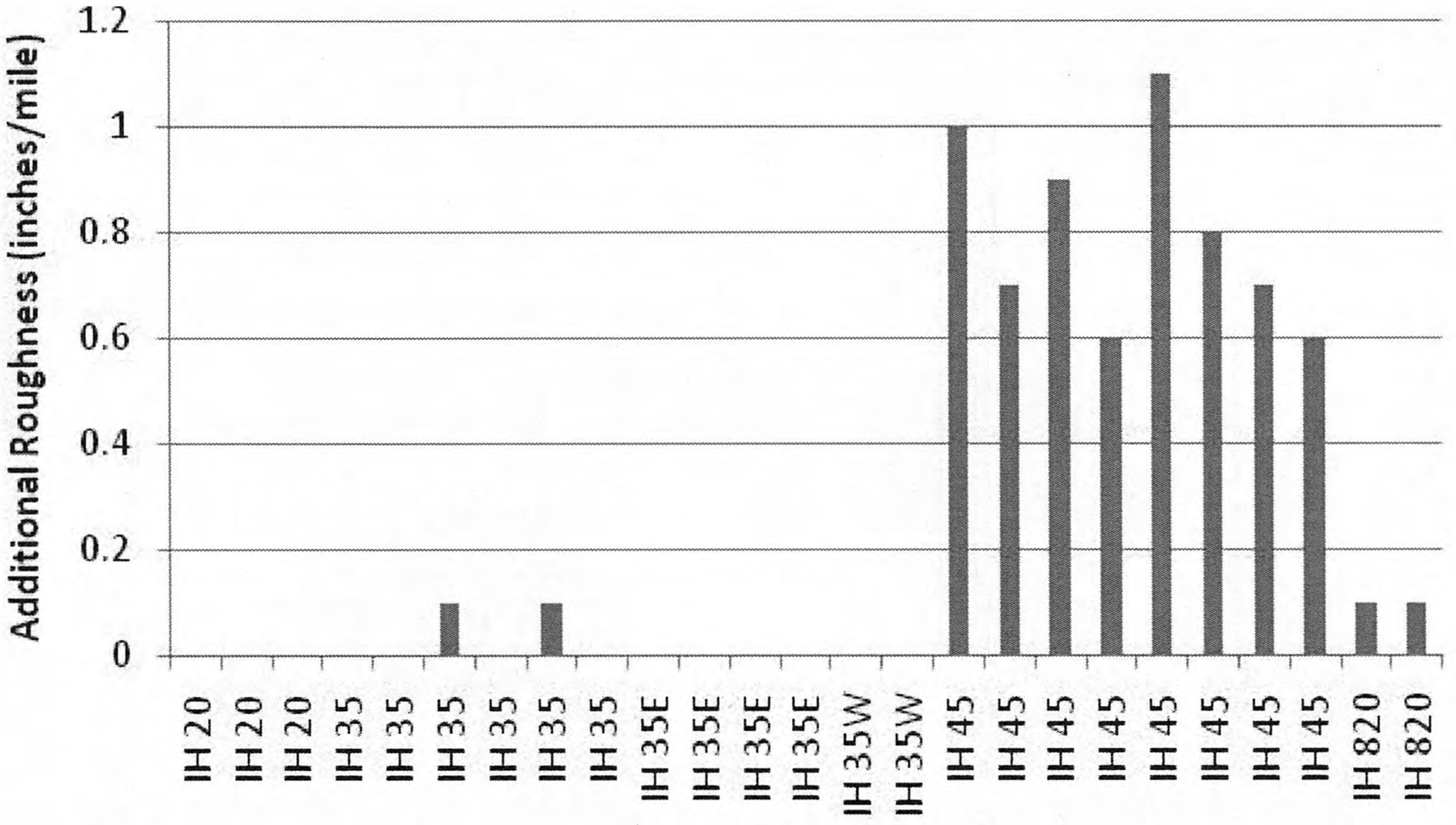


Figure A2.16: Increase in IRI Values for IH Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Due to Saltwater Traffic

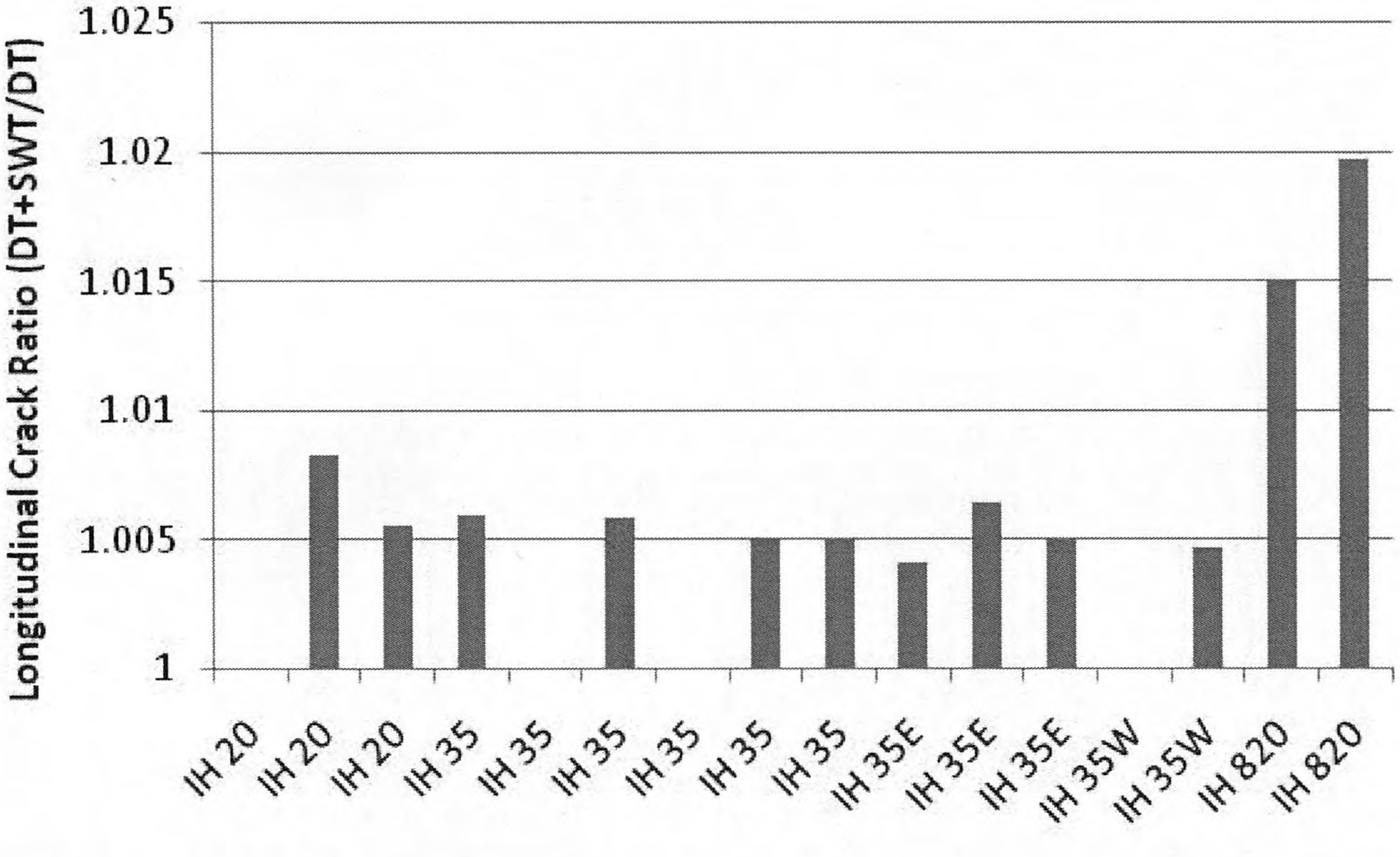


Figure A2.17: Ratio of Longitudinal Cracks on IH Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

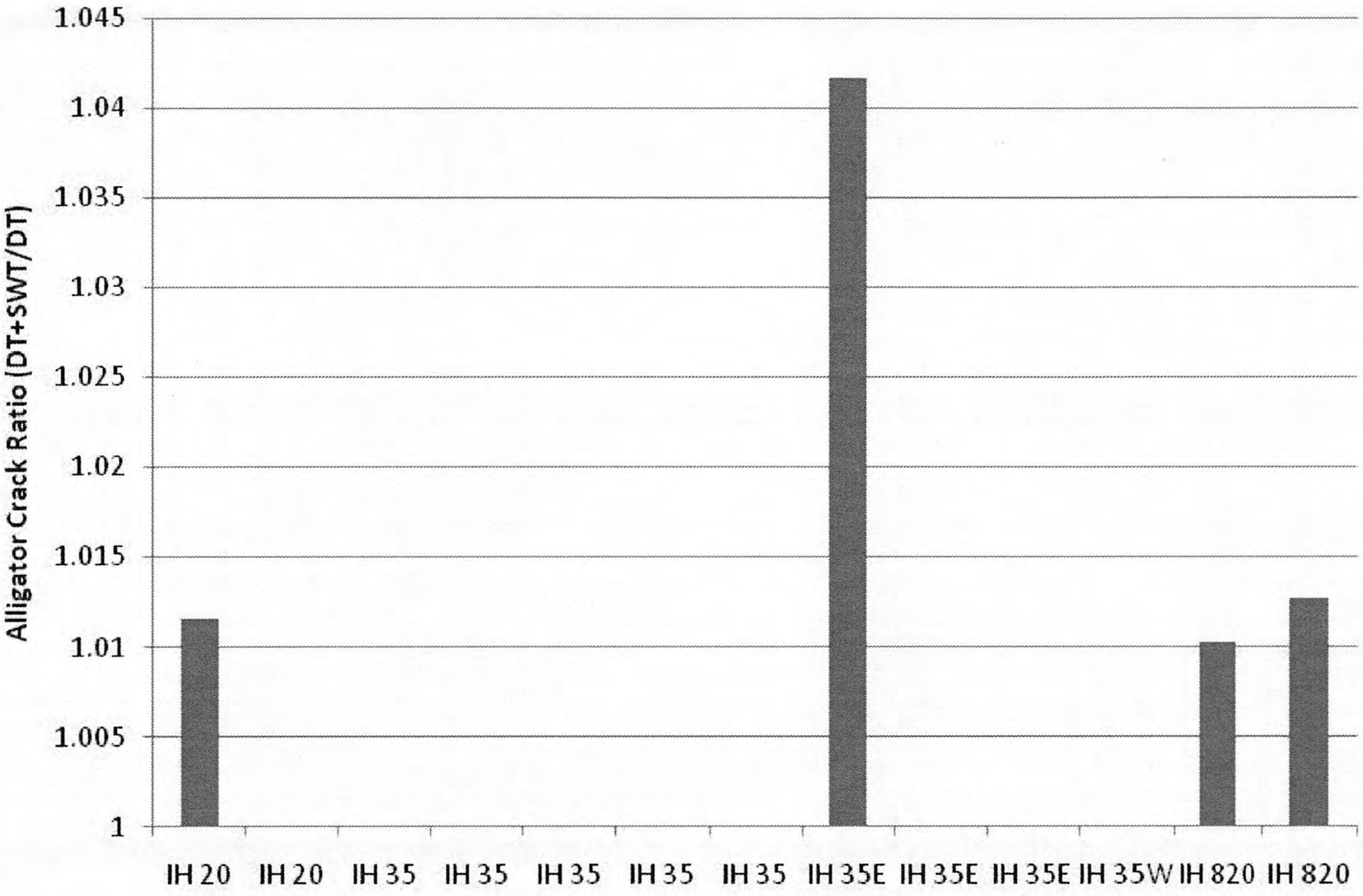


Figure A2.18: Ratio of Alligator Cracks on IH Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

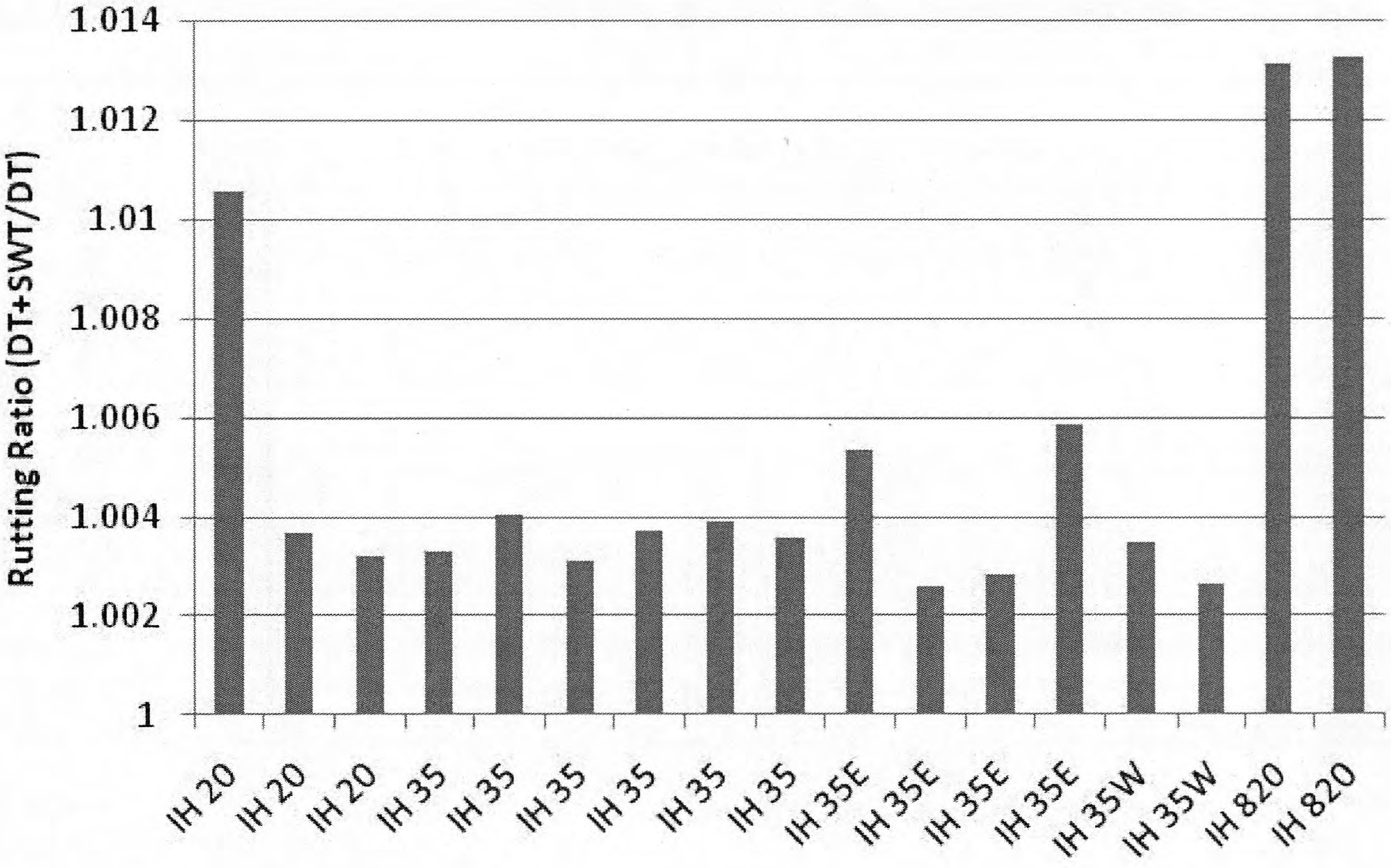


Figure A2.19: Ratio of Rut Depths on IH Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

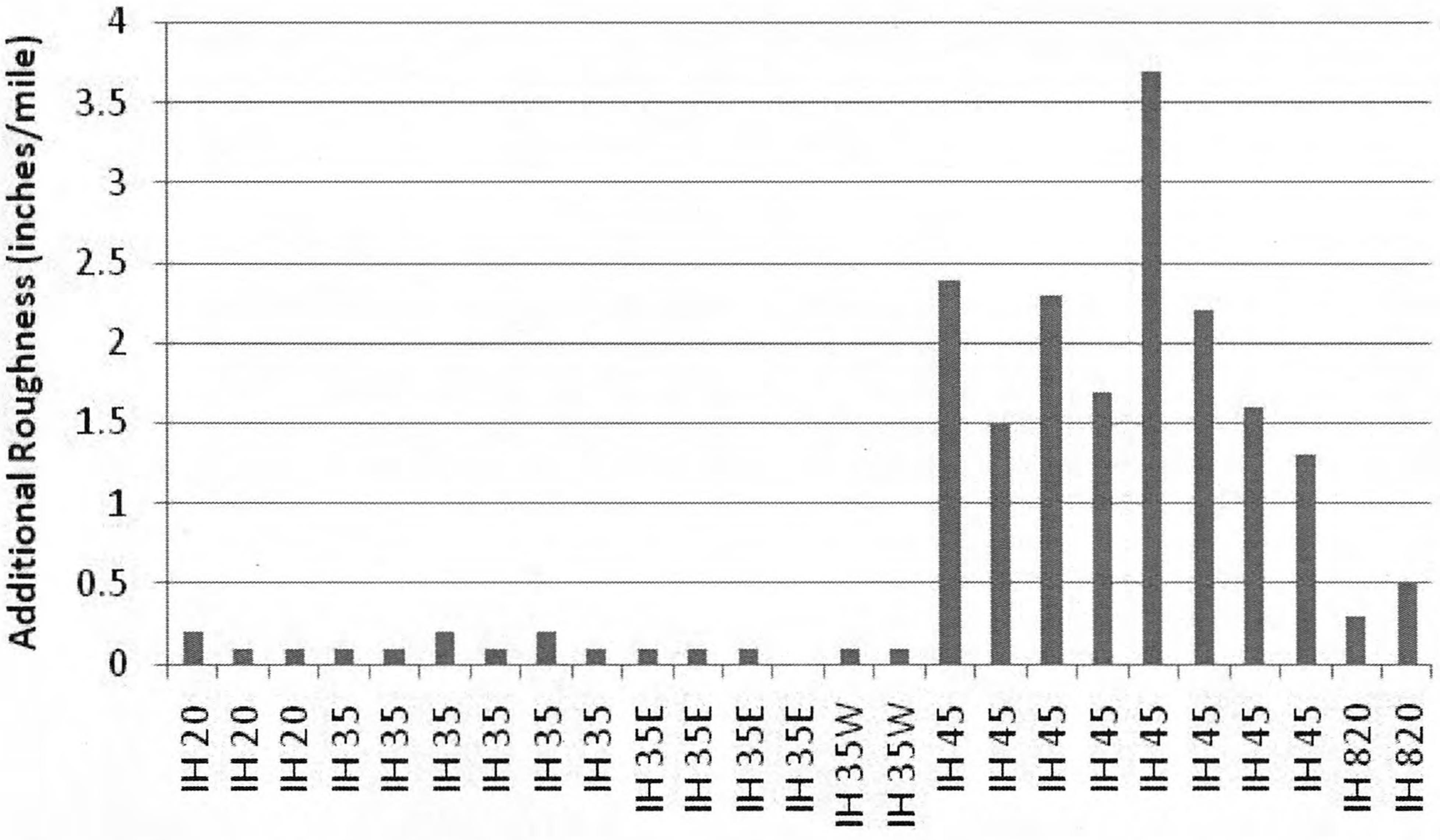


Figure A2.20: Increase in IRI Values for IH Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Due to Construction Traffic

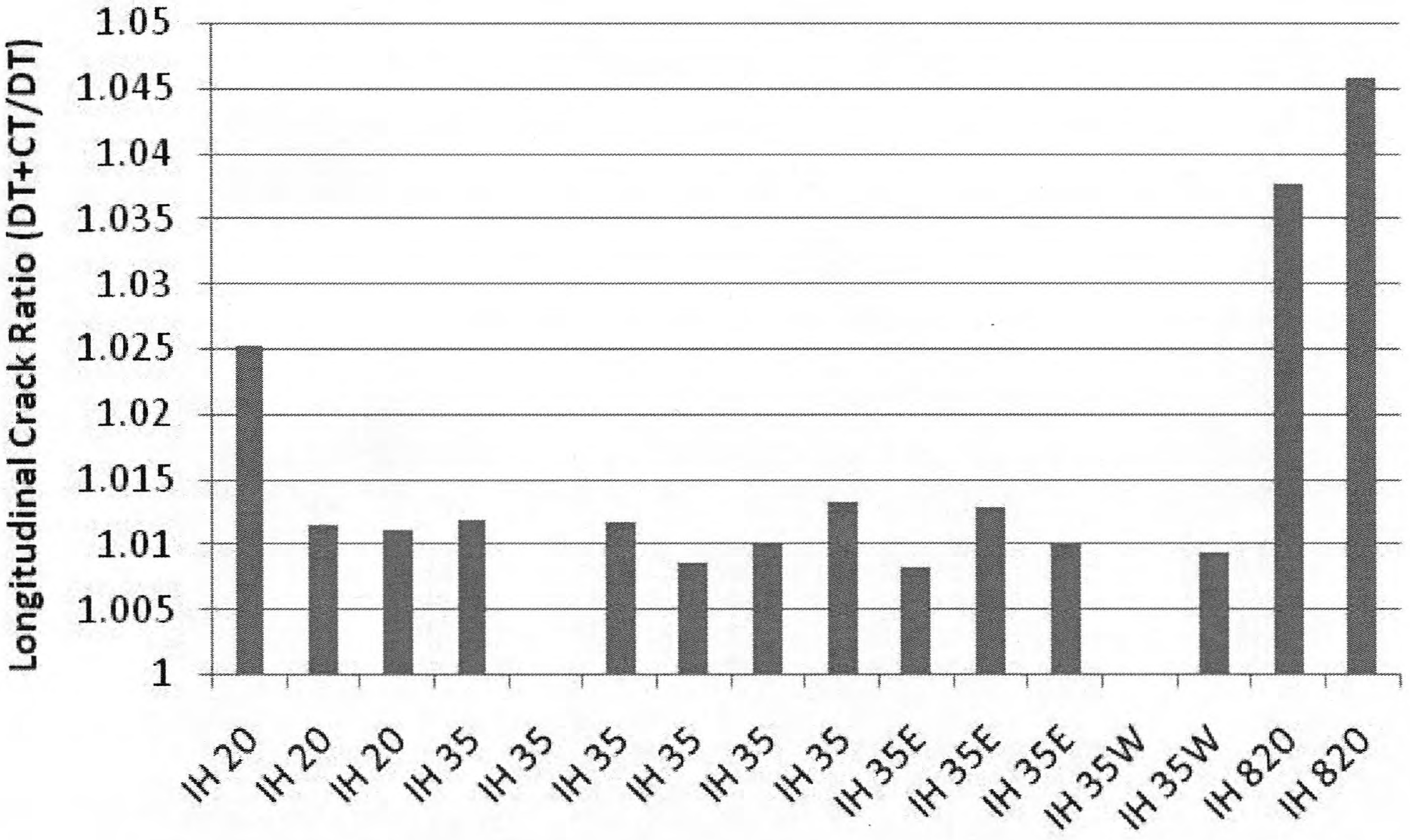


Figure A2.21: Ratio of Longitudinal Cracks on IH Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

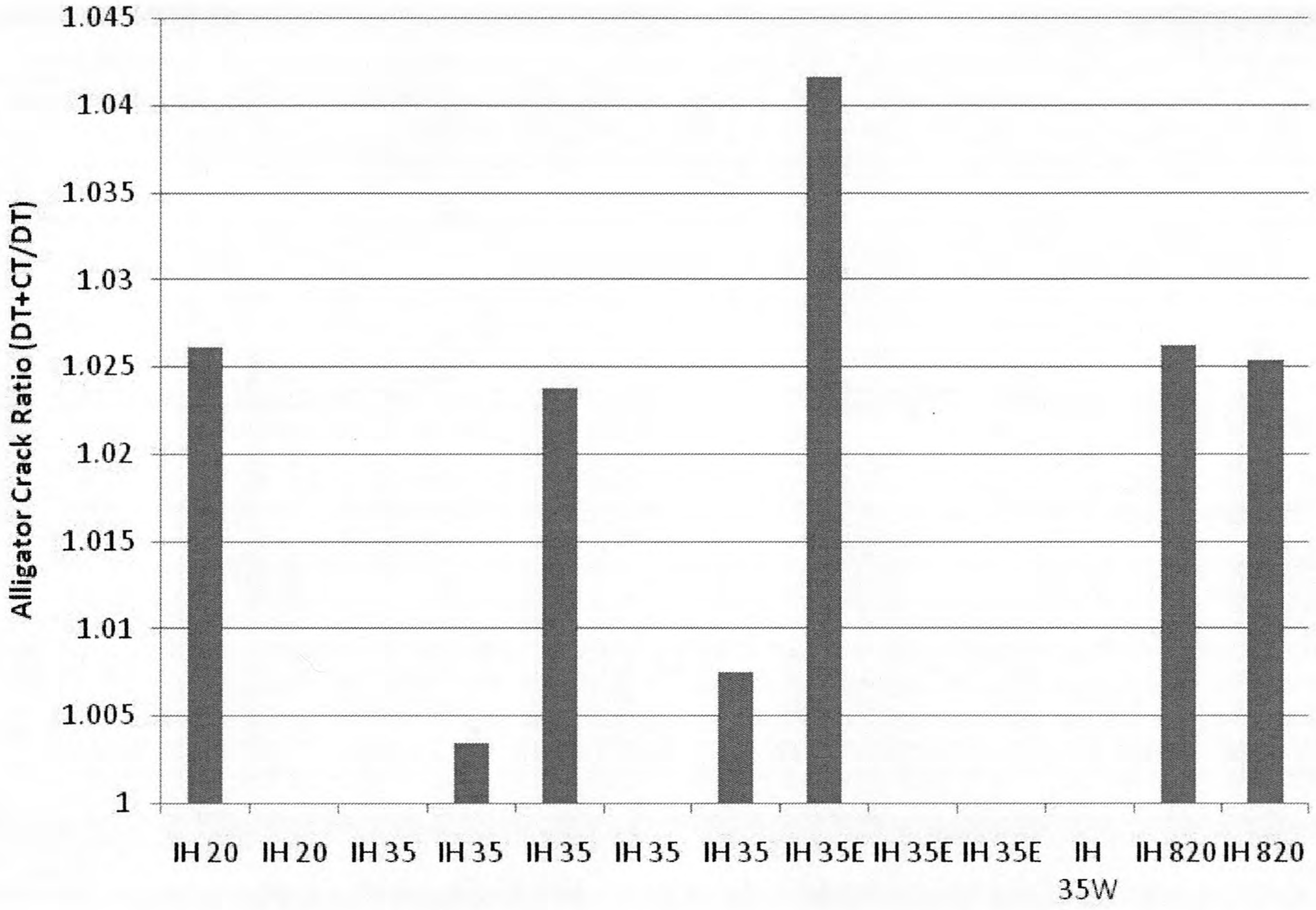


Figure A2.22: Ratio of Alligator Cracks on IH Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

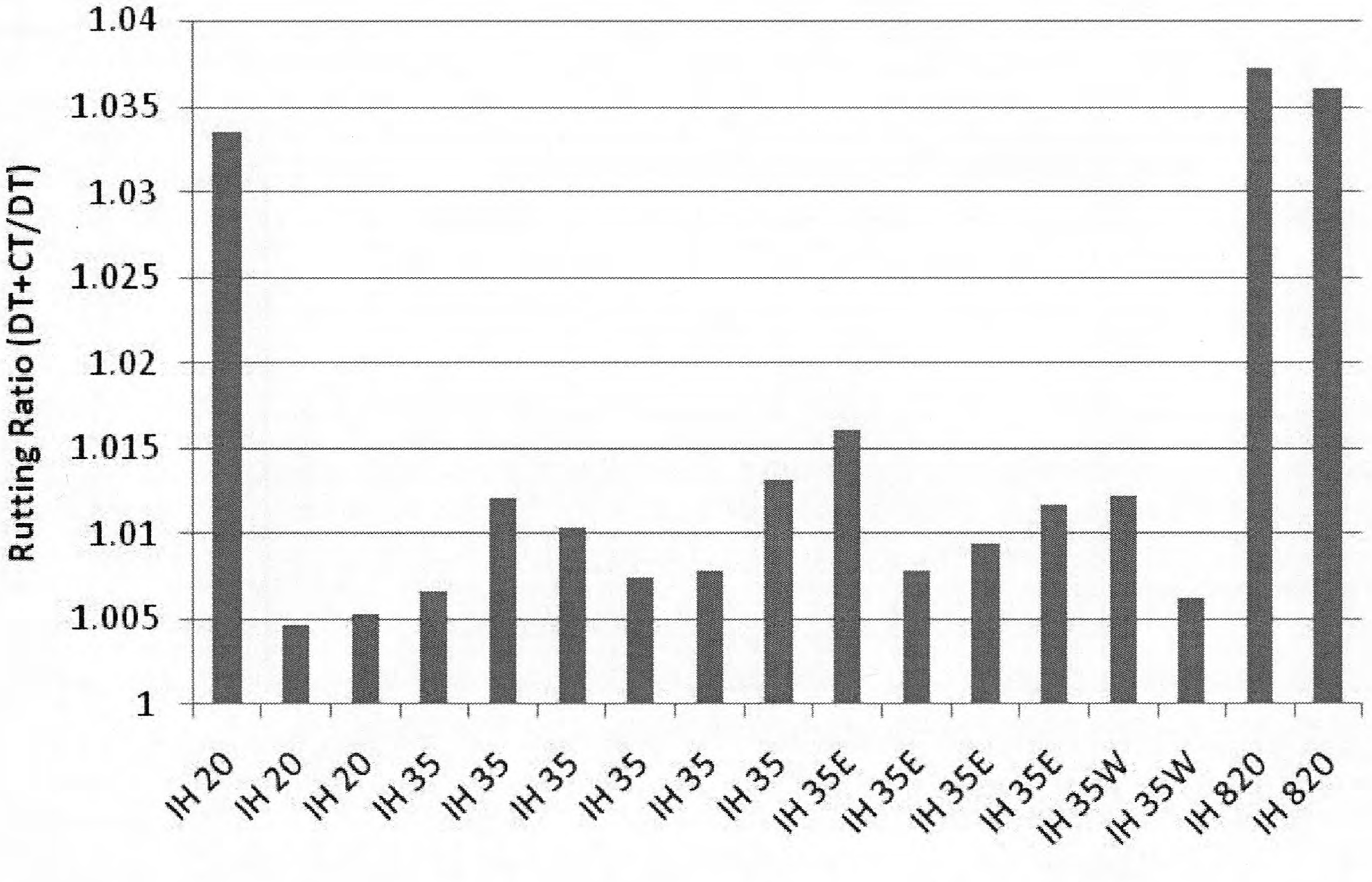


Figure A2.23: Ratio of Rut Depths on IH Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

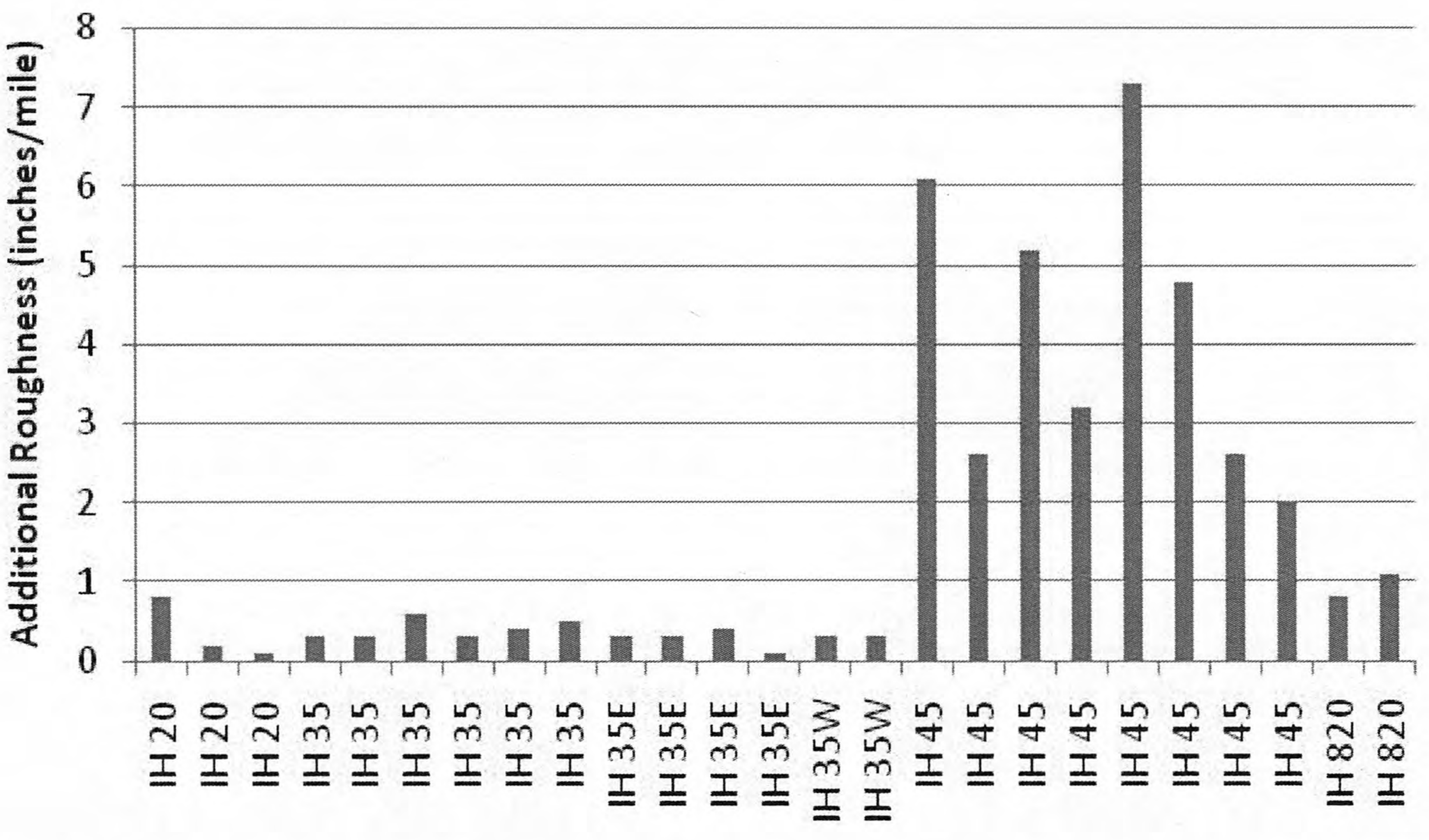


Figure A2.24: Increase in IRI Values for IH Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

US Highway Sections

Due to Rig Traffic

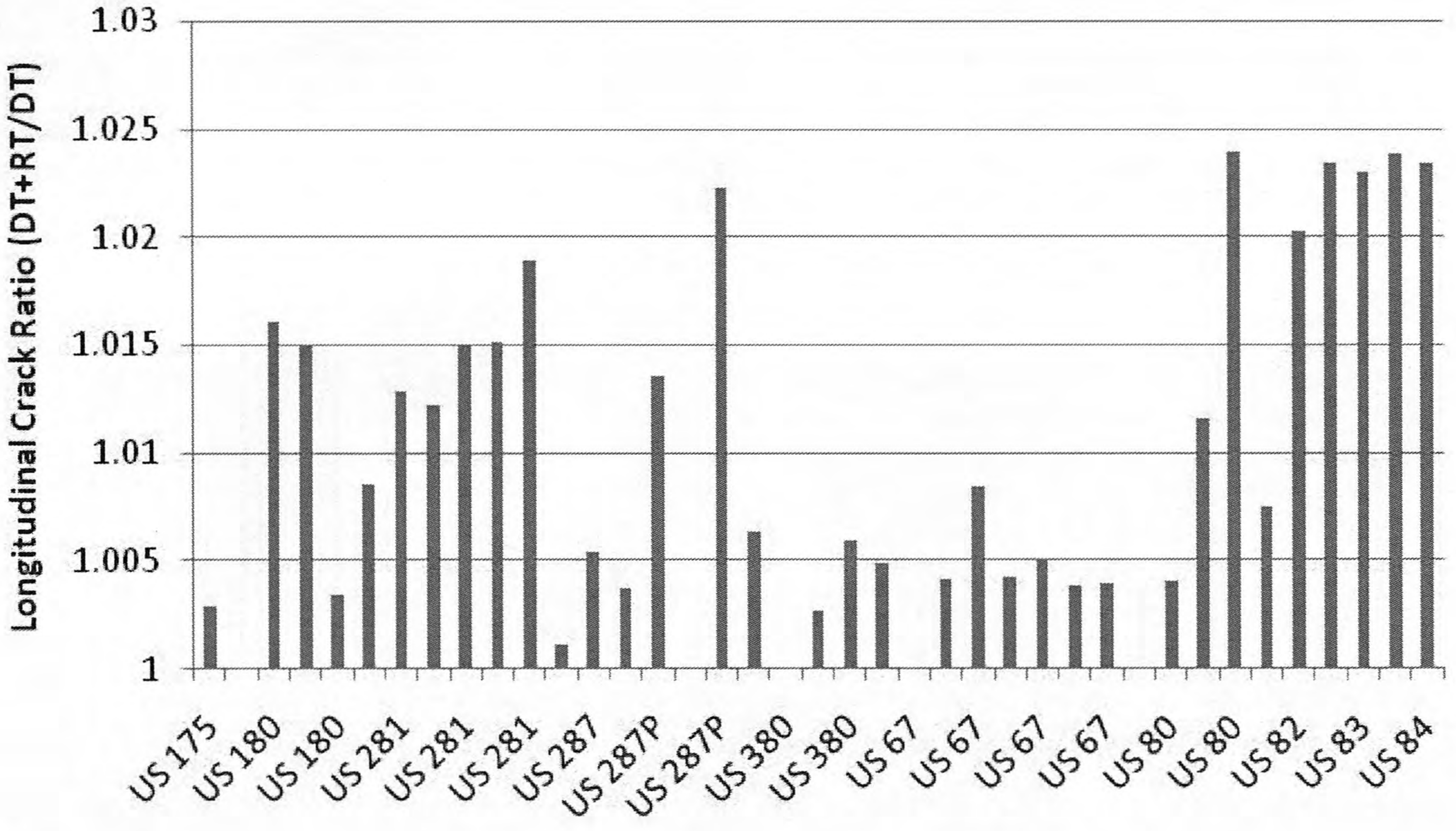


Figure A2.25: Ratio of Longitudinal Cracks on US Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

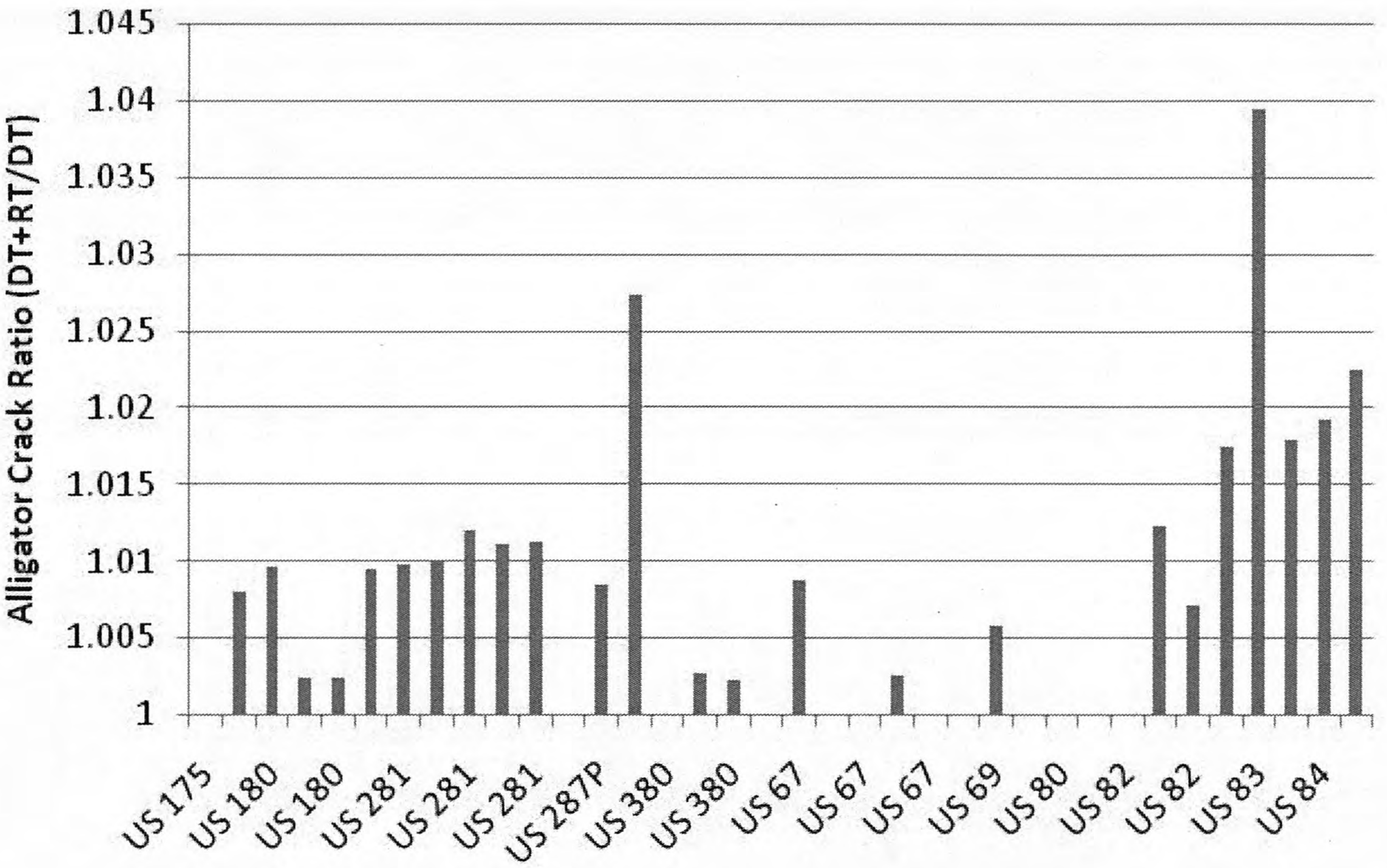


Figure A2.26: Ratio of Alligator Cracks on US Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

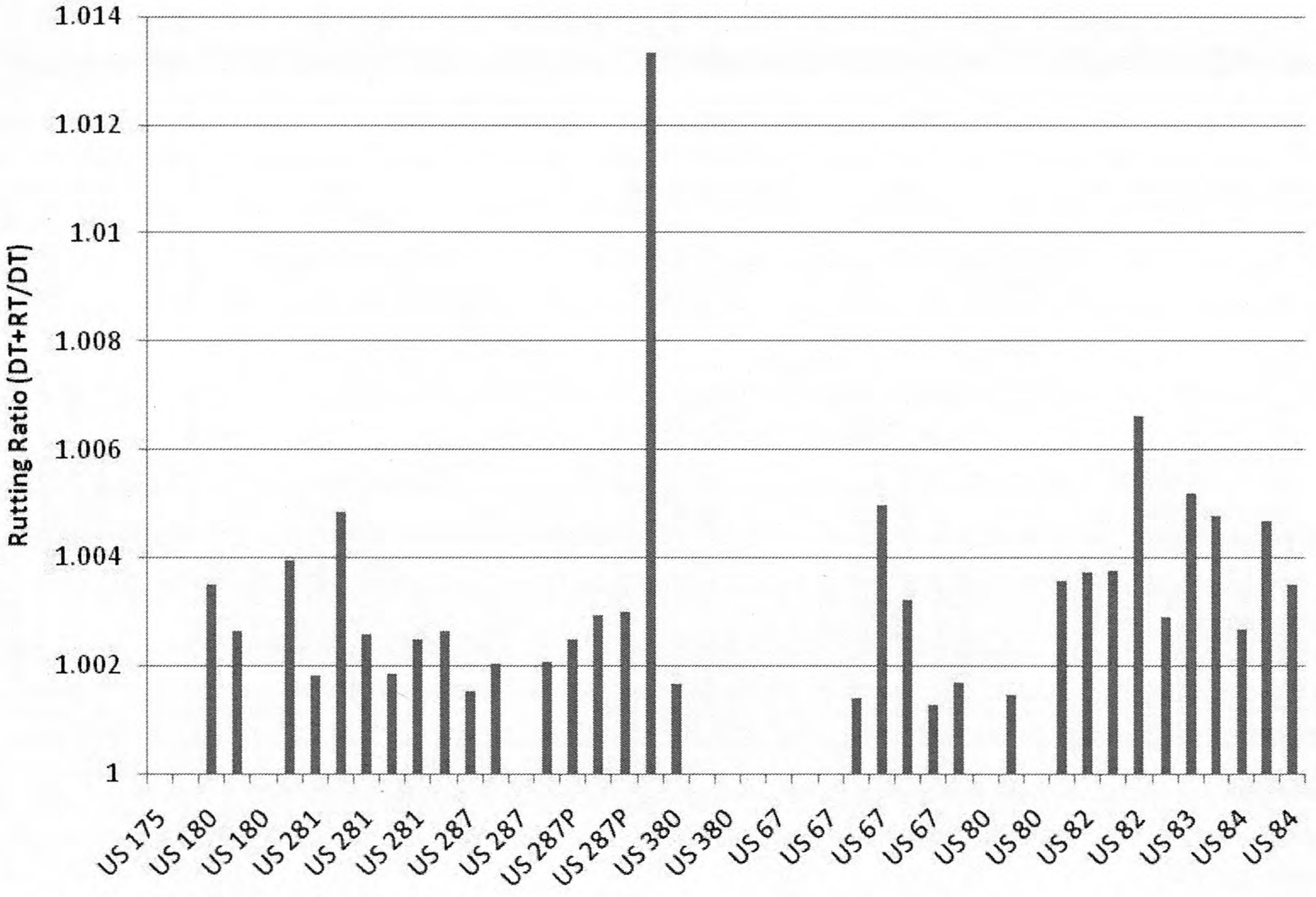


Figure A2.27: Ratio of Rut Depths on US Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

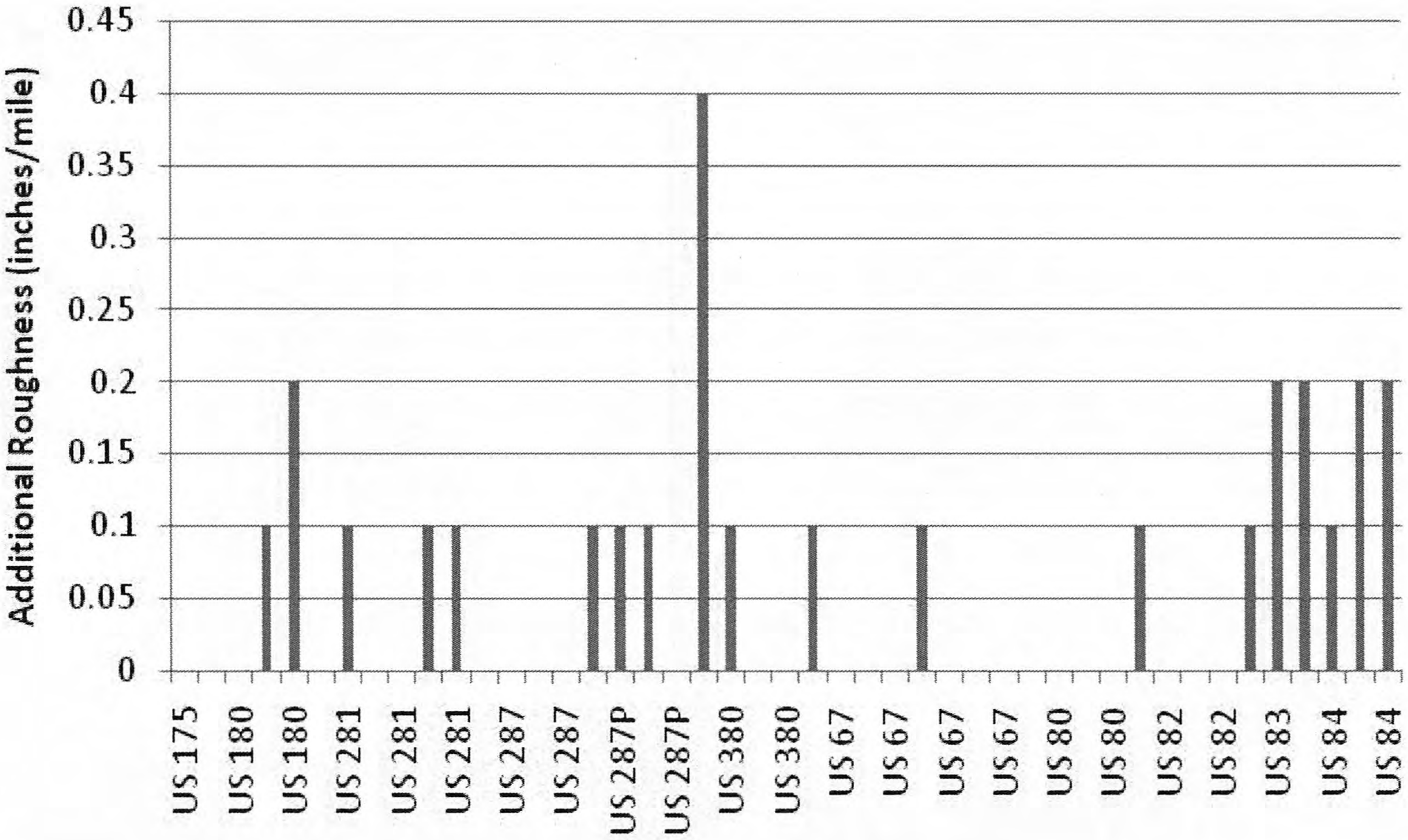


Figure A2.28: Increase in IRI Values for US Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Due to Saltwater Traffic

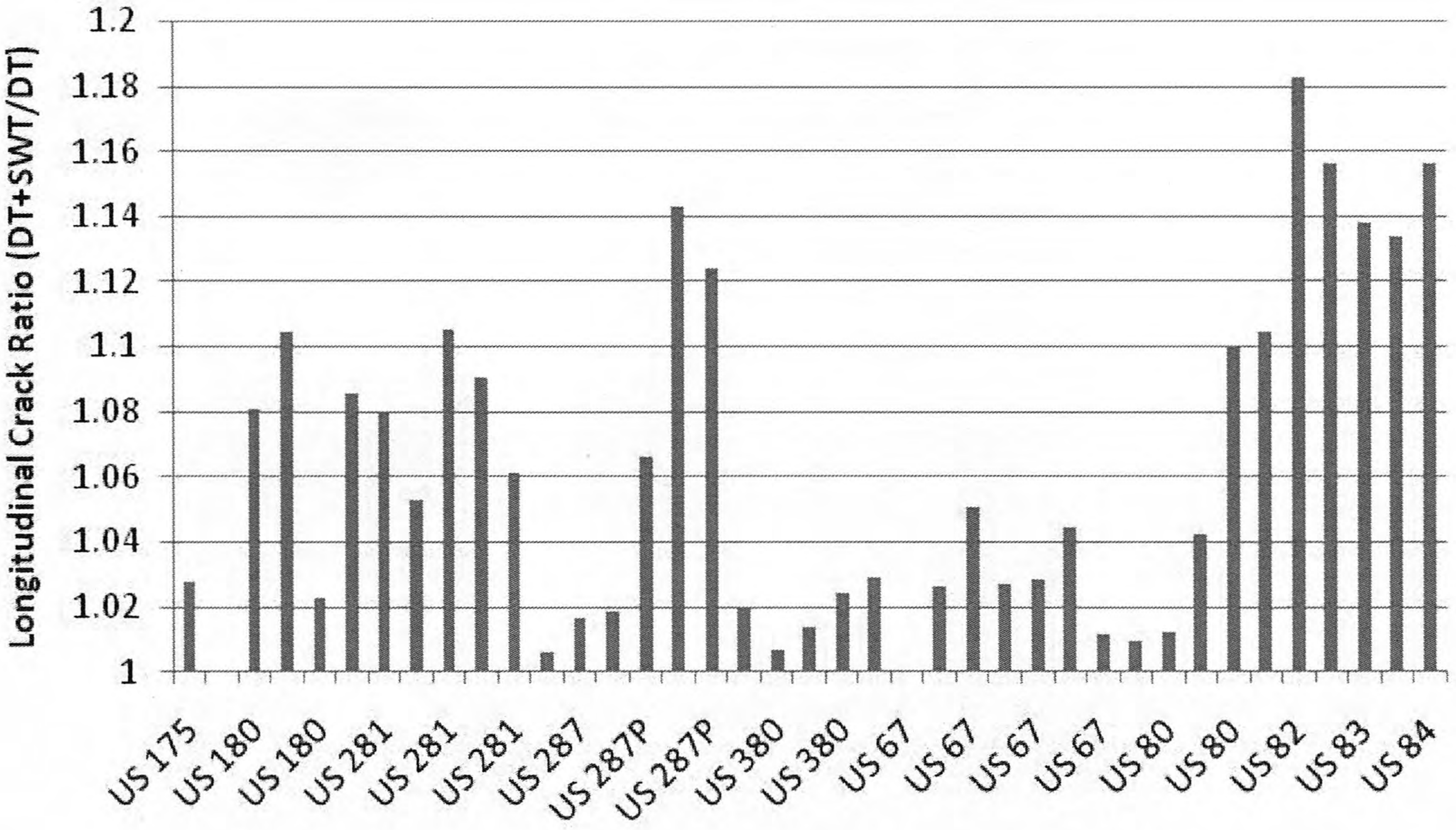


Figure A2.29: Ratio of Longitudinal Cracks on US Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

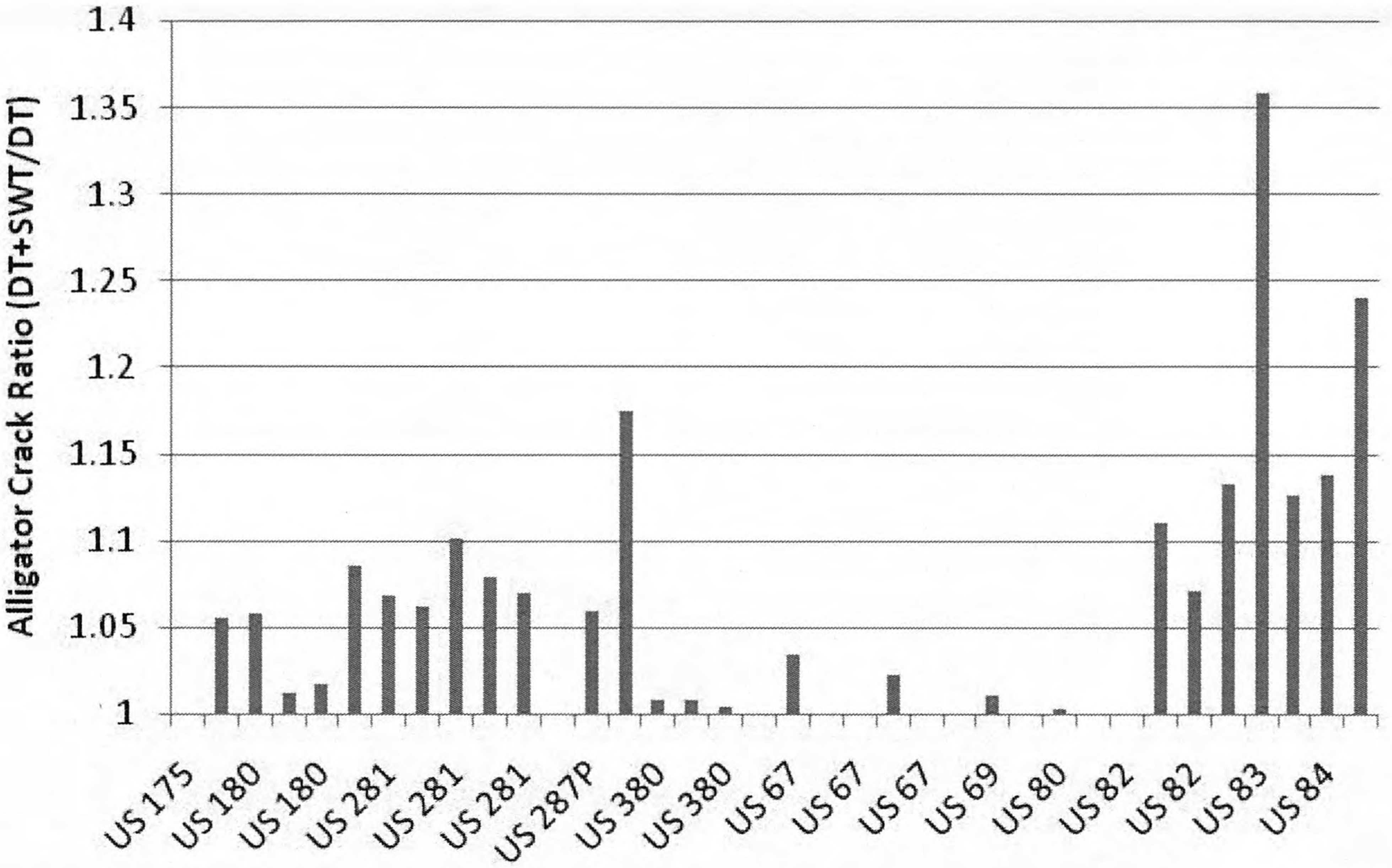


Figure A2.30: Ratio of Alligator Cracks on US Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

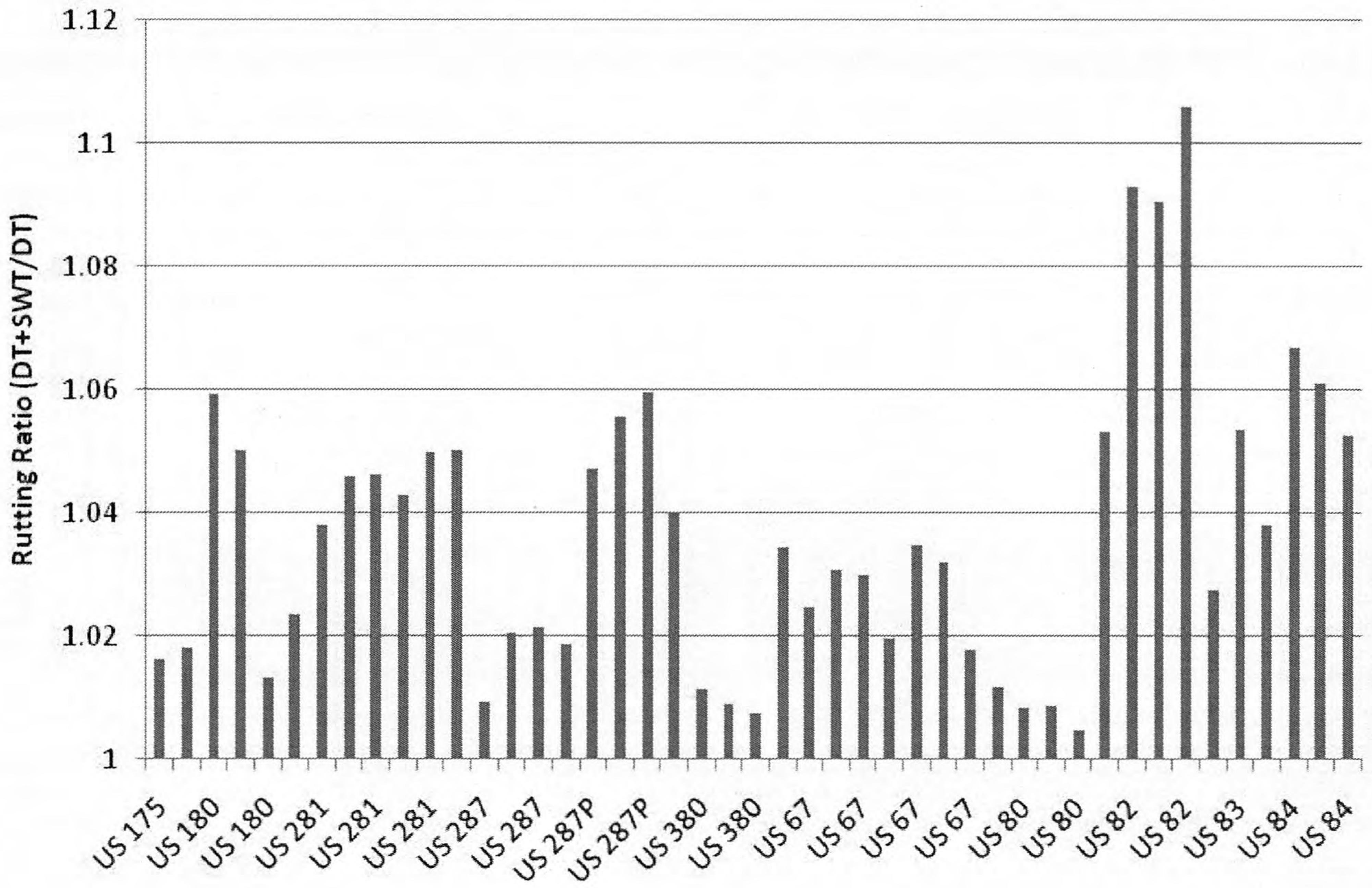


Figure A2.31: Ratio of Rut Depths on US Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

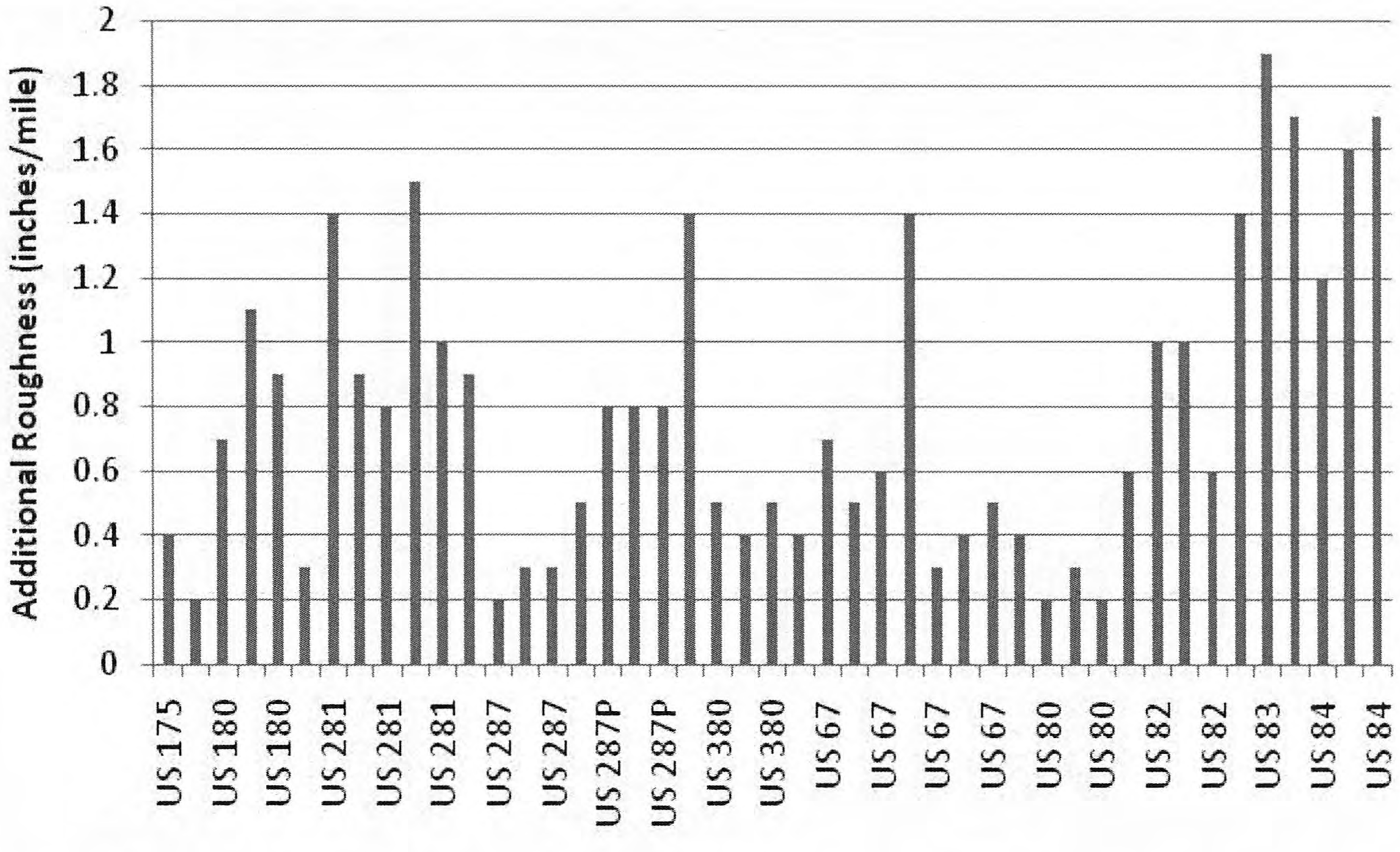


Figure A2.32: Increase in IRI Values for US Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Due to Construction Traffic

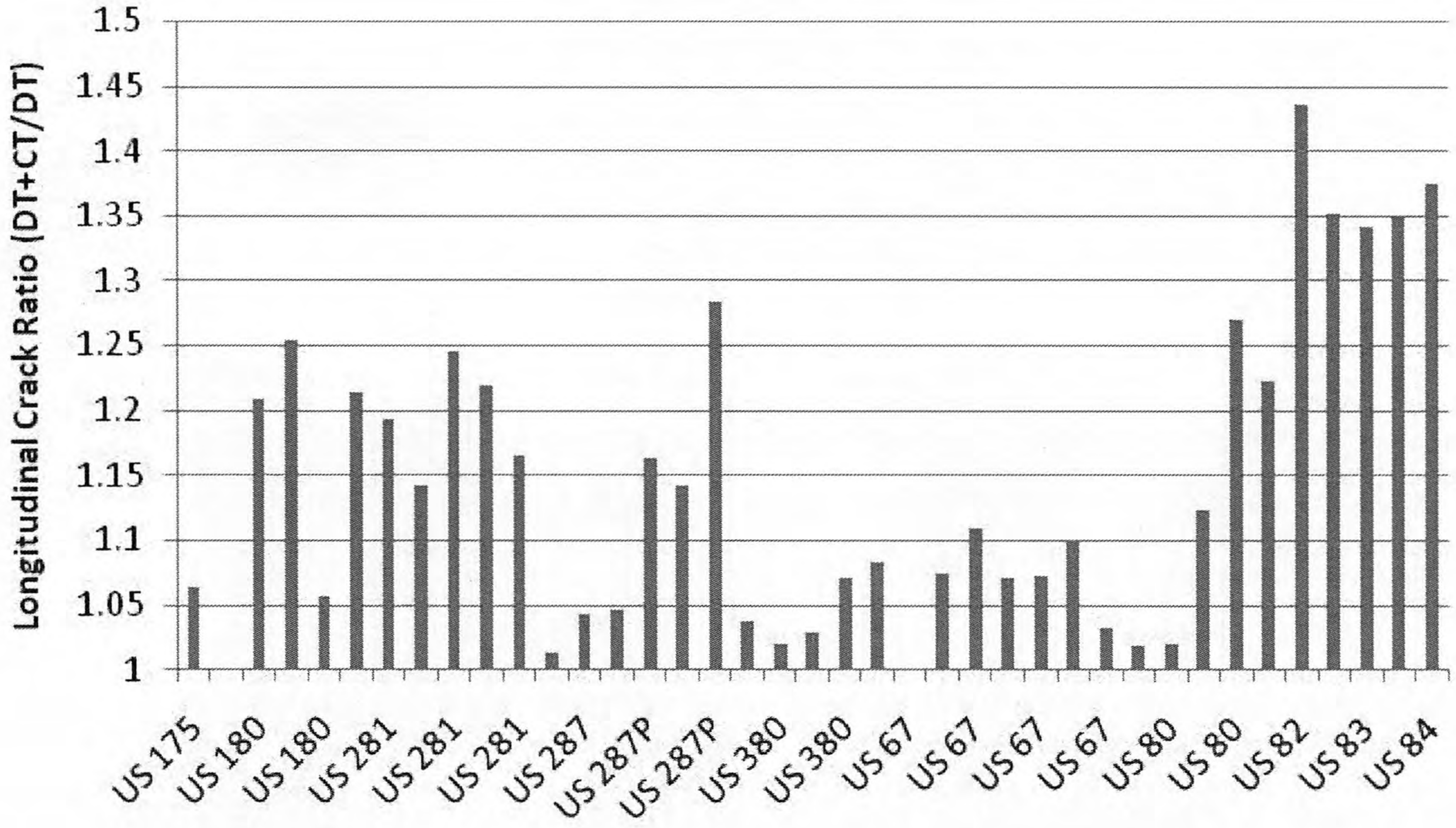


Figure A2.33: Ratio of Longitudinal Cracks on US Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

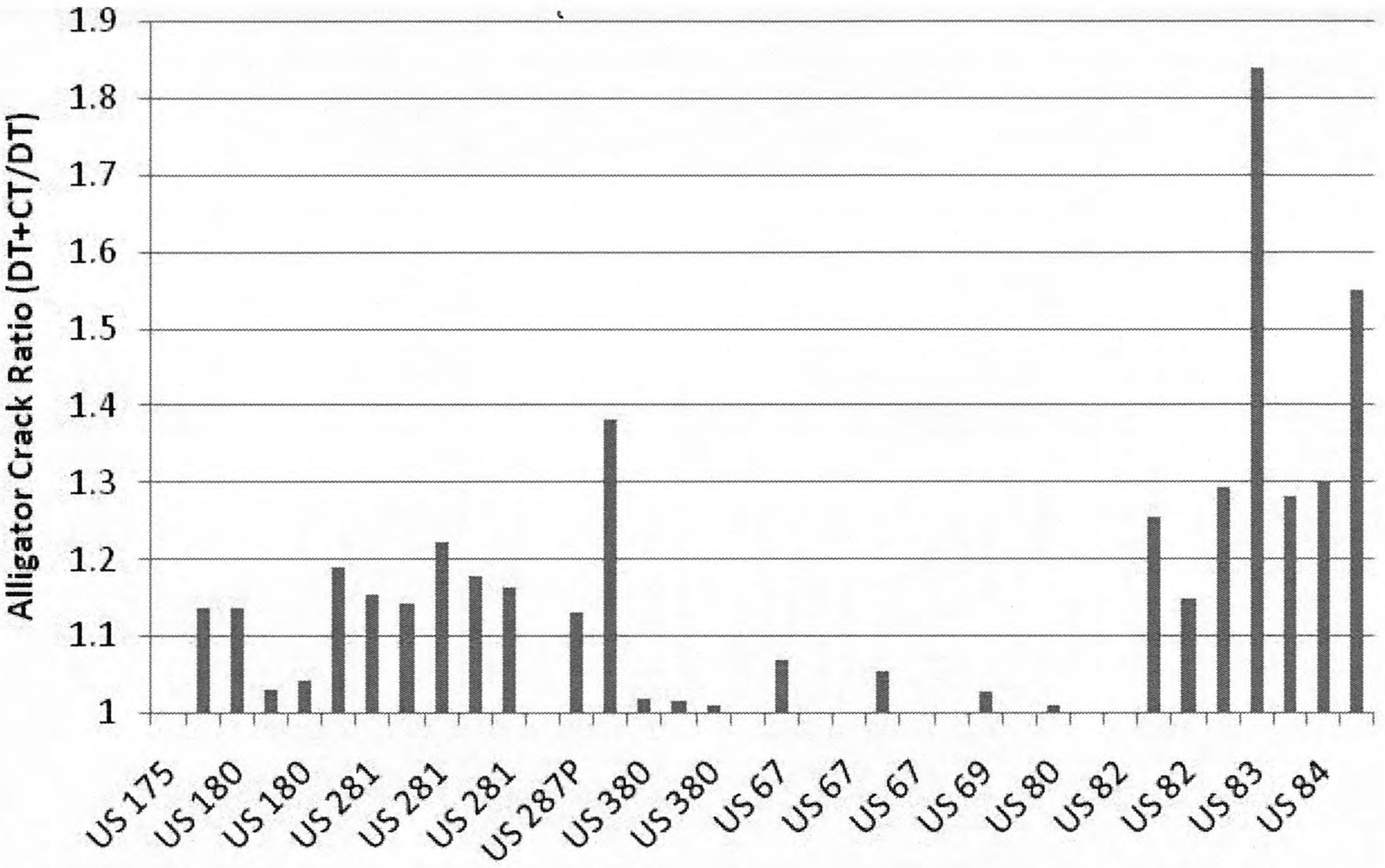


Figure A2.34: Ratio of Alligator Cracks on US Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

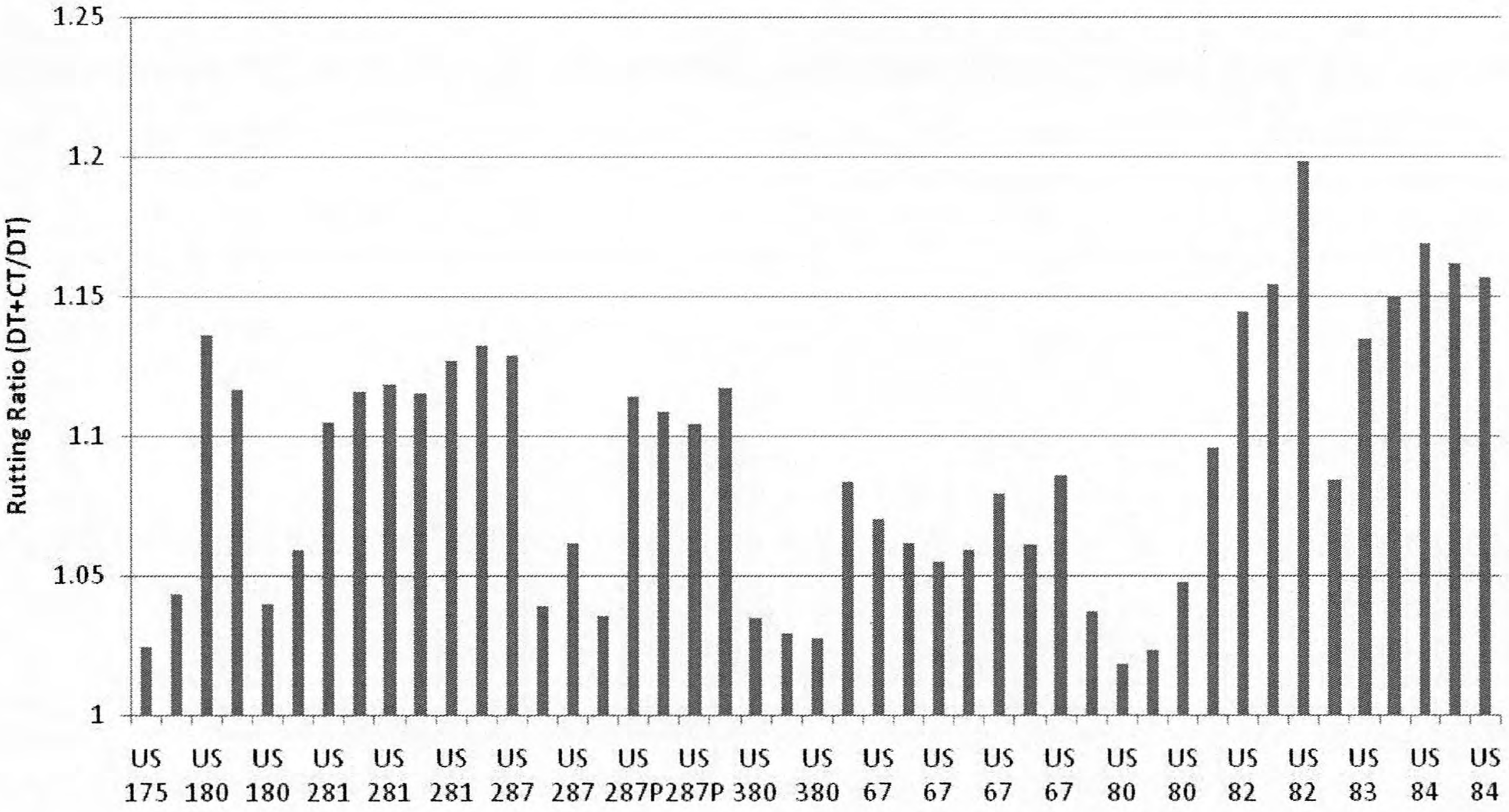


Figure A2.35: Ratio of Rut Depths on US Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

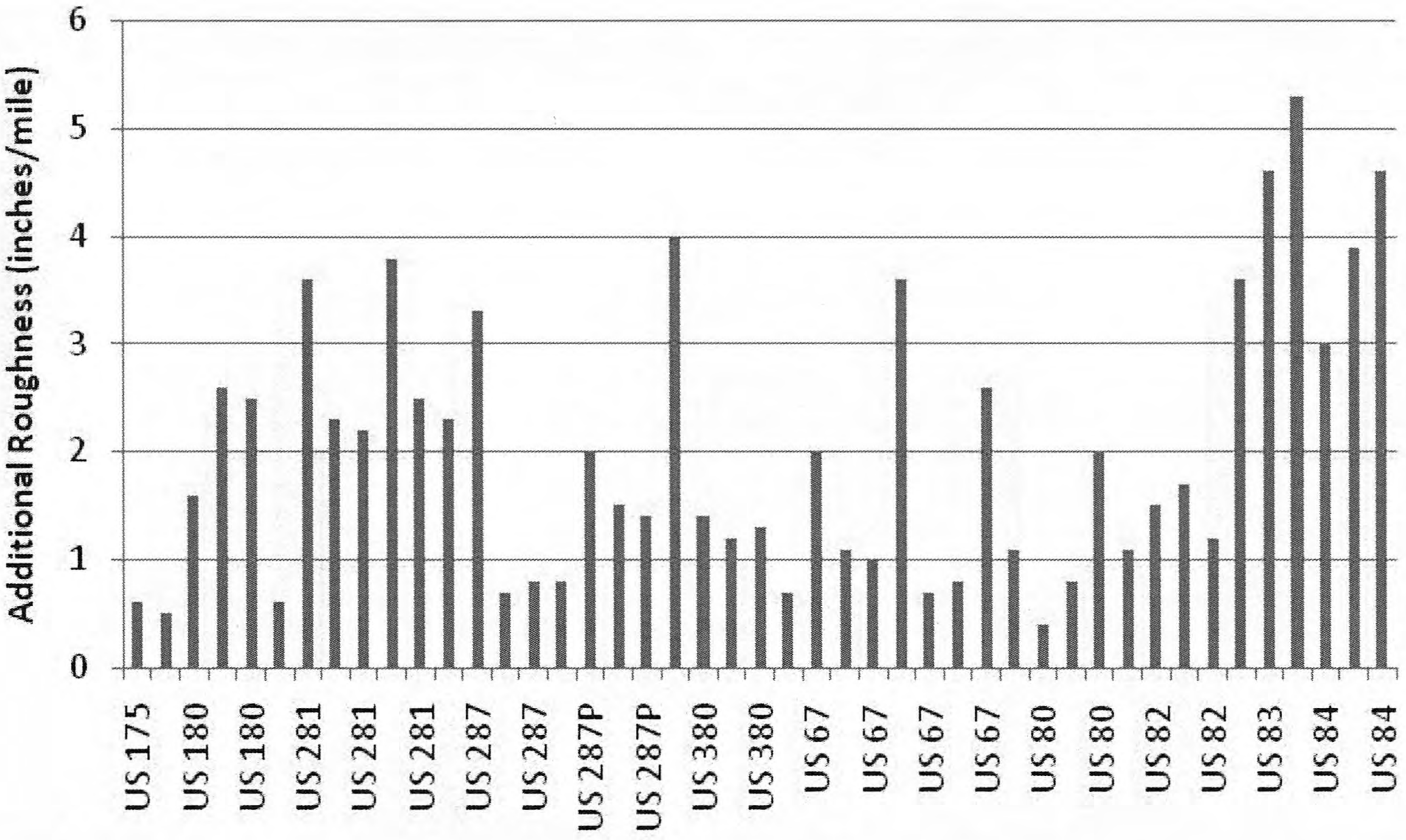


Figure A2.36: Increase in IRI Values for US Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

State Highway Sections

Due to Rig Traffic

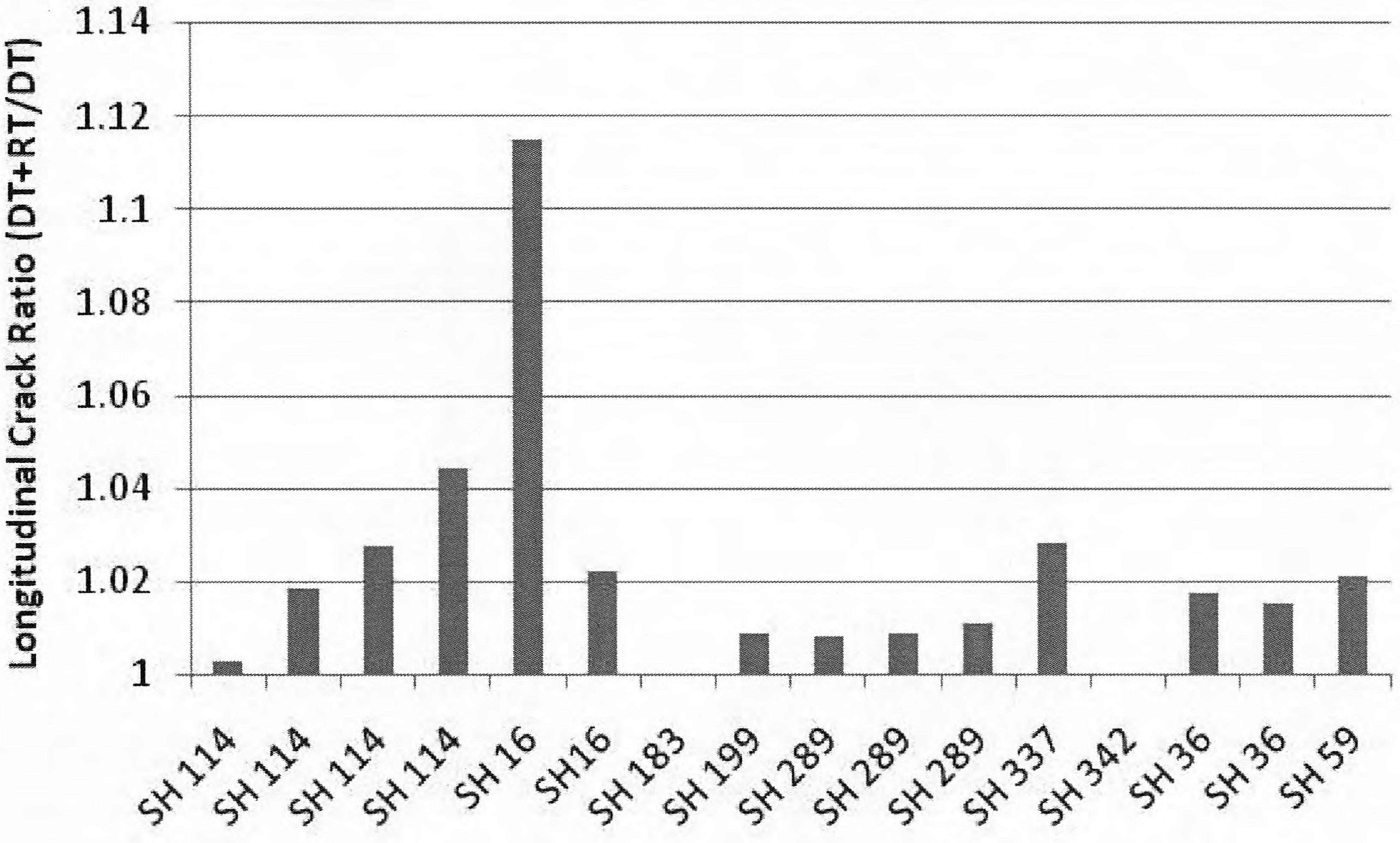


Figure A2.37: Ratio of Longitudinal Cracks on State Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

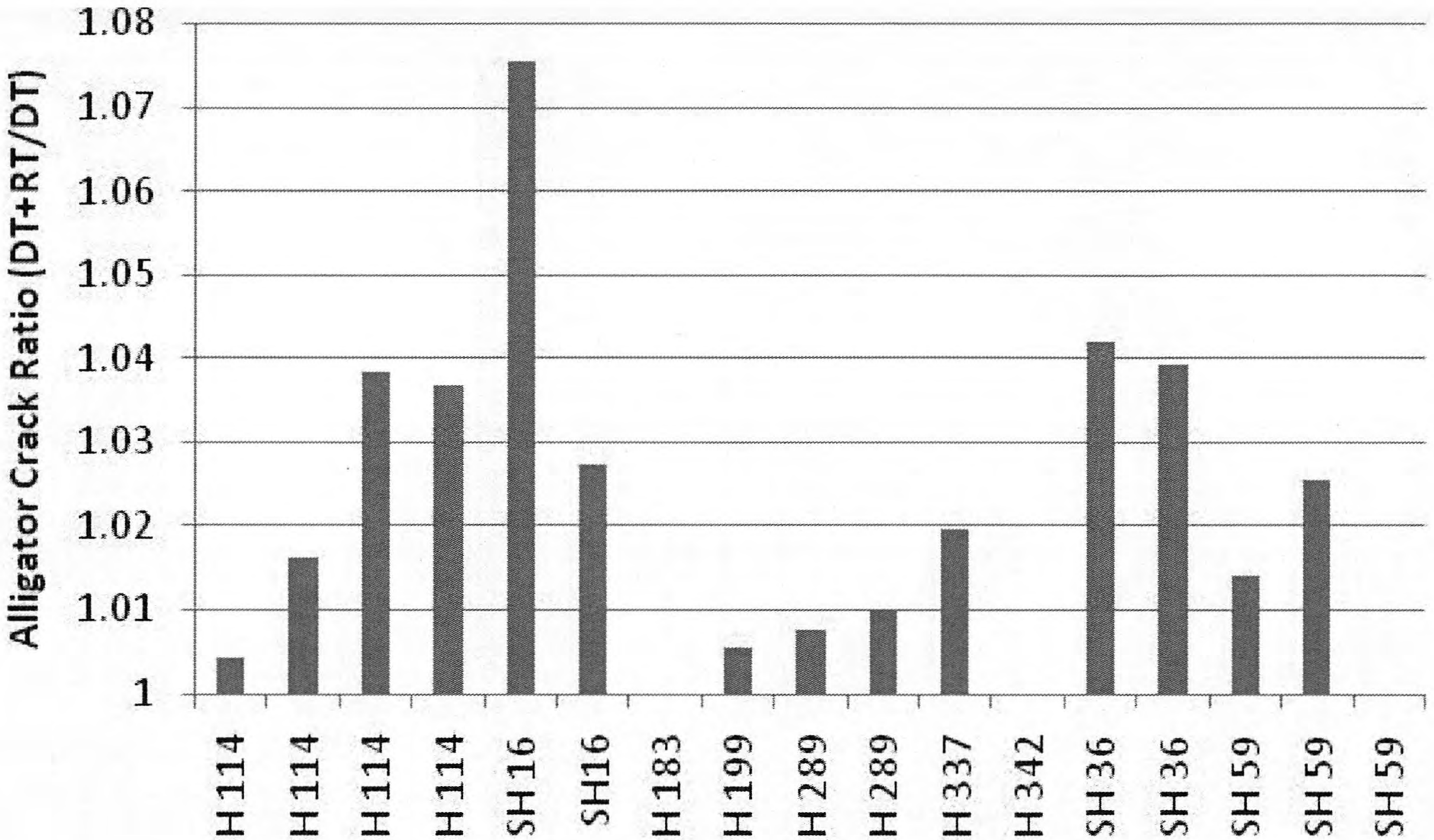


Figure A2.38: Ratio of Alligator Cracks on State Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

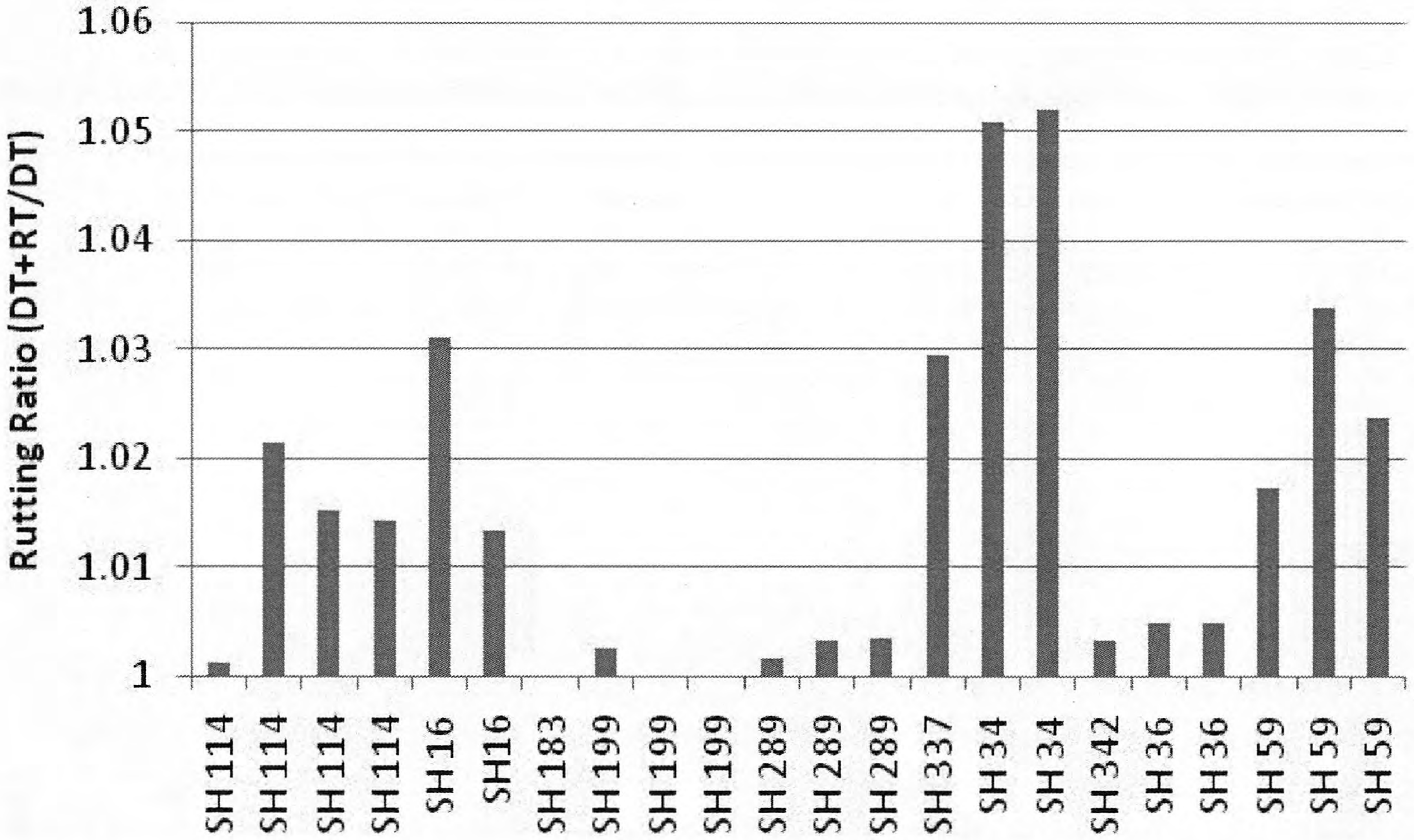


Figure A2.39: Ratio of Rut Depths on State Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

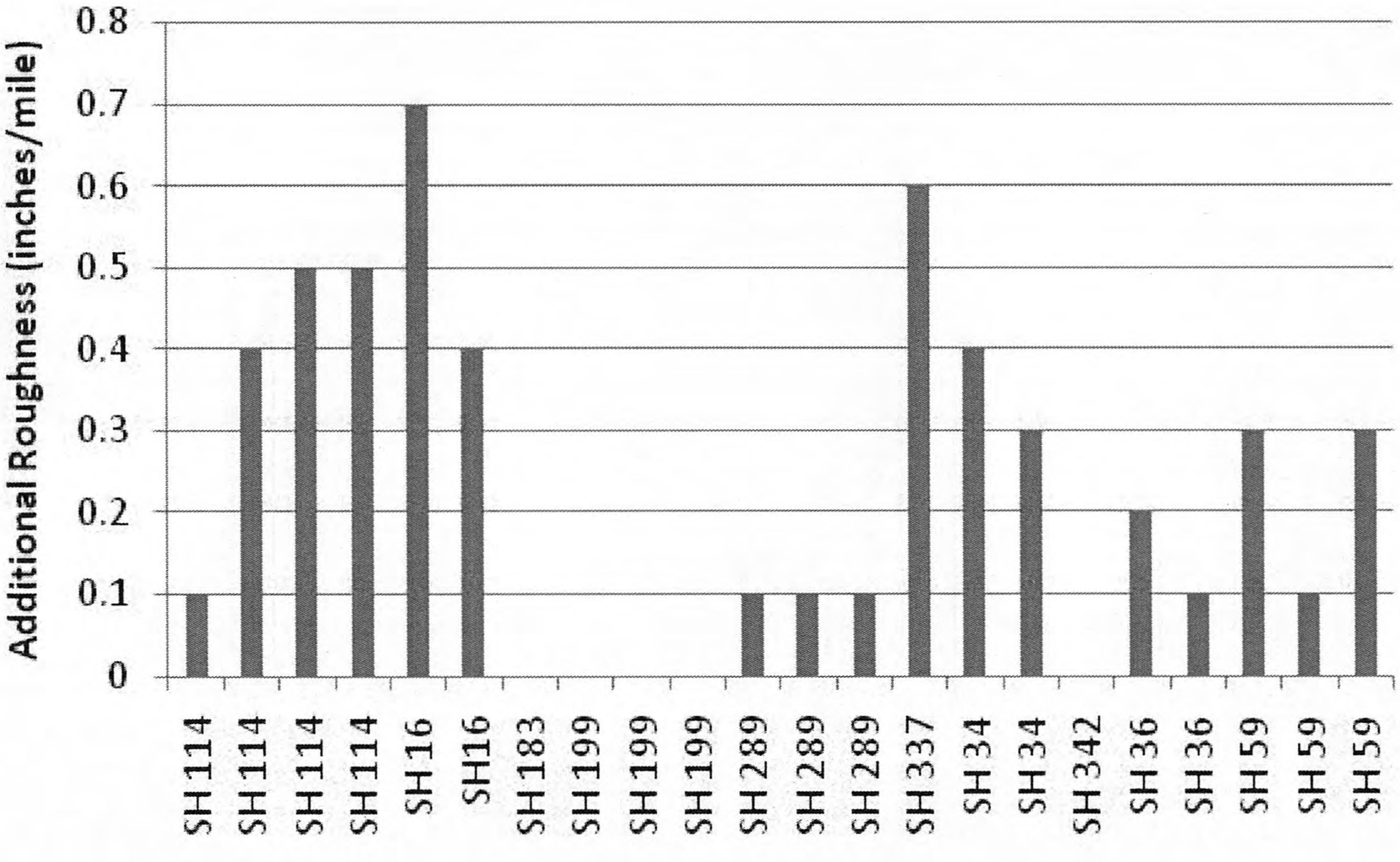


Figure A2.40: Increase in IRI Values for State Highway Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Due to Saltwater Traffic

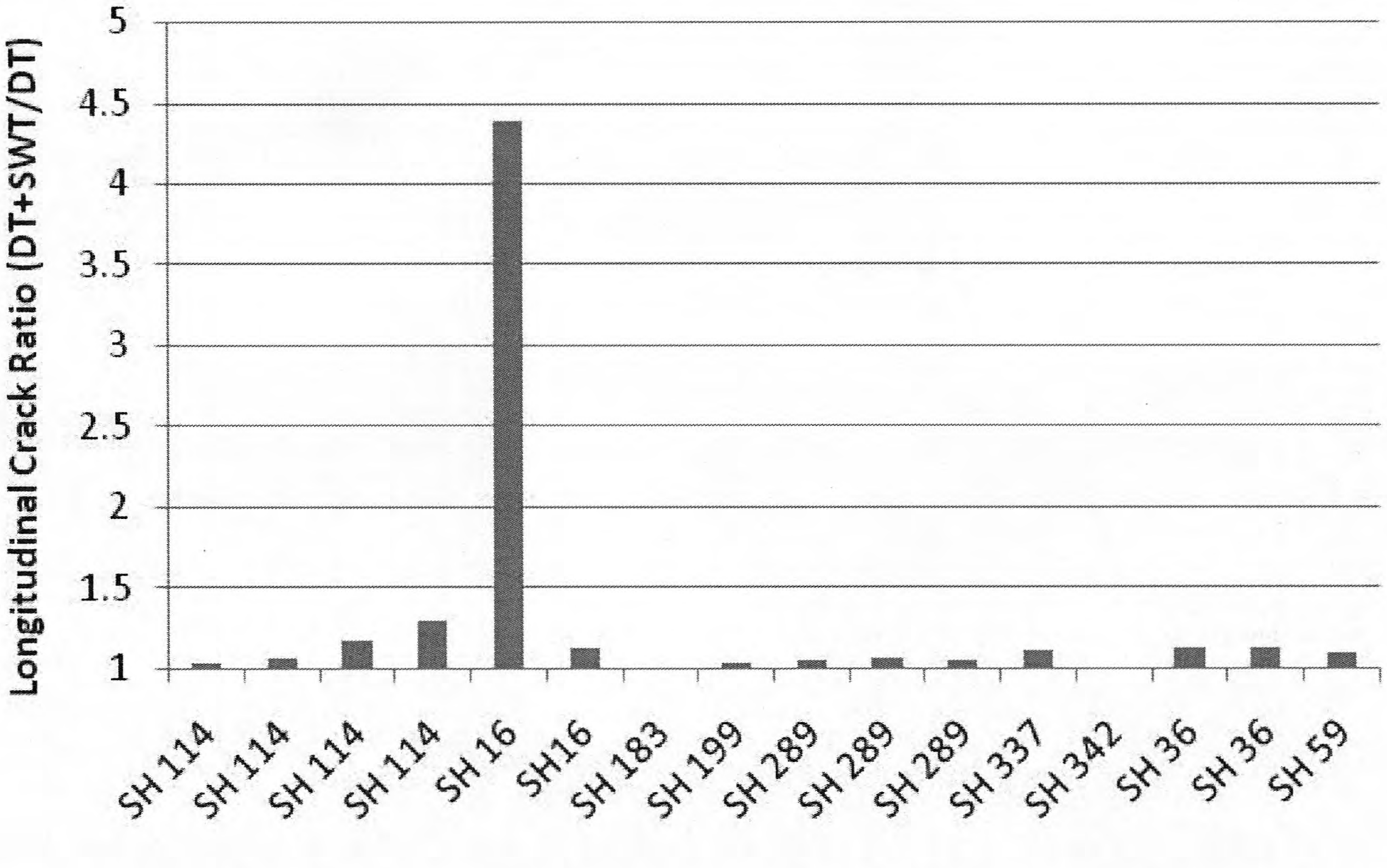


Figure A2.41: Ratio of Longitudinal Cracks on State Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

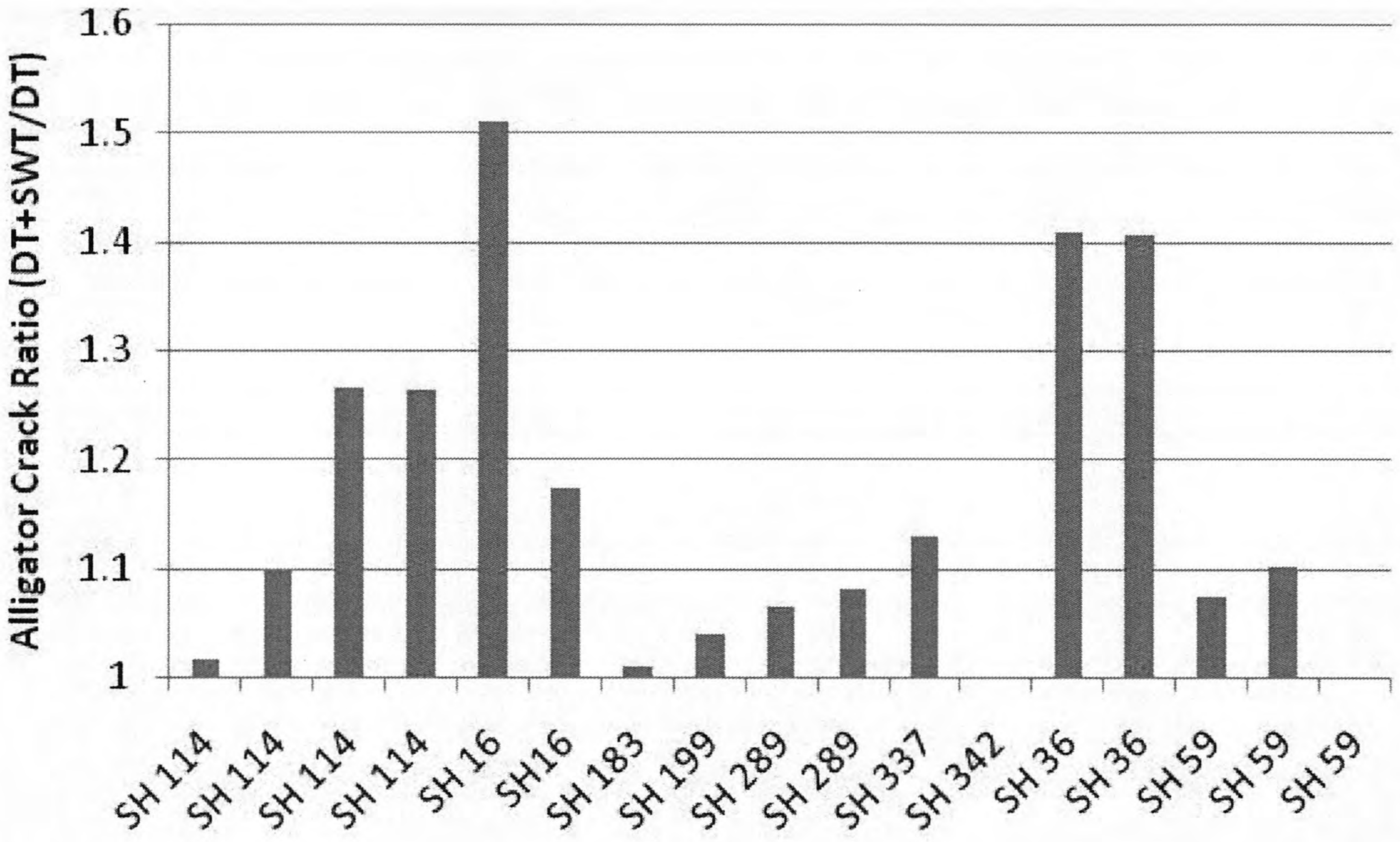


Figure A2.42: Ratio of Alligator Cracks on State Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

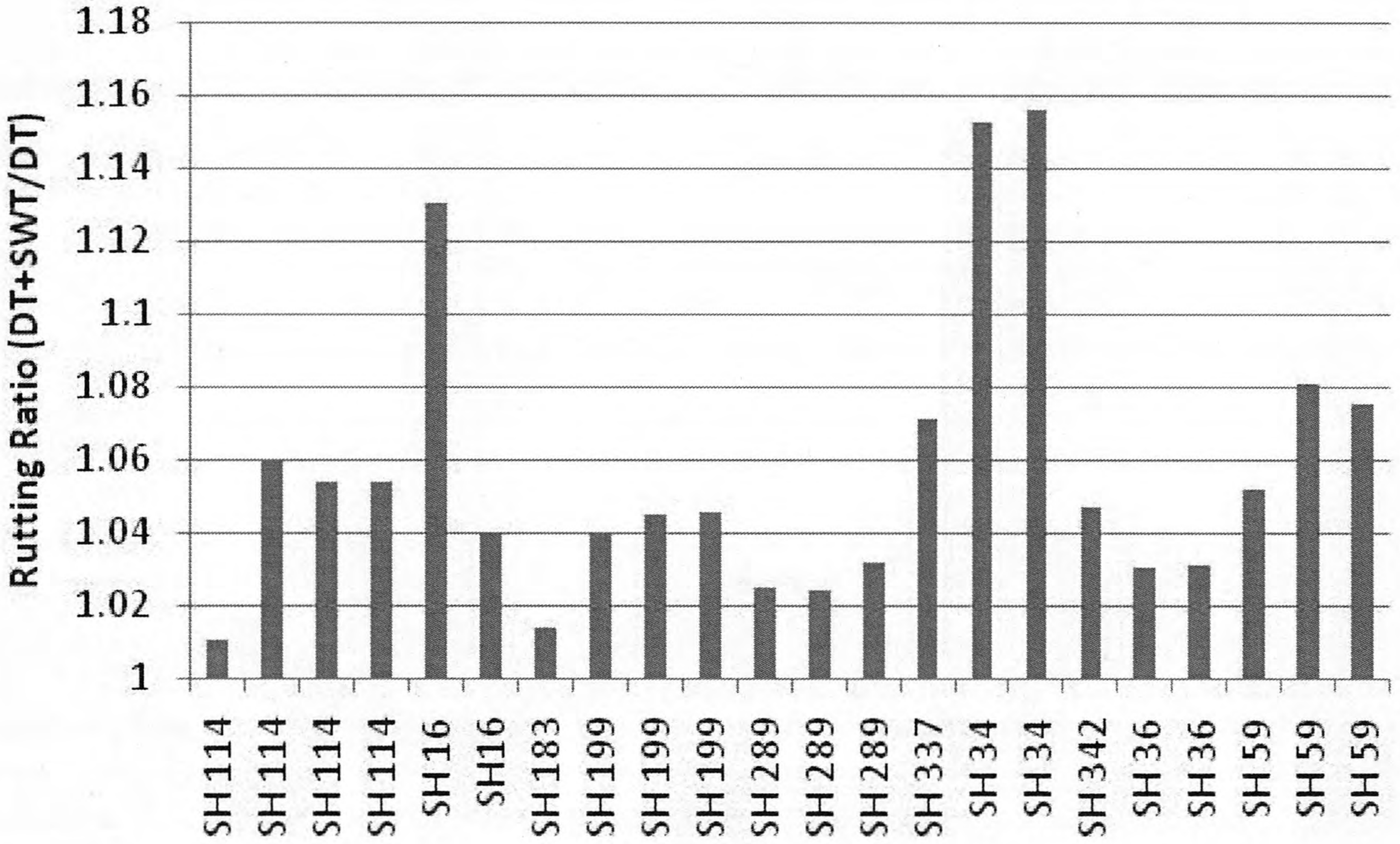


Figure A2.43: Ratio of Rut Depths on State Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

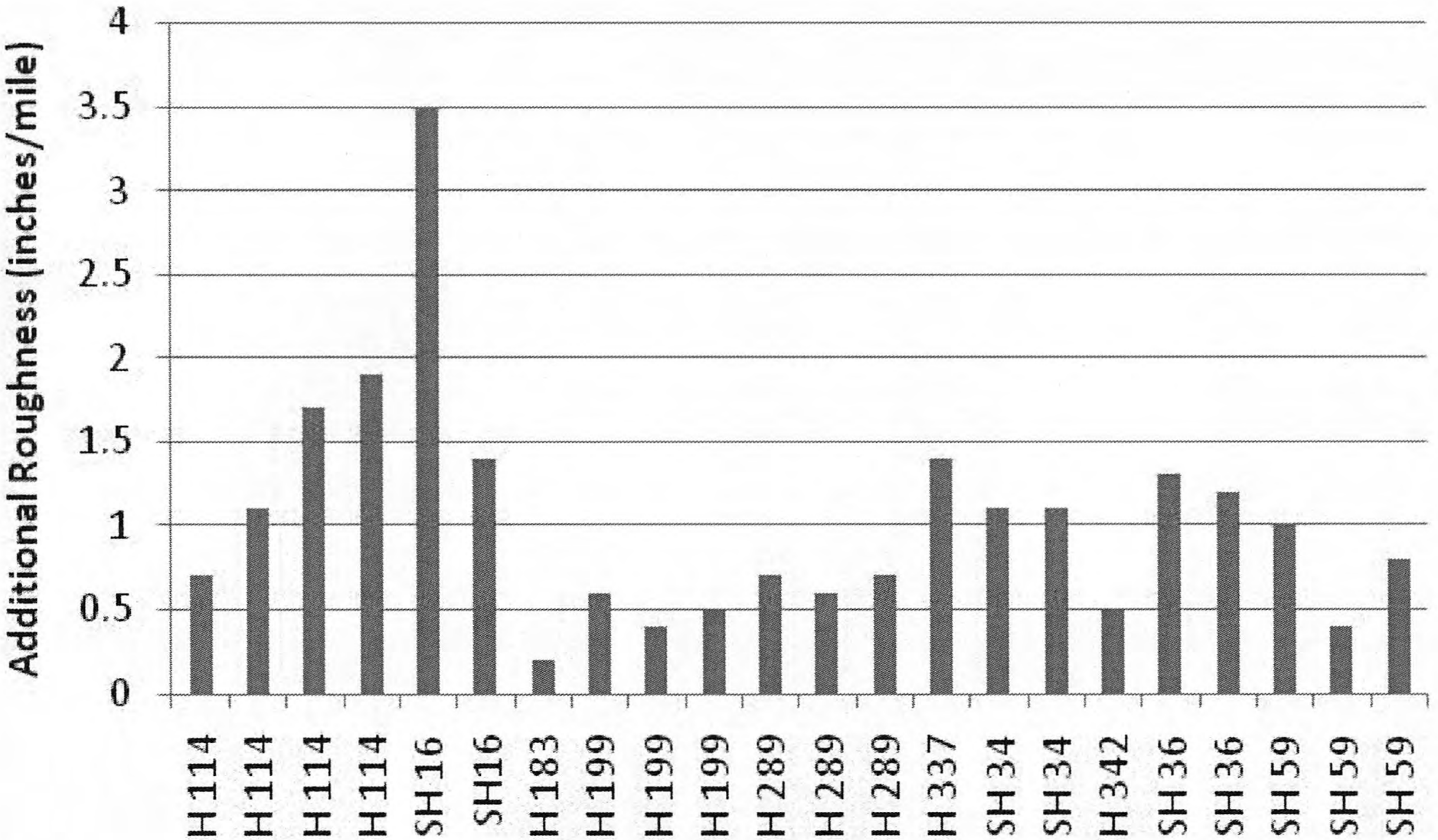


Figure A2.44: Increase in IRI Values for State Highway Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Due to Construction Traffic

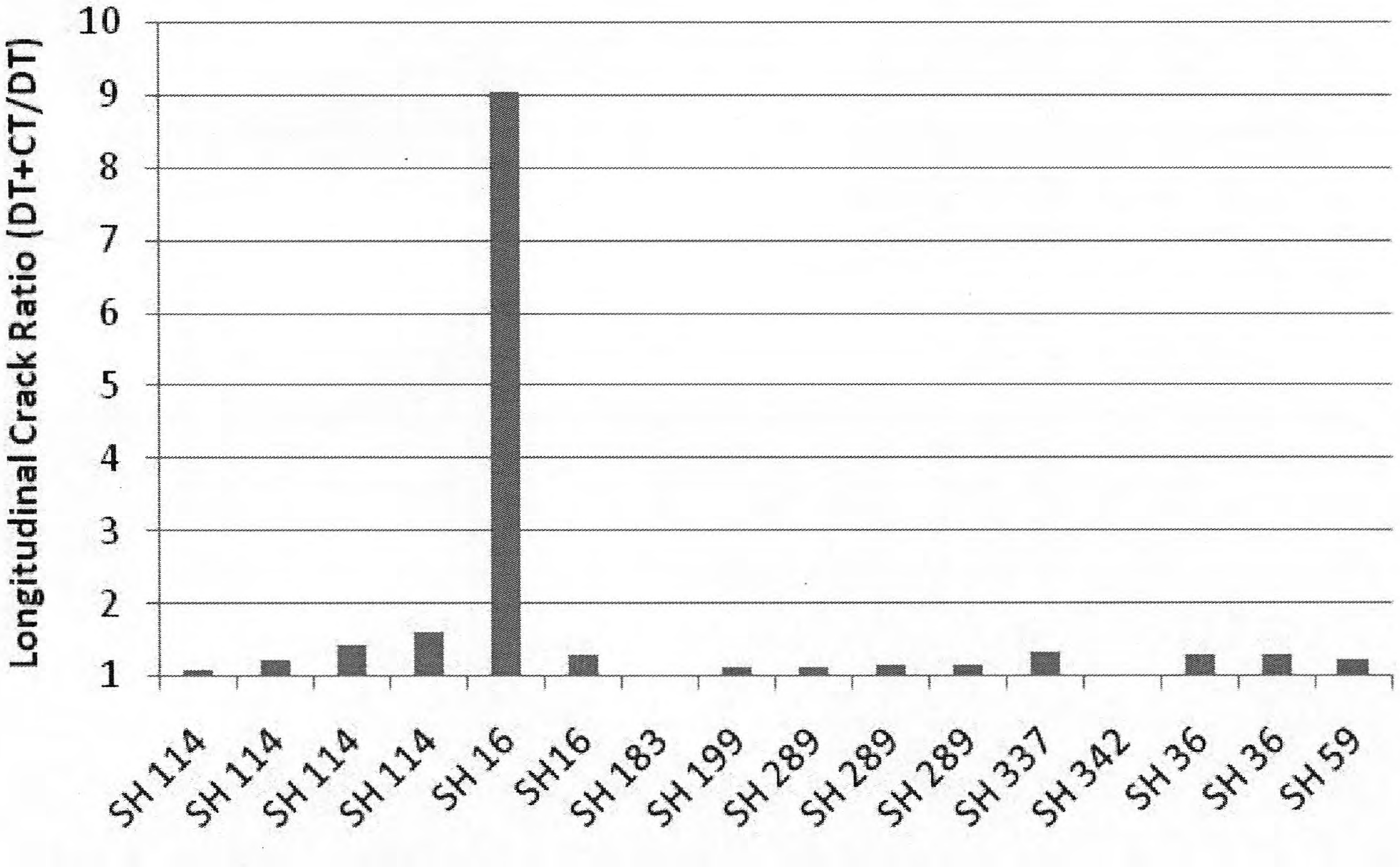


Figure A2.45: Ratio of Longitudinal Cracks on State Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

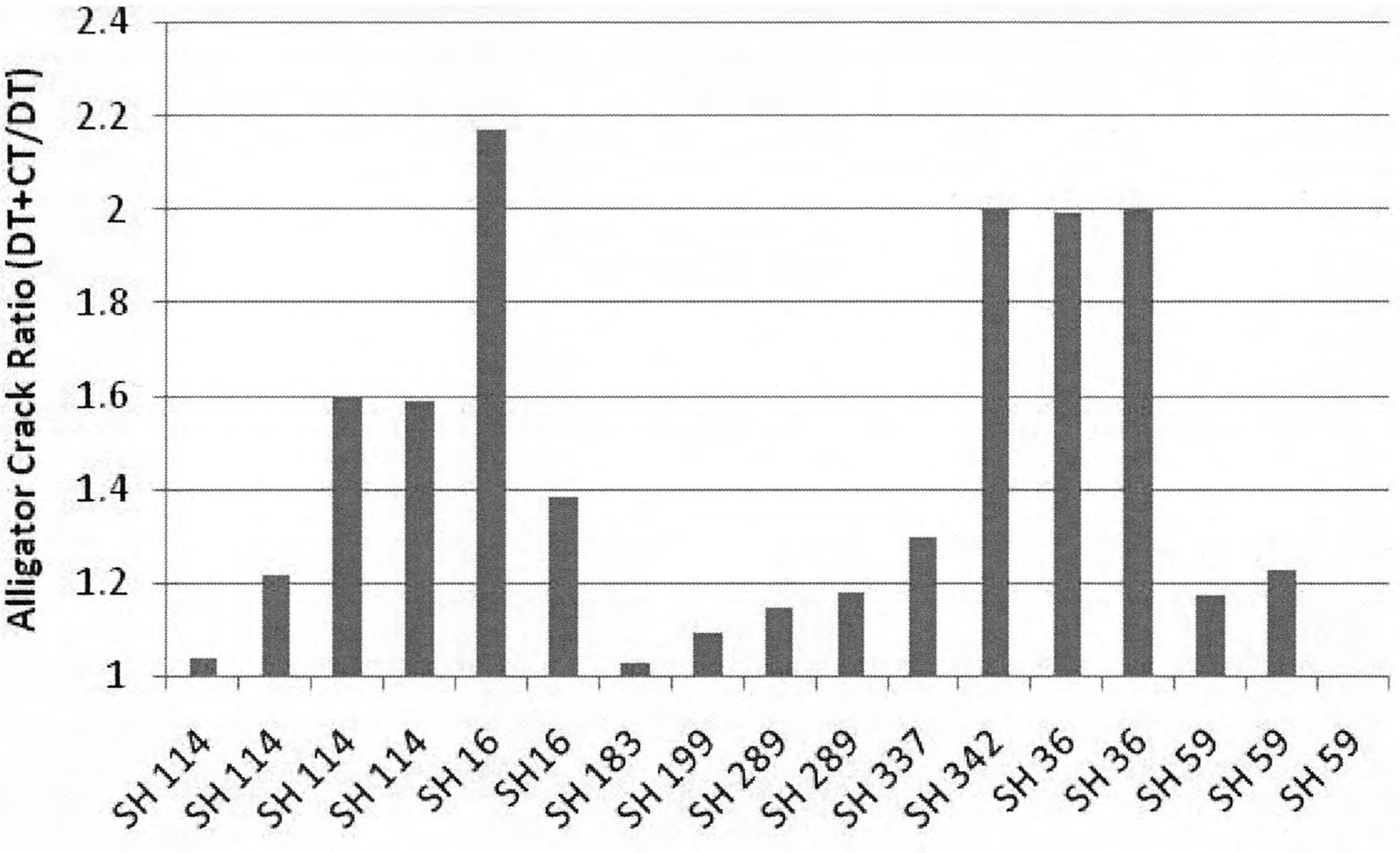


Figure A2.46: Ratio of Alligator Cracks on State Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

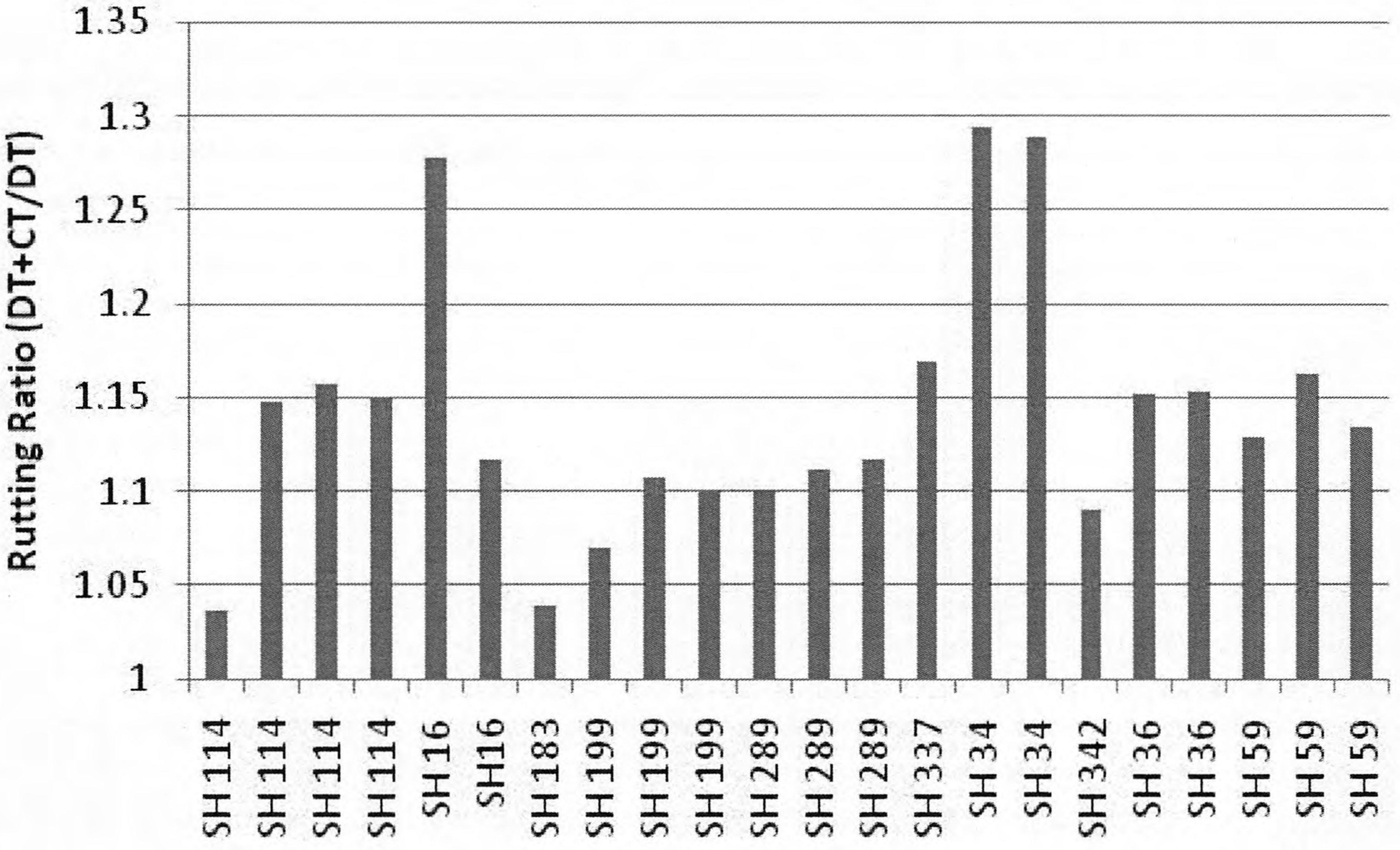


Figure A2.47: Ratio of Rut Depths on State Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

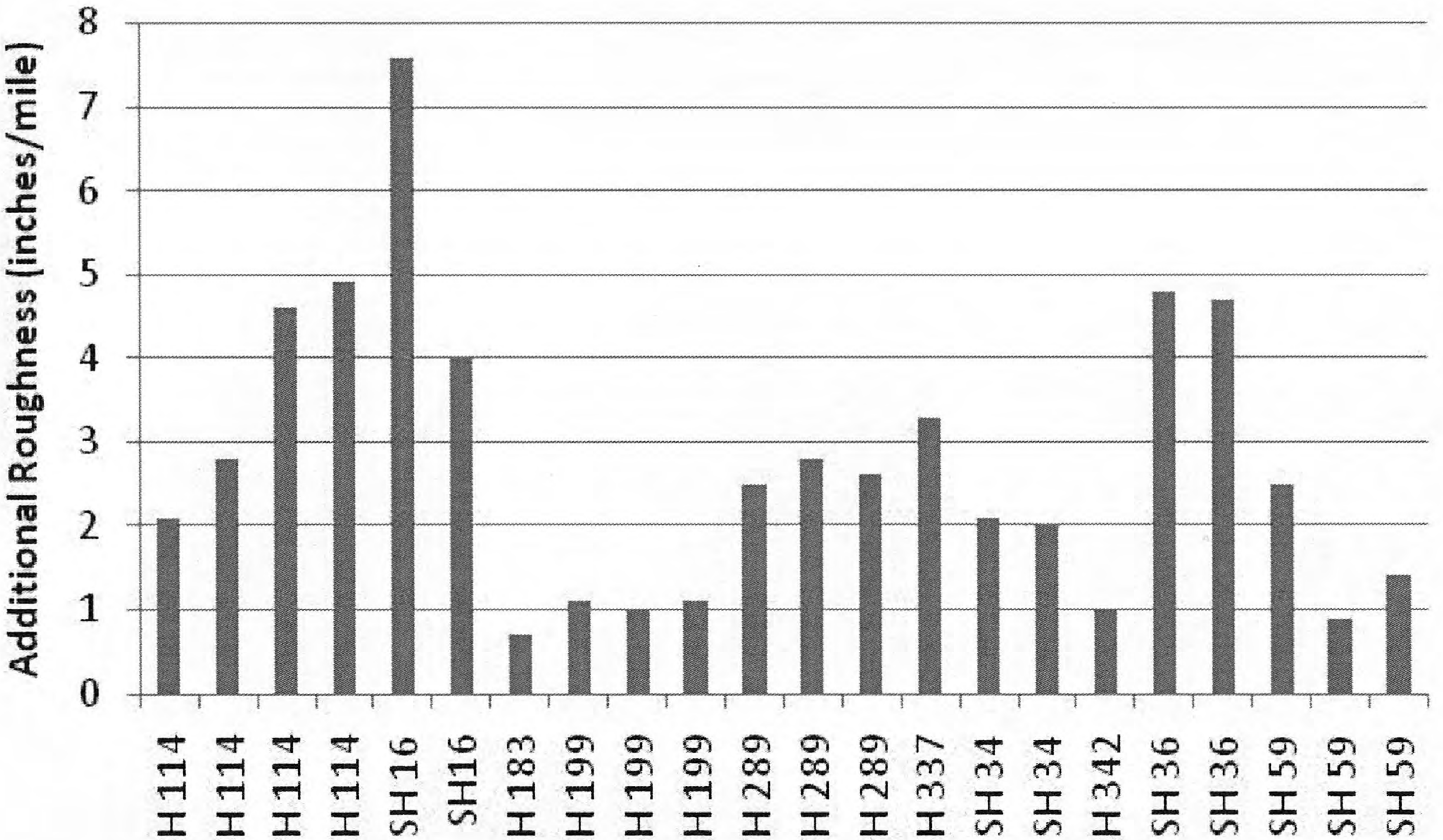


Figure A2.48: Increase in IRI Values for State Highway Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

FM Roads

Due to Rig Traffic

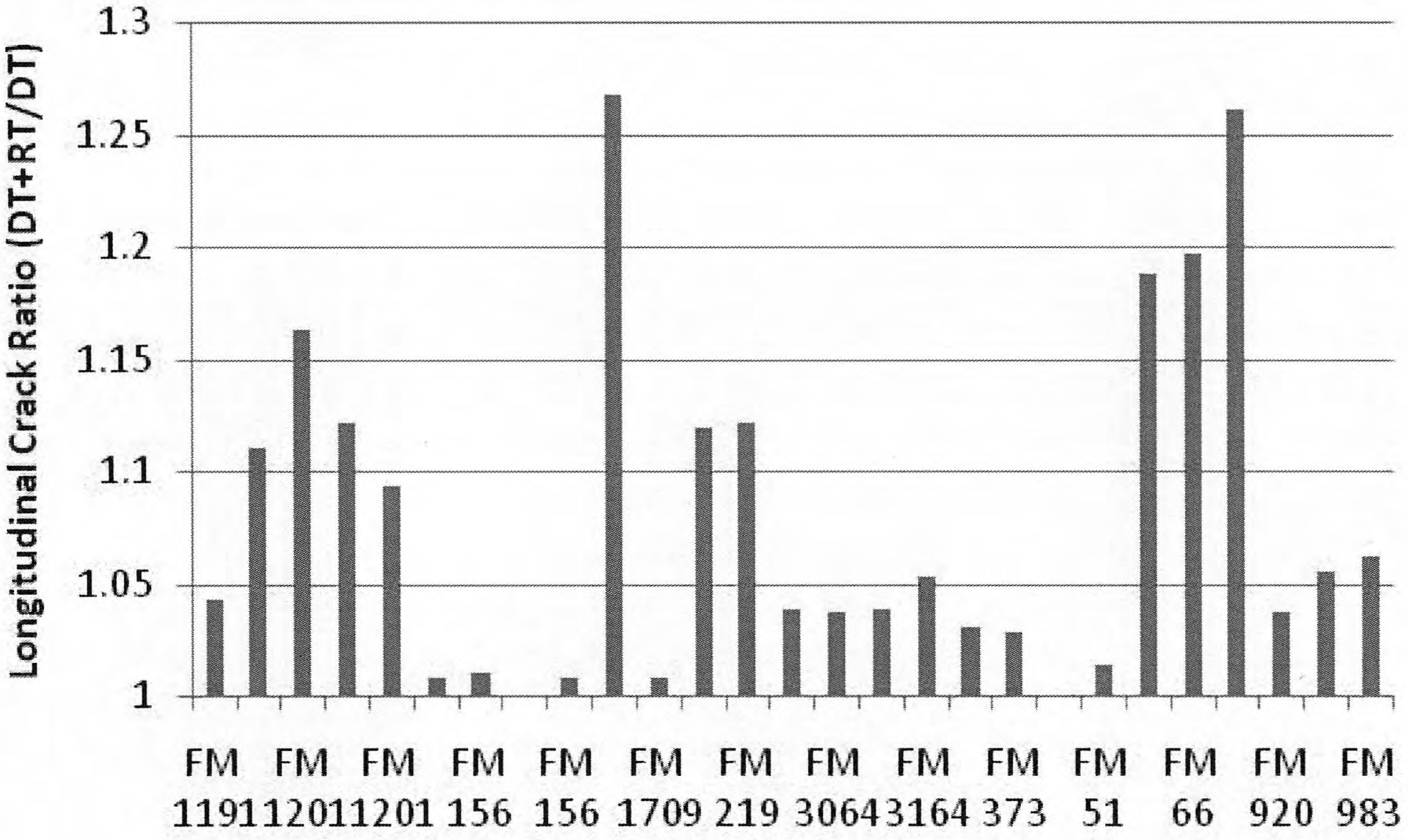


Figure A2.49: Ratio of Longitudinal Cracks on FM Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

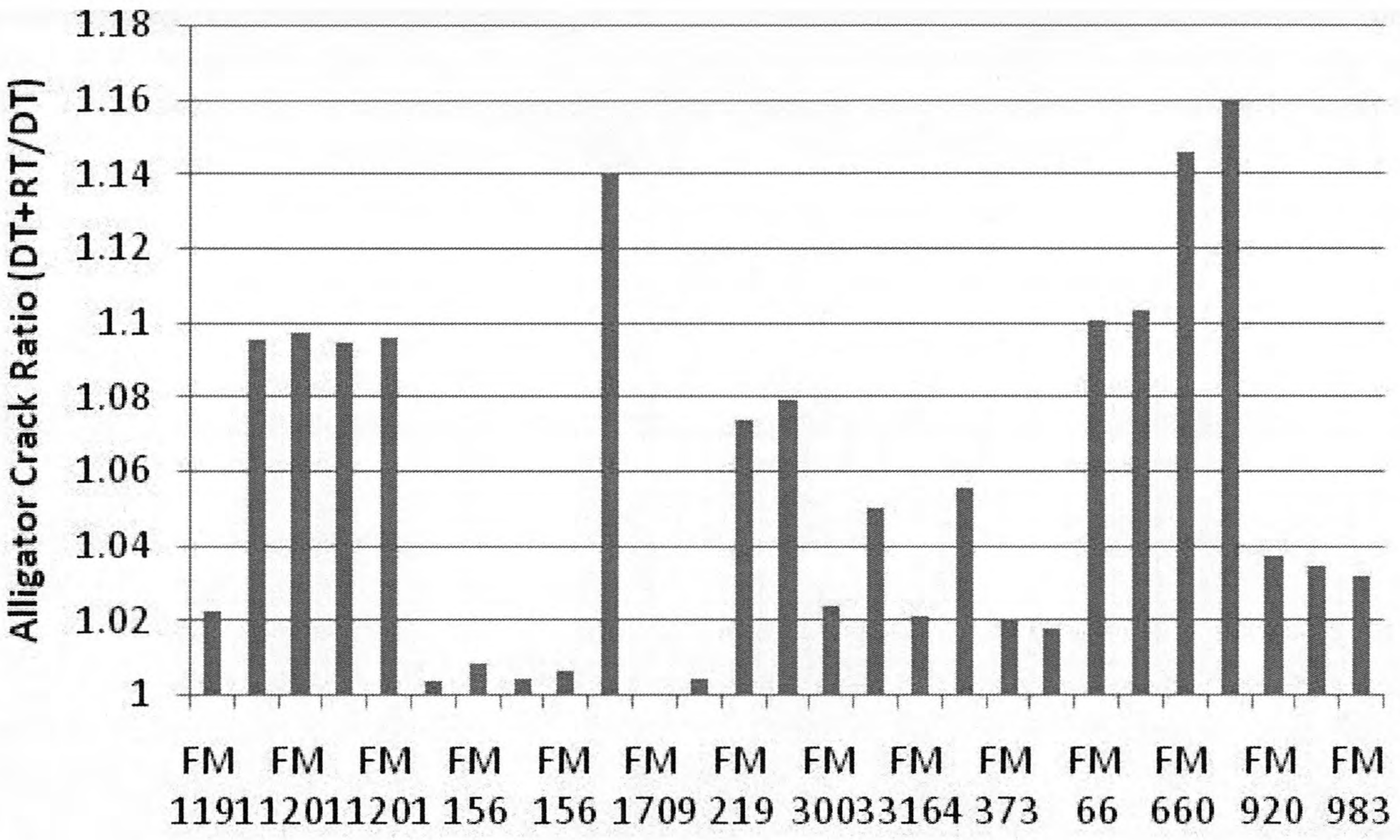


Figure A2.50: Ratio of Alligator Cracks on FM Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

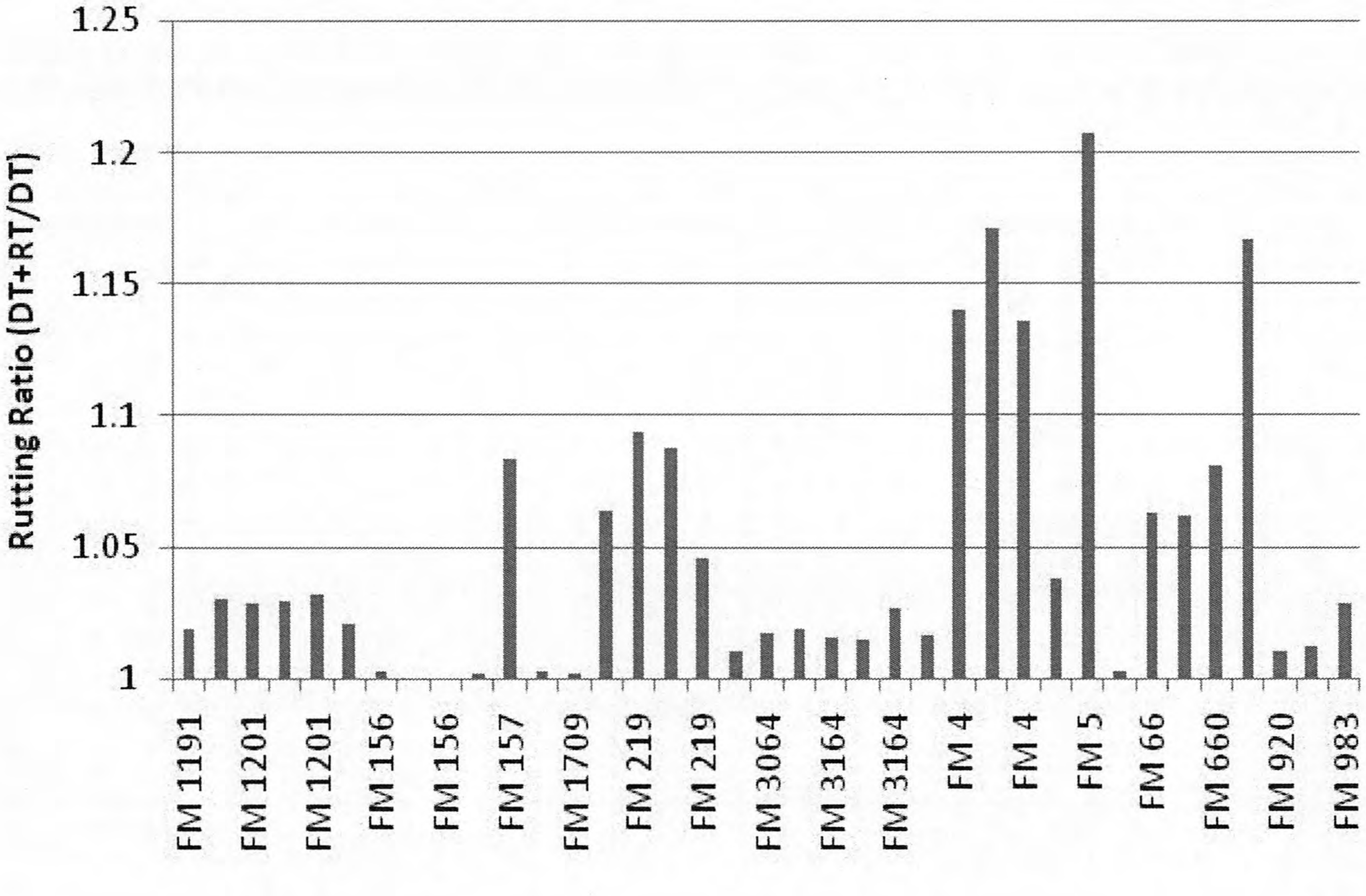


Figure A2.51: Ratio of Rut Depths on FM Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

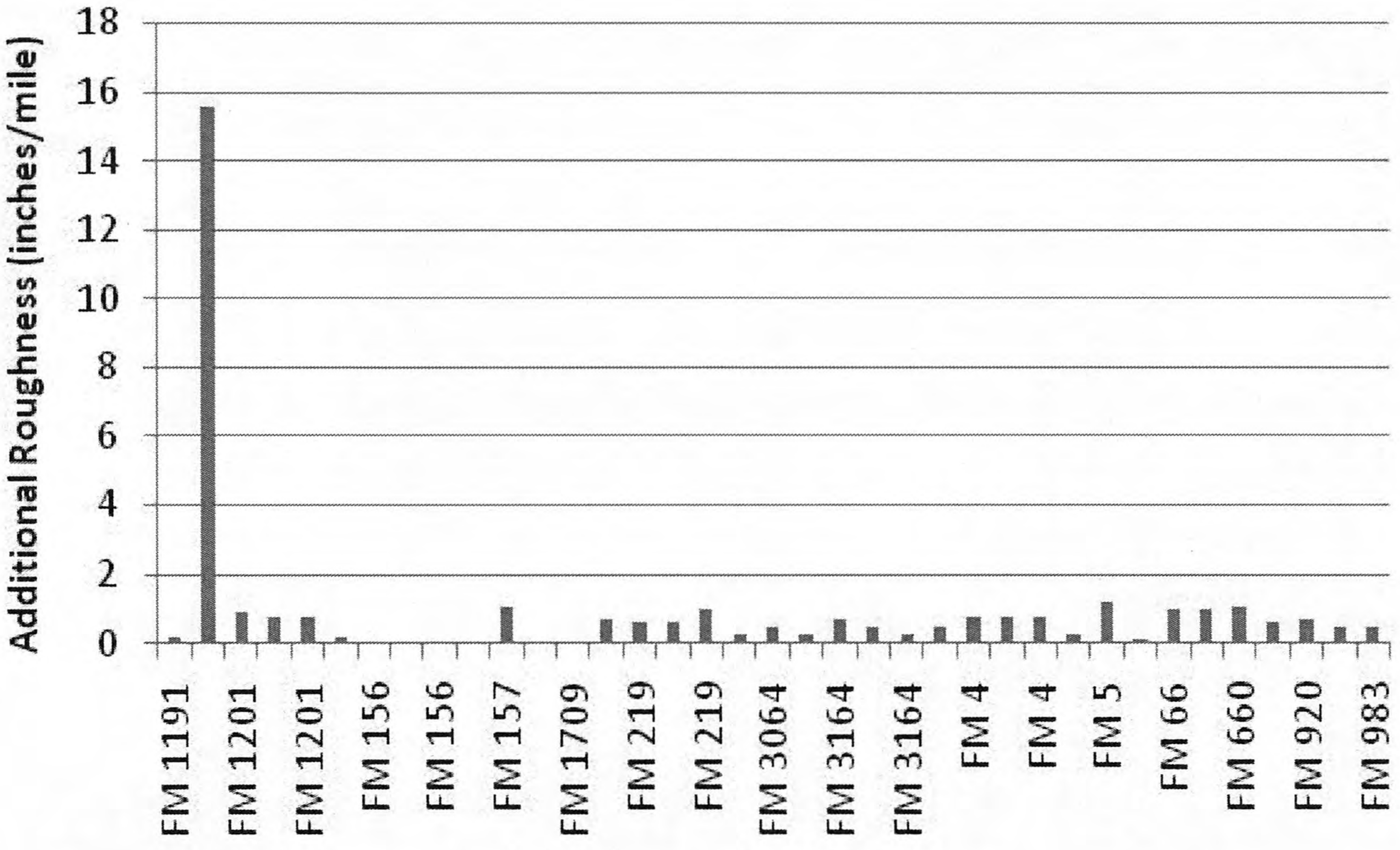


Figure A2.52: Increase in IRI Values for FM Sections due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Due to Saltwater Traffic

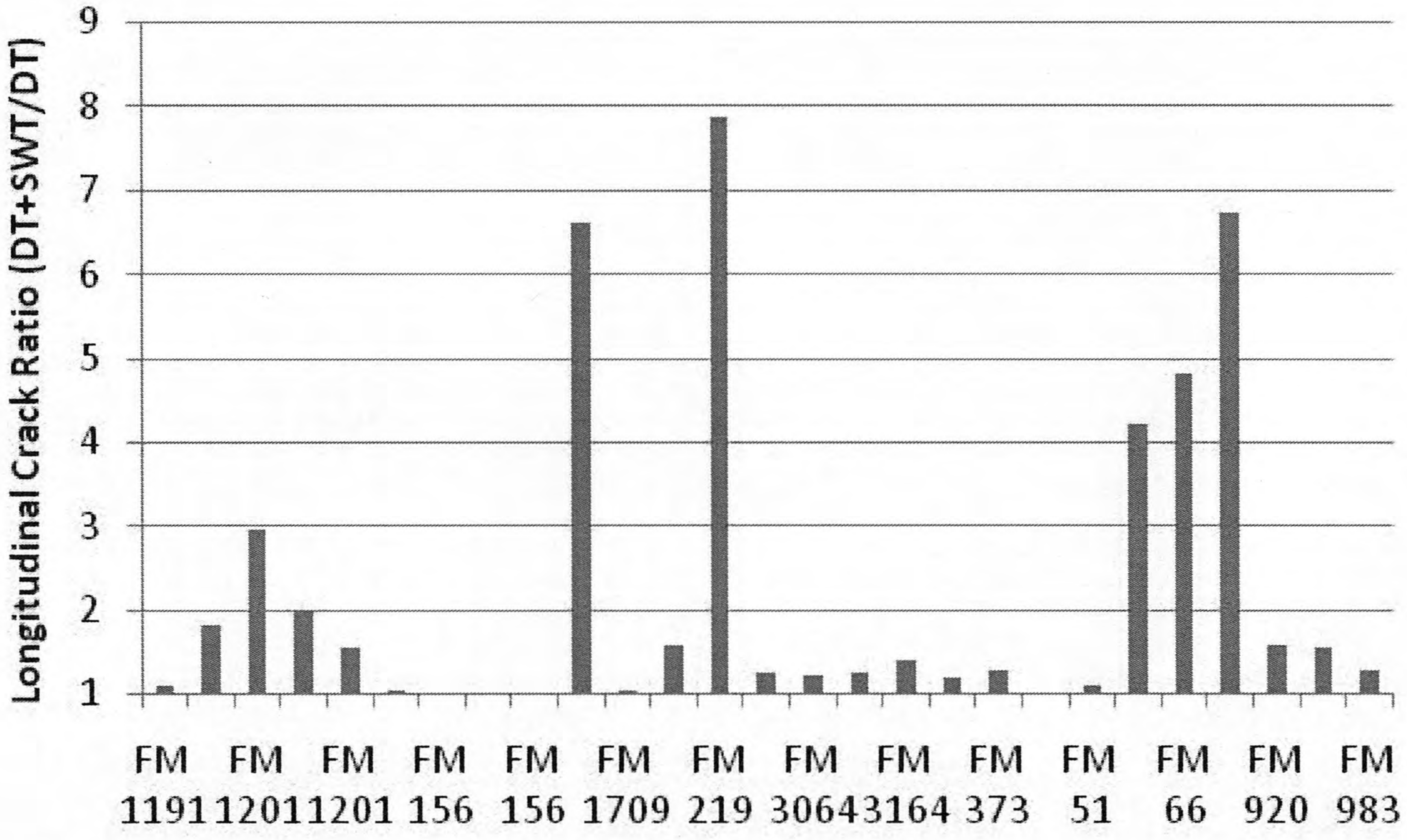


Figure A2.53: Ratio of Longitudinal Cracks on FM Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

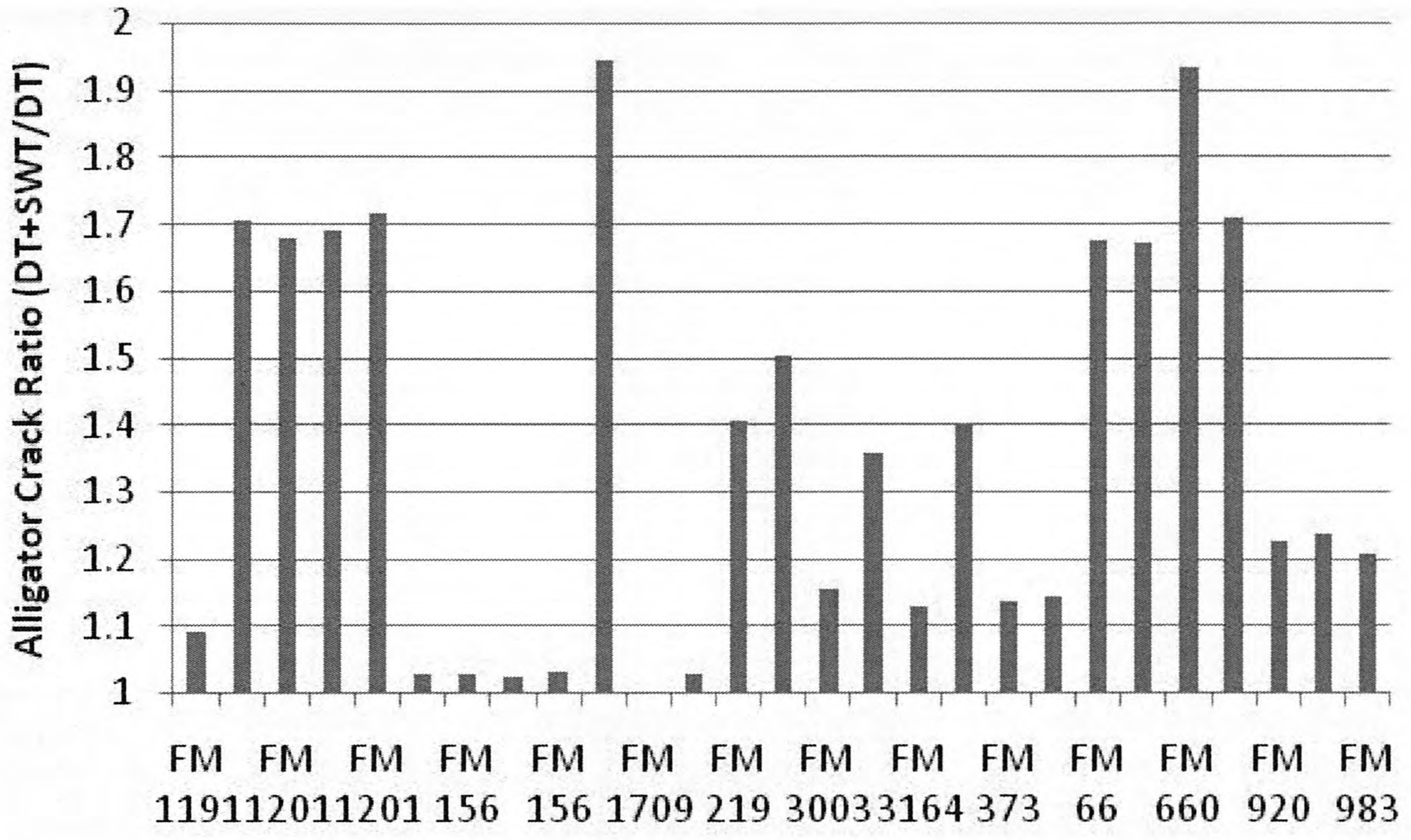


Figure A2.54: Ratio of Alligator Cracks on FM Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

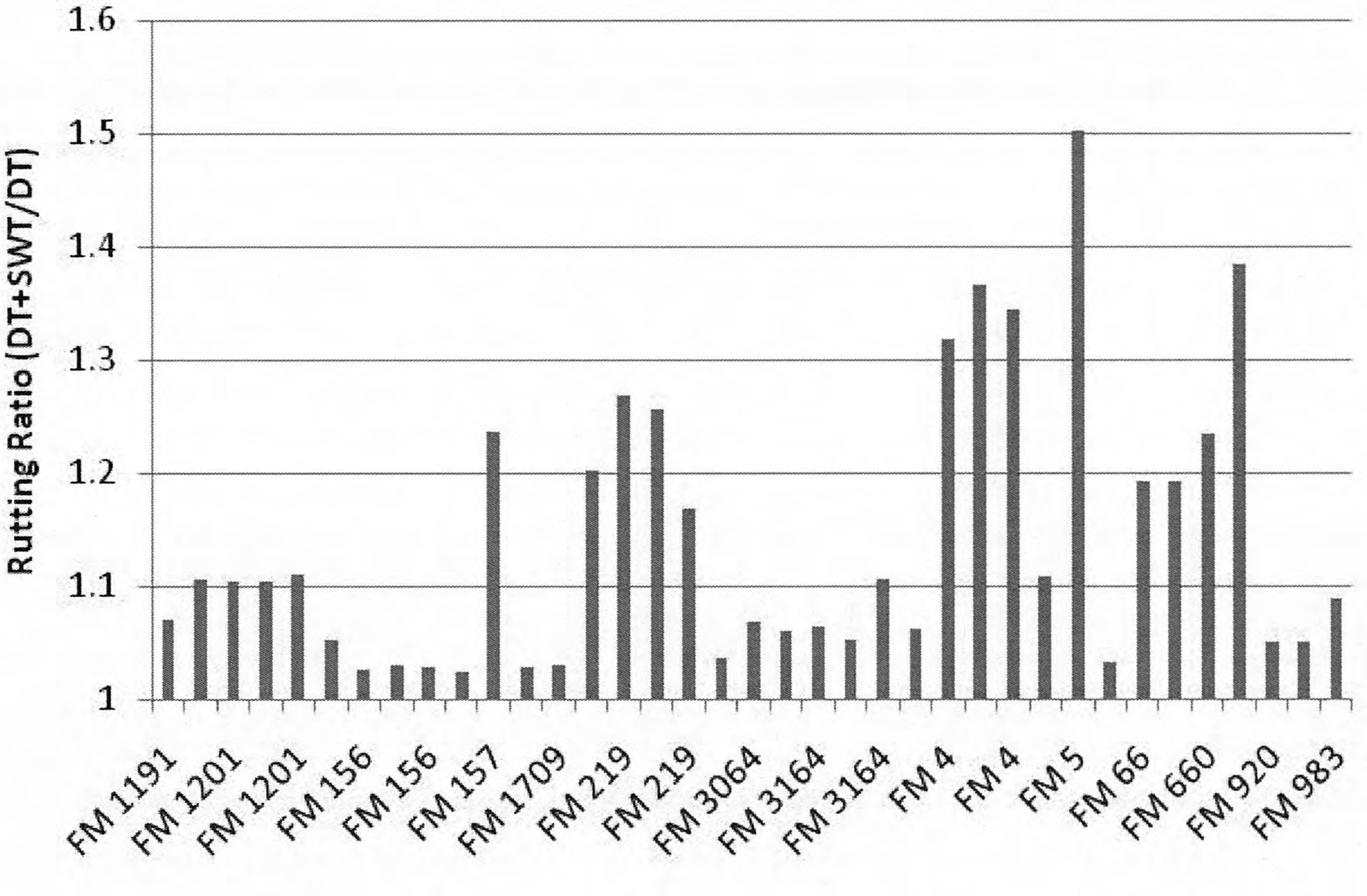


Figure A2.55: Ratio of Rut Depths on FM Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

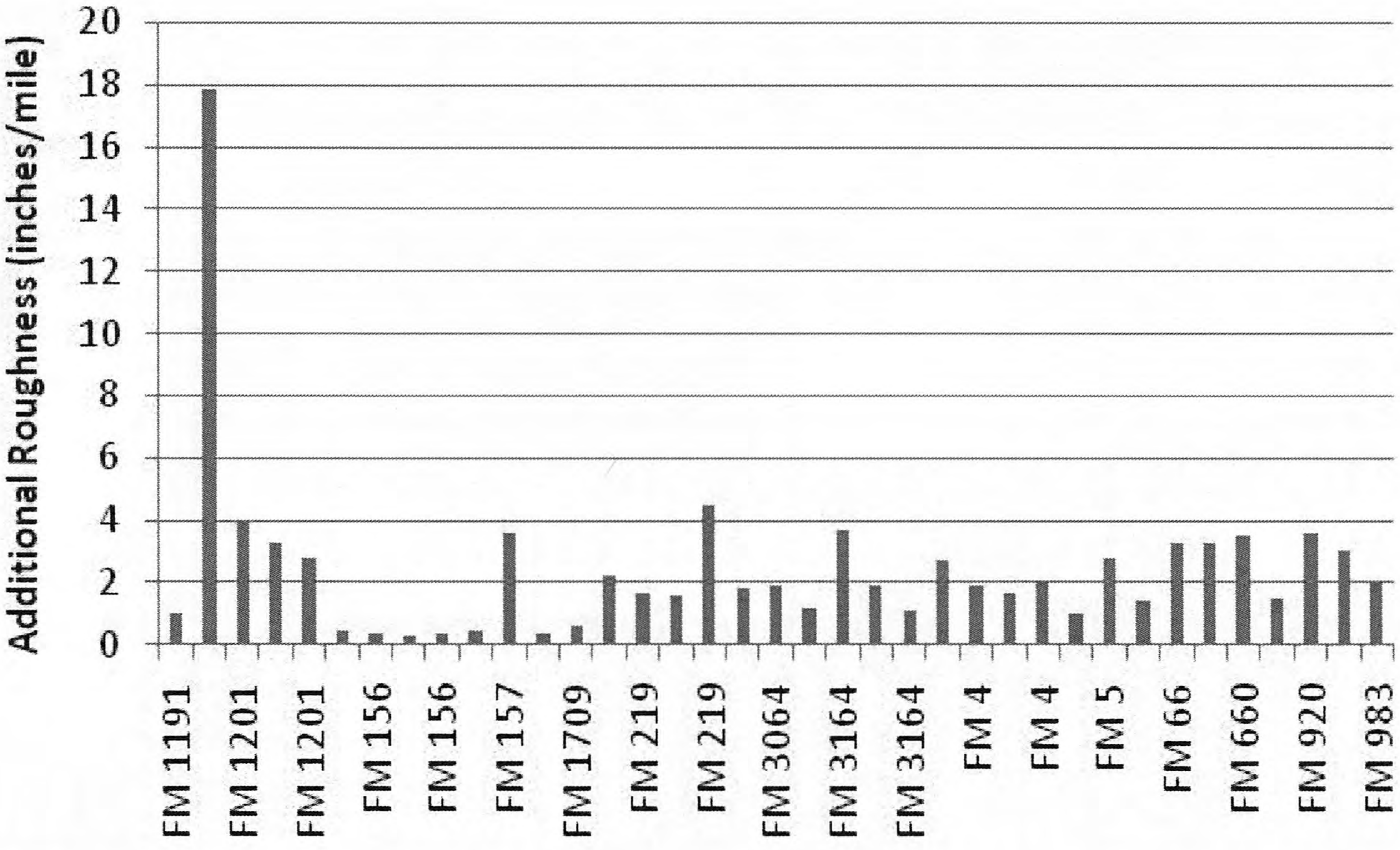


Figure A2.56: Increase in IRI Values for FM Sections due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Due to Construction Traffic

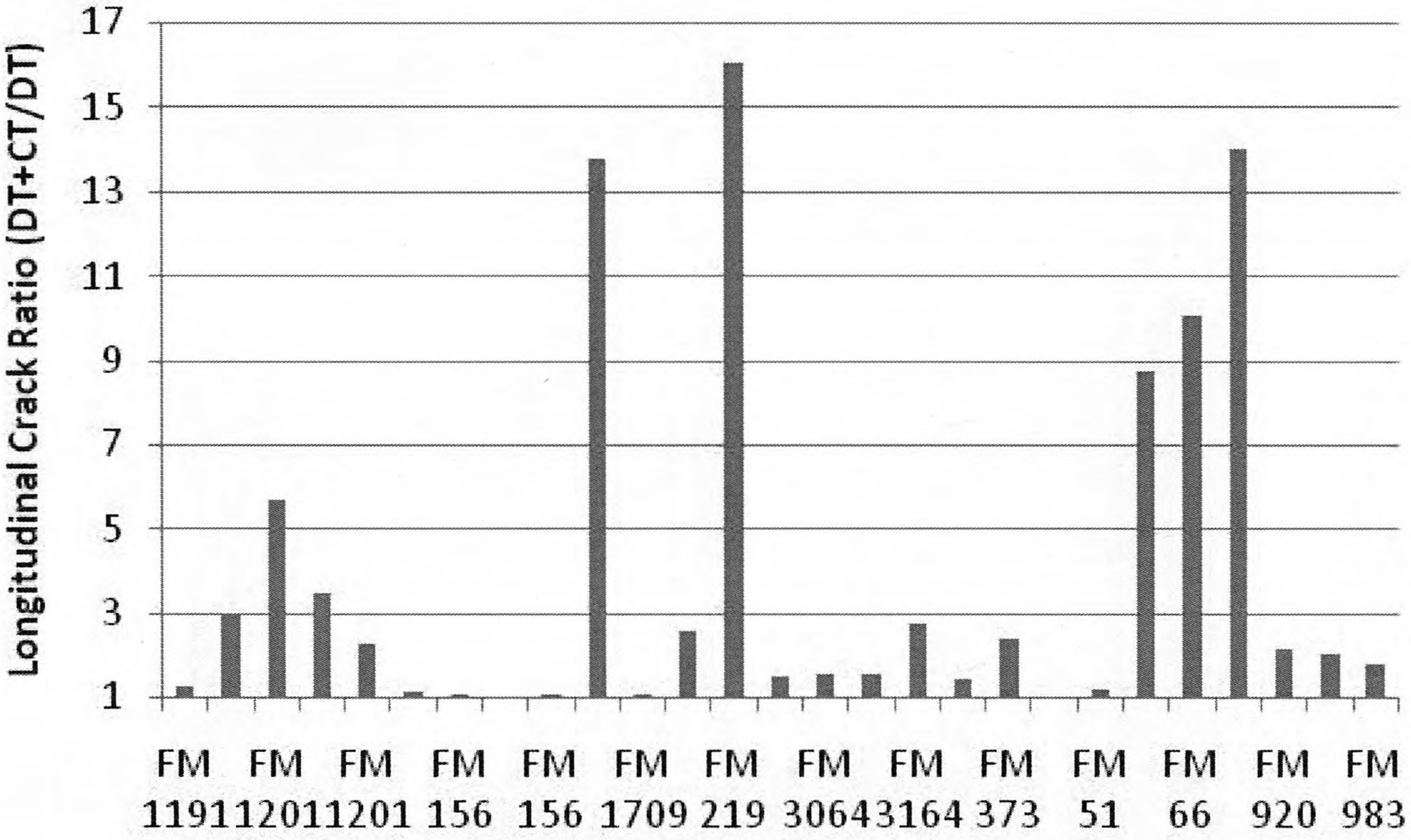


Figure A2.57: Ratio of Longitudinal Cracks on FM Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

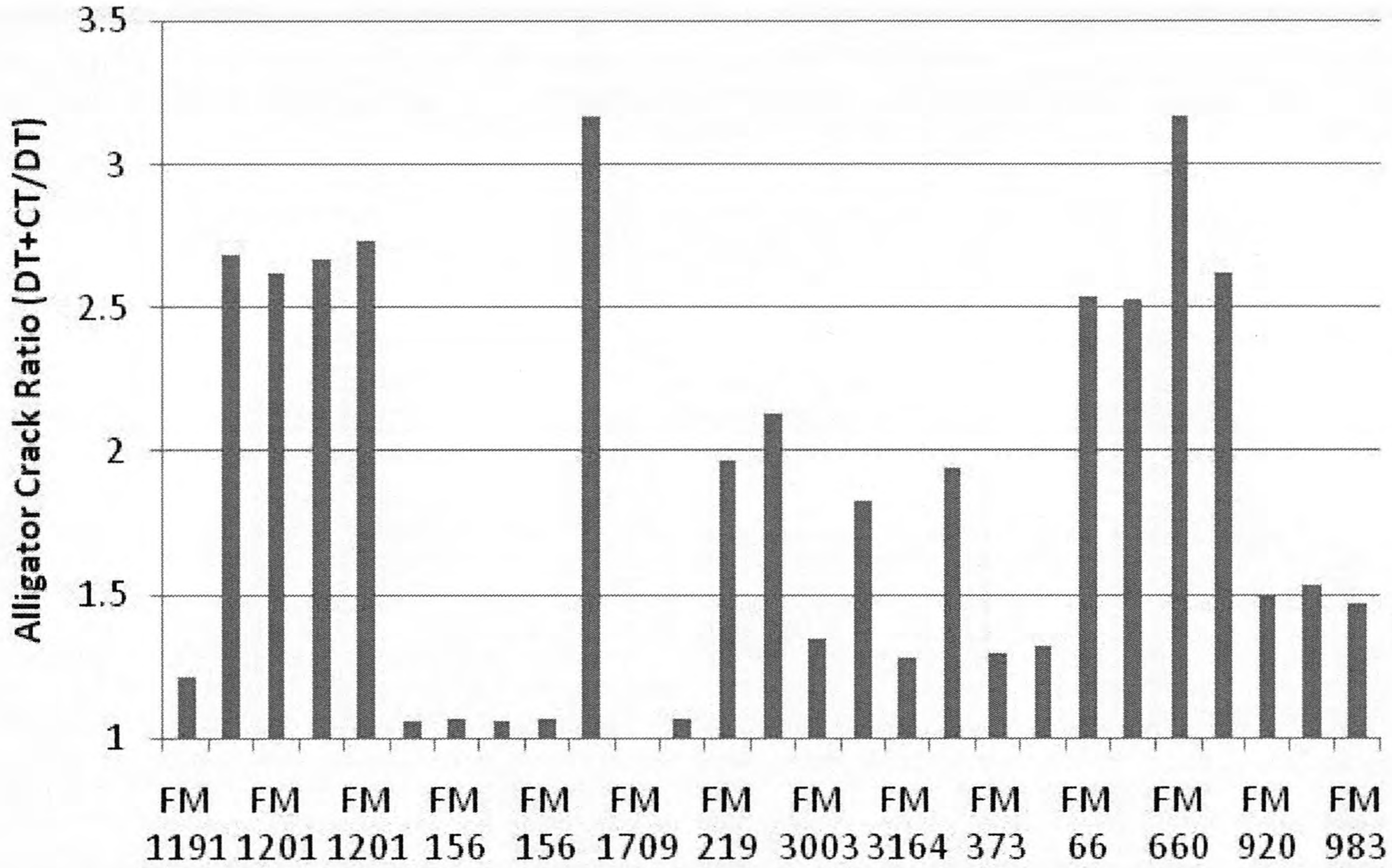


Figure A2.58: Ratio of Alligator Cracks on FM Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

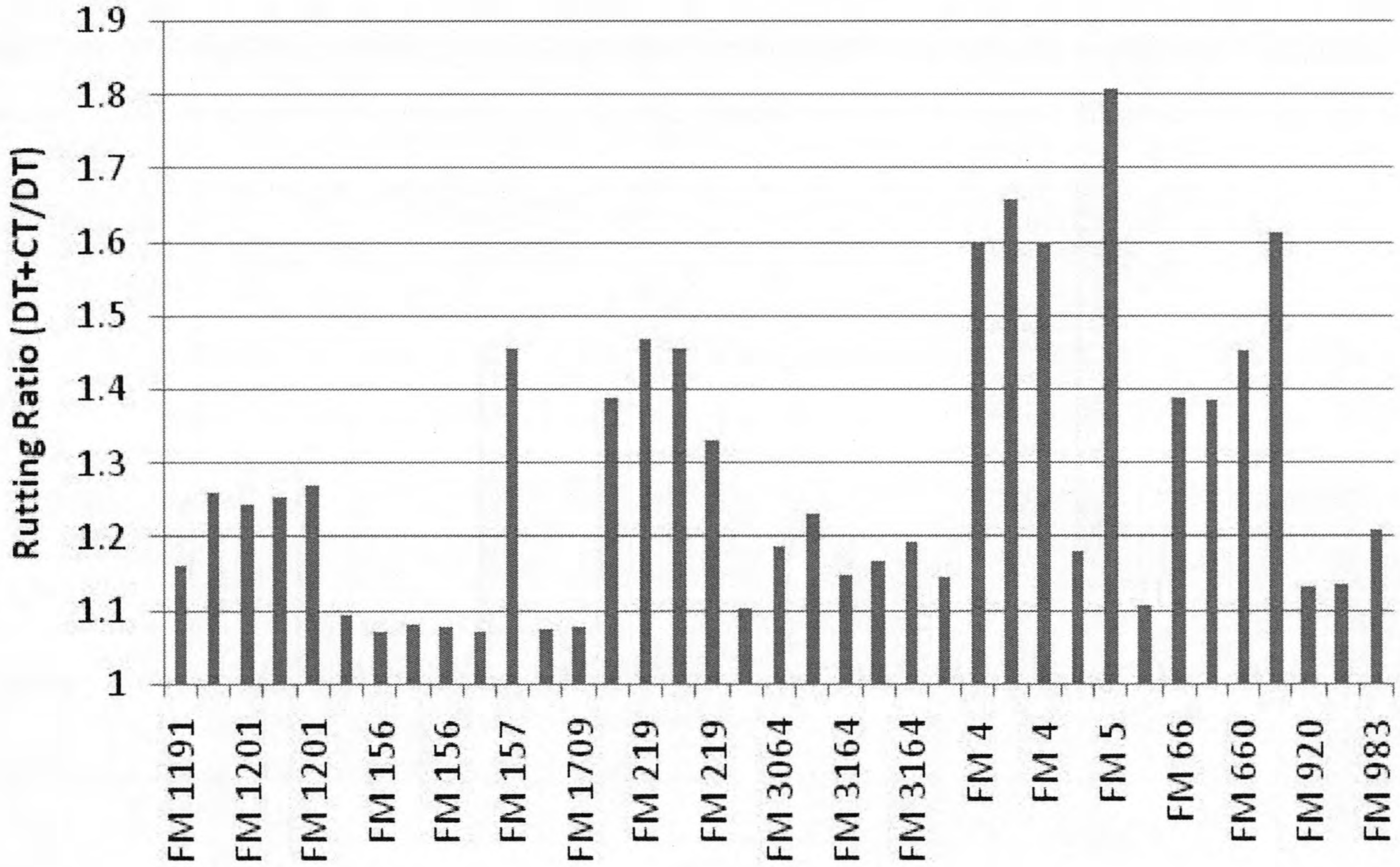


Figure A2.59: Ratio of Rut Depths on FM Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

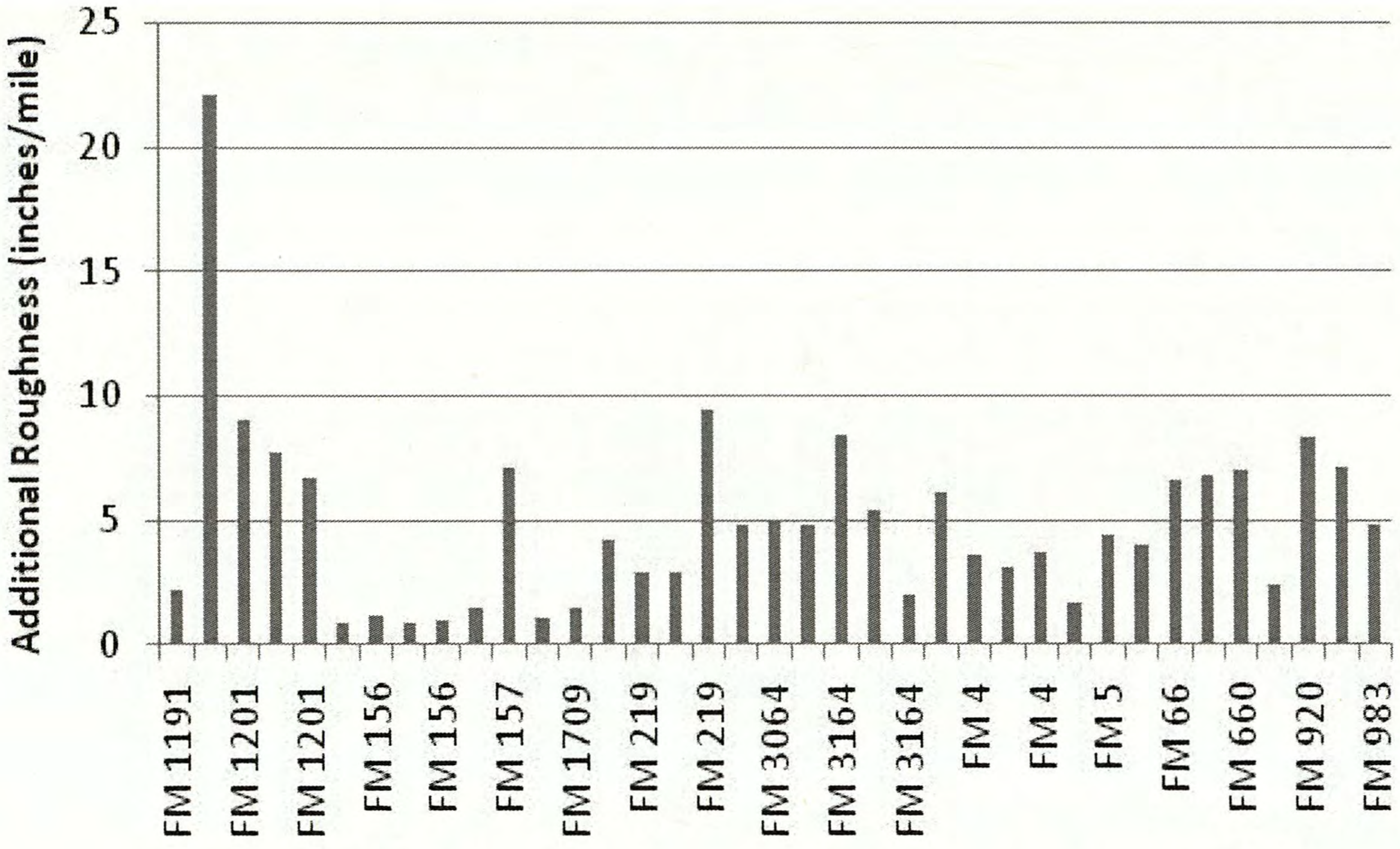


Figure A2.60: Increase in IRI Values for FM Sections due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Additional Damage Imposed by the Crude Oil Industry Operating in the Permian Basin Region

Interstate Highway Sections

Due to Construction Traffic

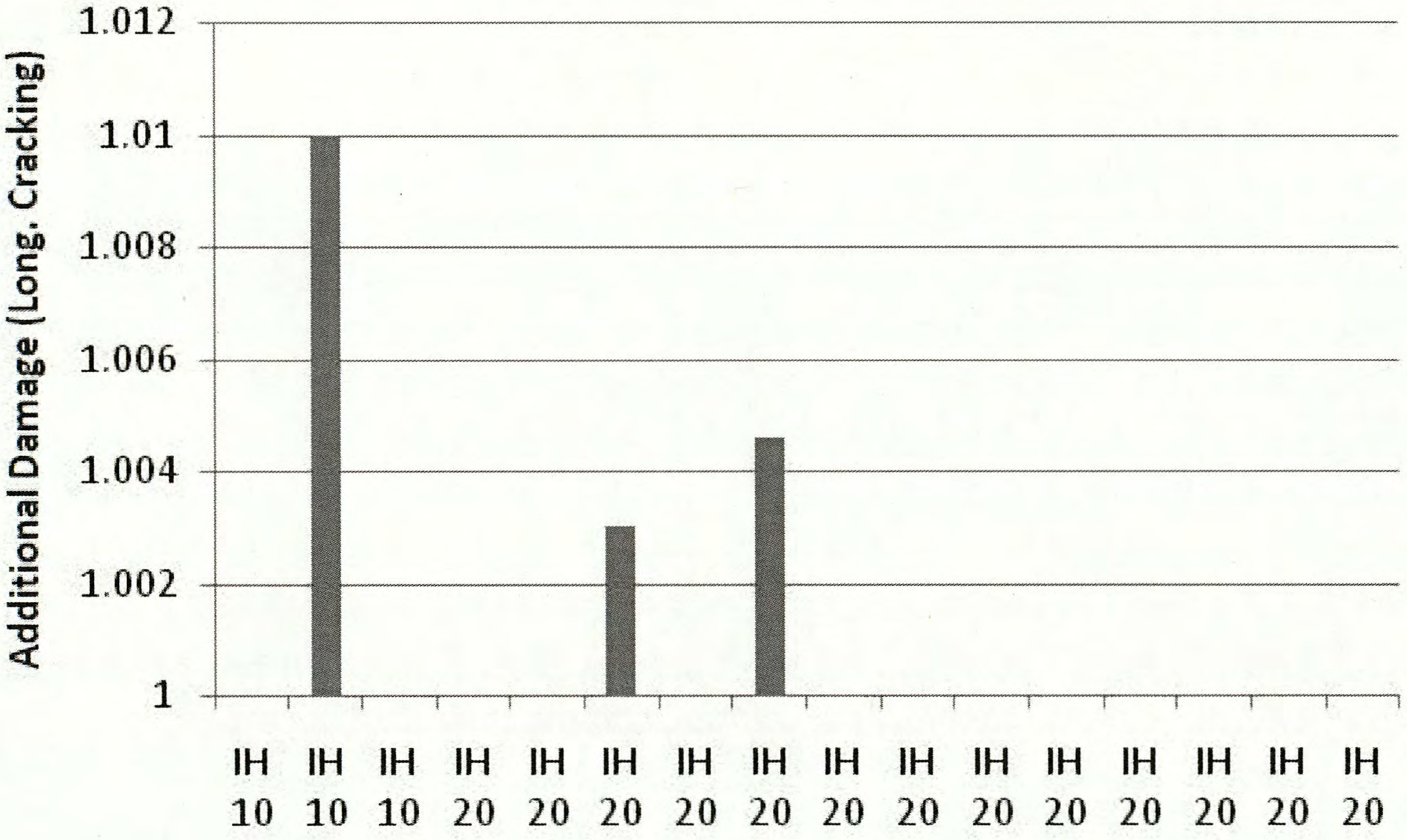


Figure A2.61: Ratio of Longitudinal Cracks on IH Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

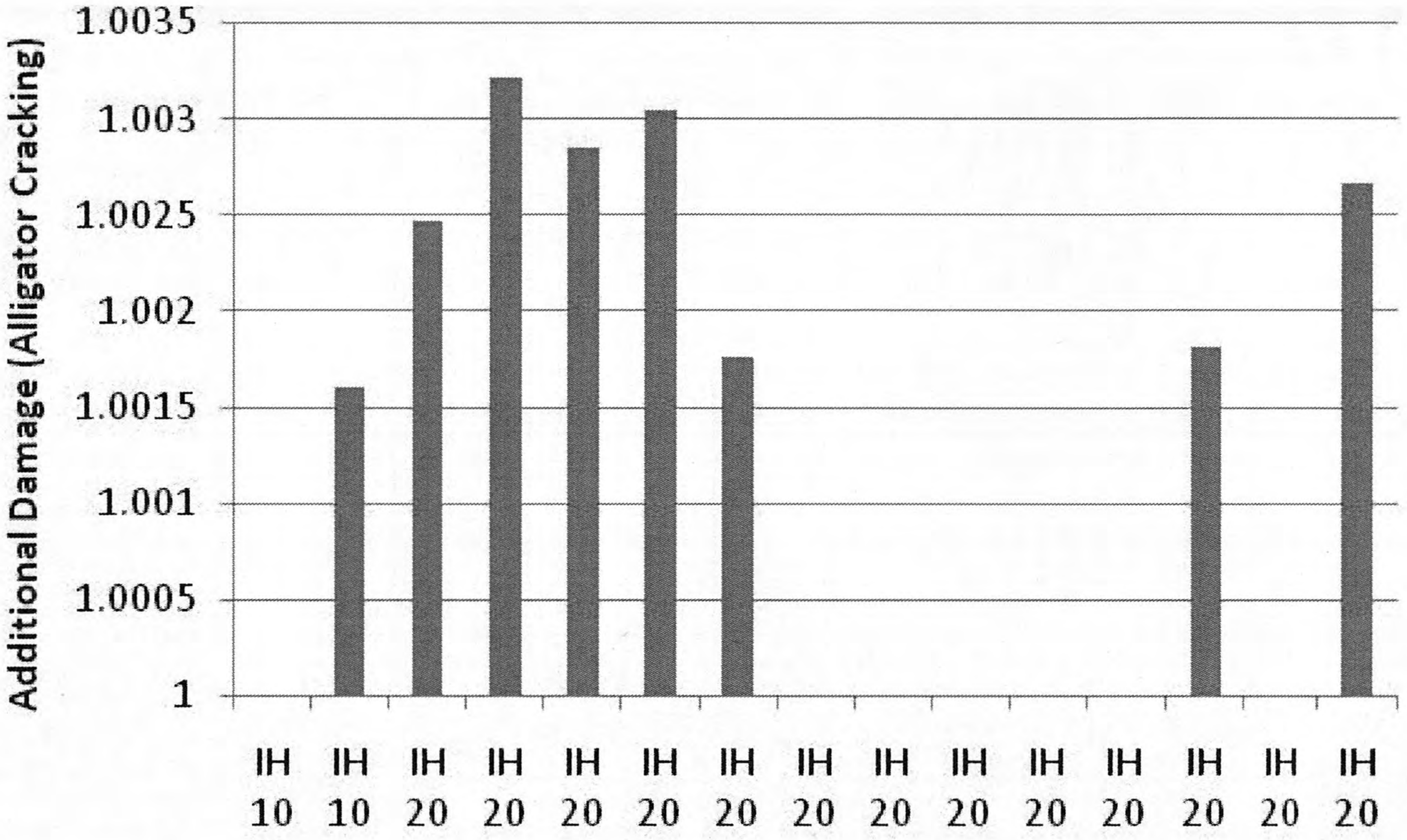


Figure A2.62: Ratio of Alligator Cracks on IH Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

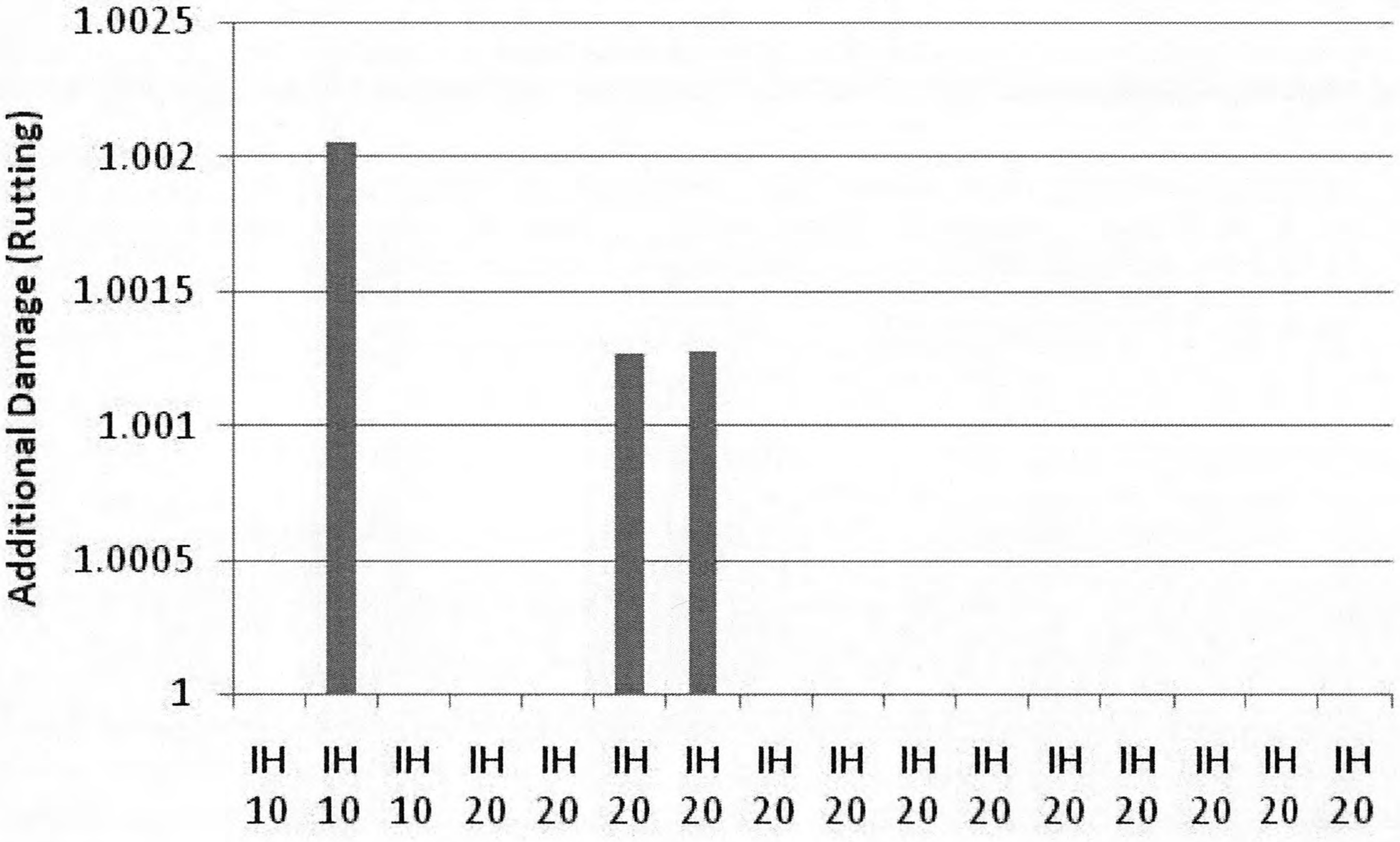


Figure A2.63: Ratio of Rut Depths on IH Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

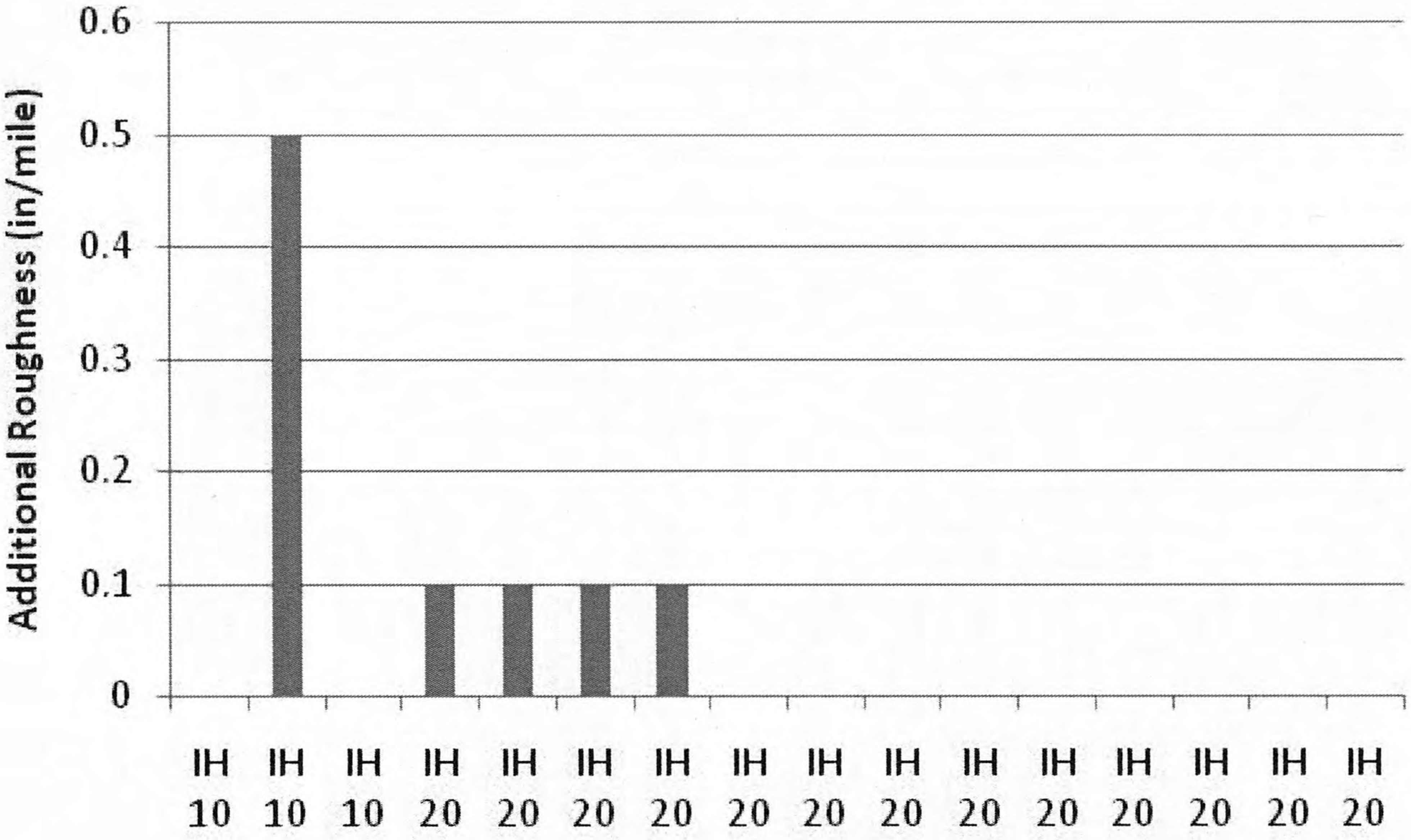


Figure A2.64: Increase in IRI Values for IH Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Due to Production Traffic

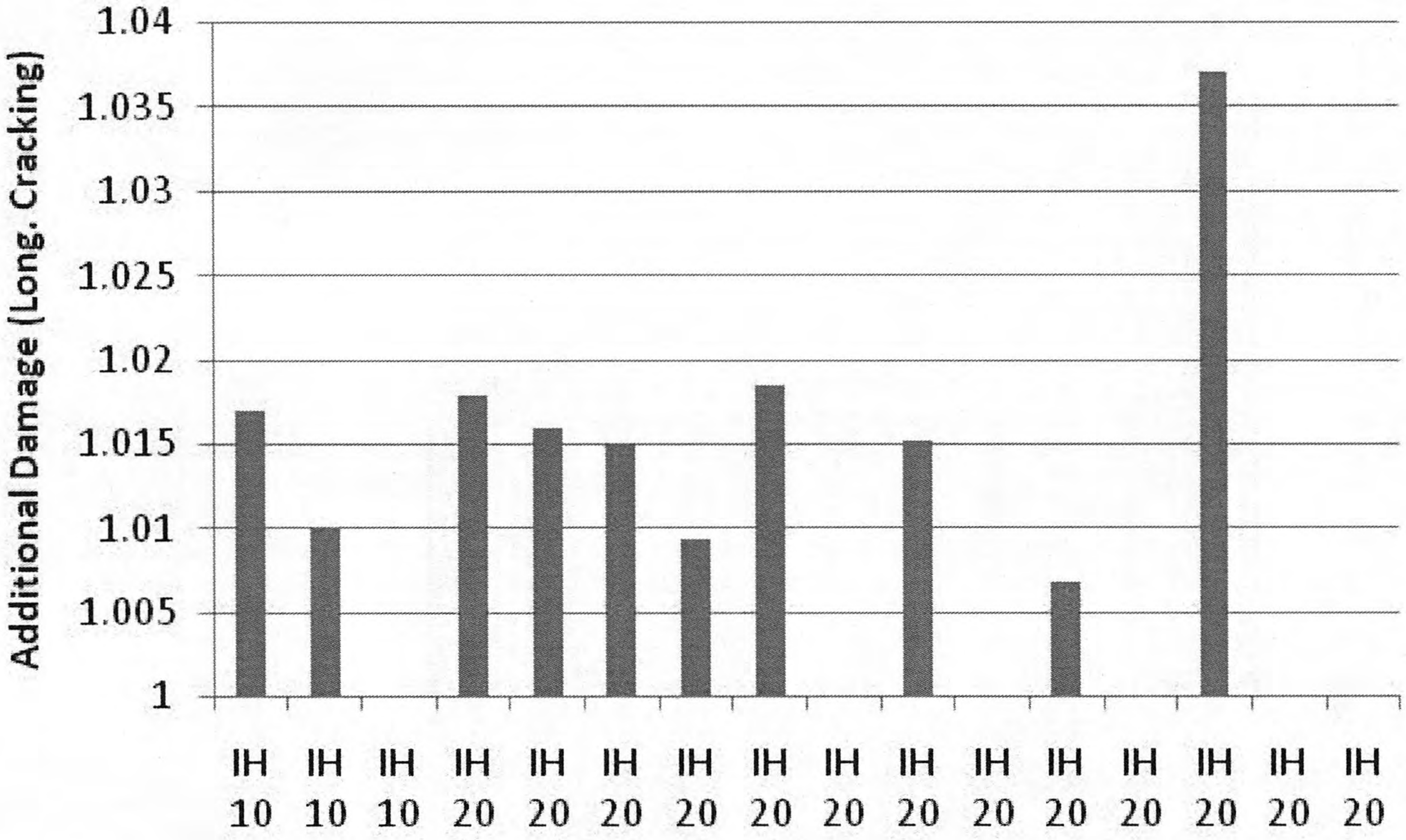


Figure A2.65: Ratio of Longitudinal Cracks on IH Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

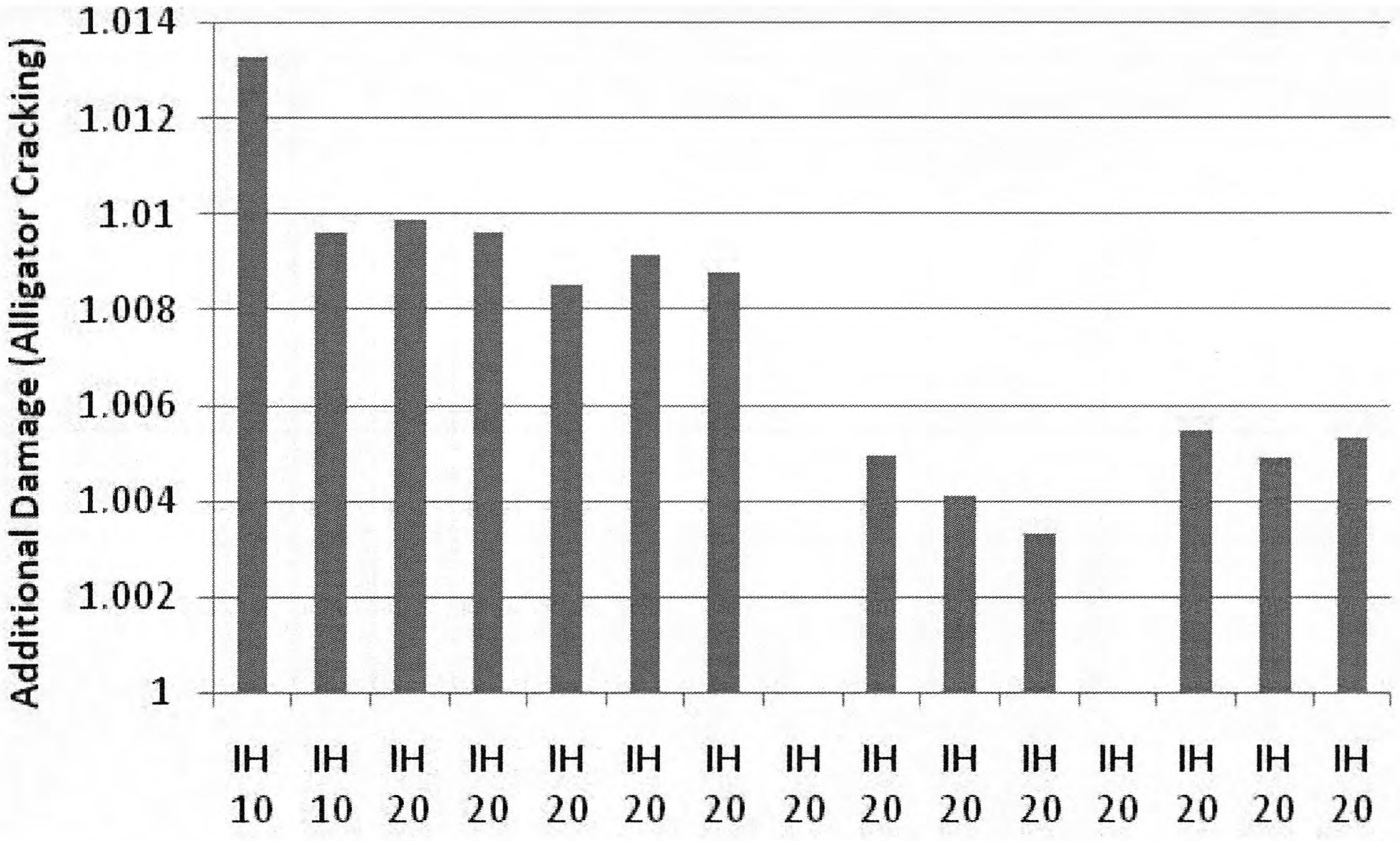


Figure A2.66: Ratio of Alligator Cracks on IH Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

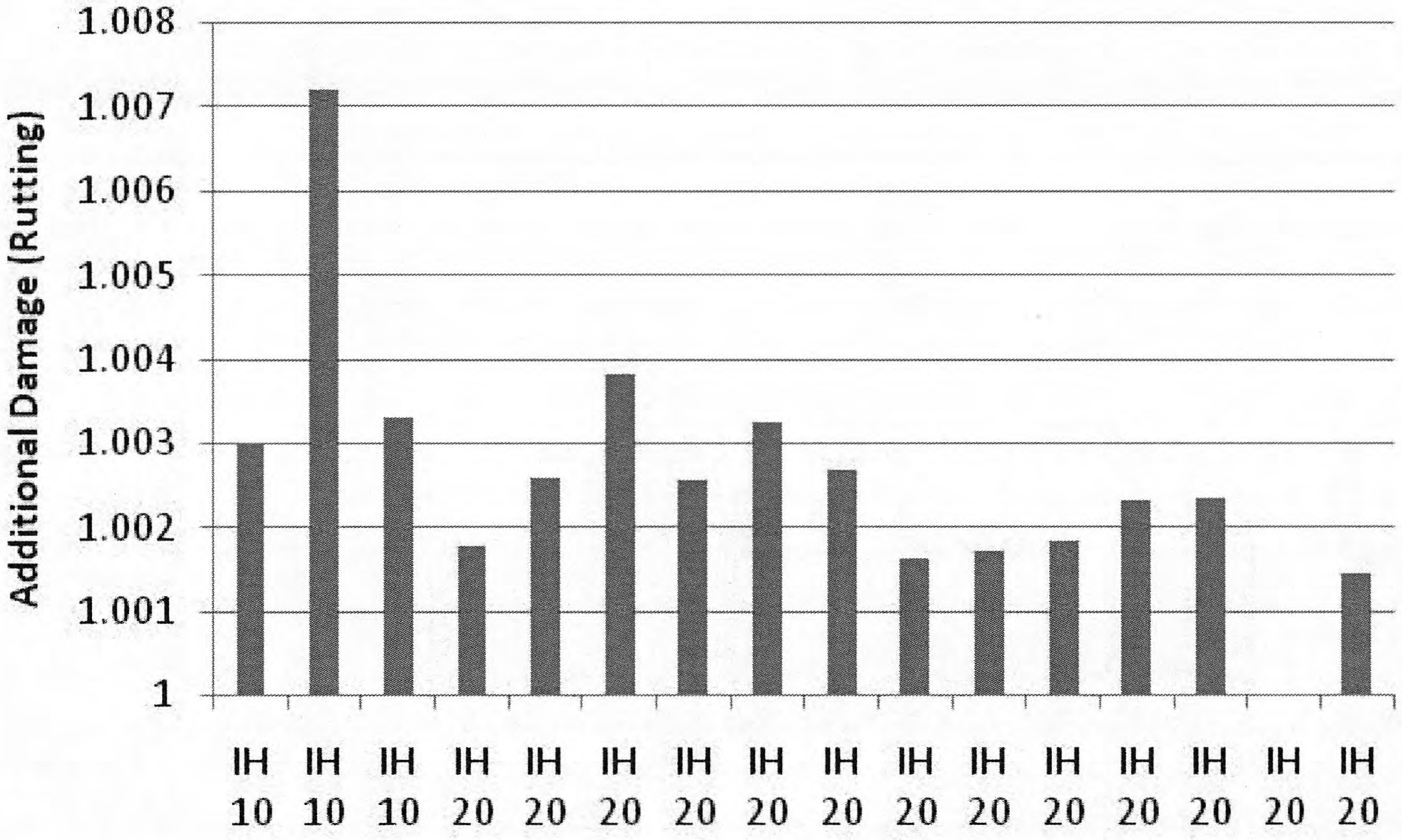


Figure A2.67: Ratio of Rut Depths on IH Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

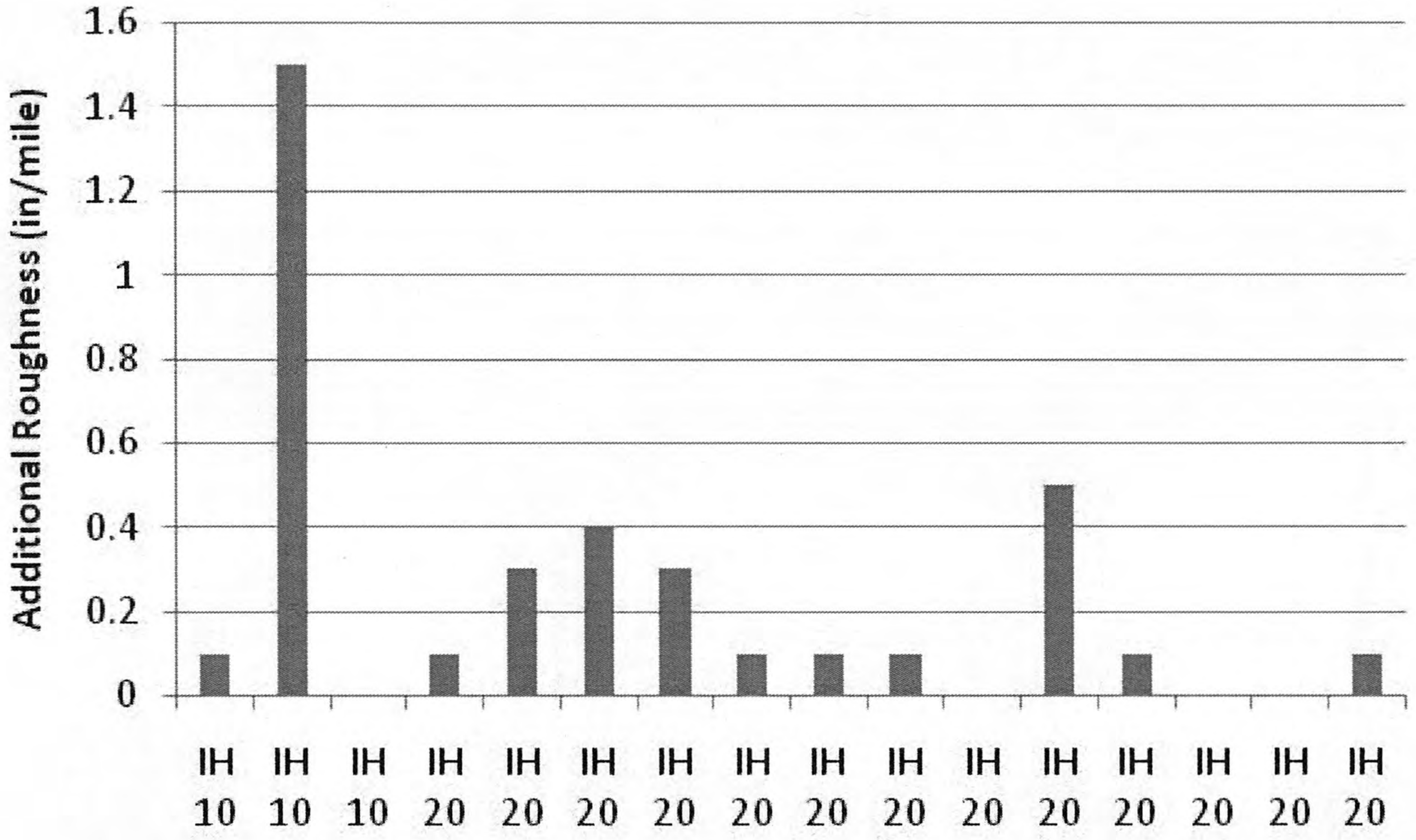


Figure A2.68: Increase in IRI Values for IH Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

US Highway Sections

Due to Construction Traffic

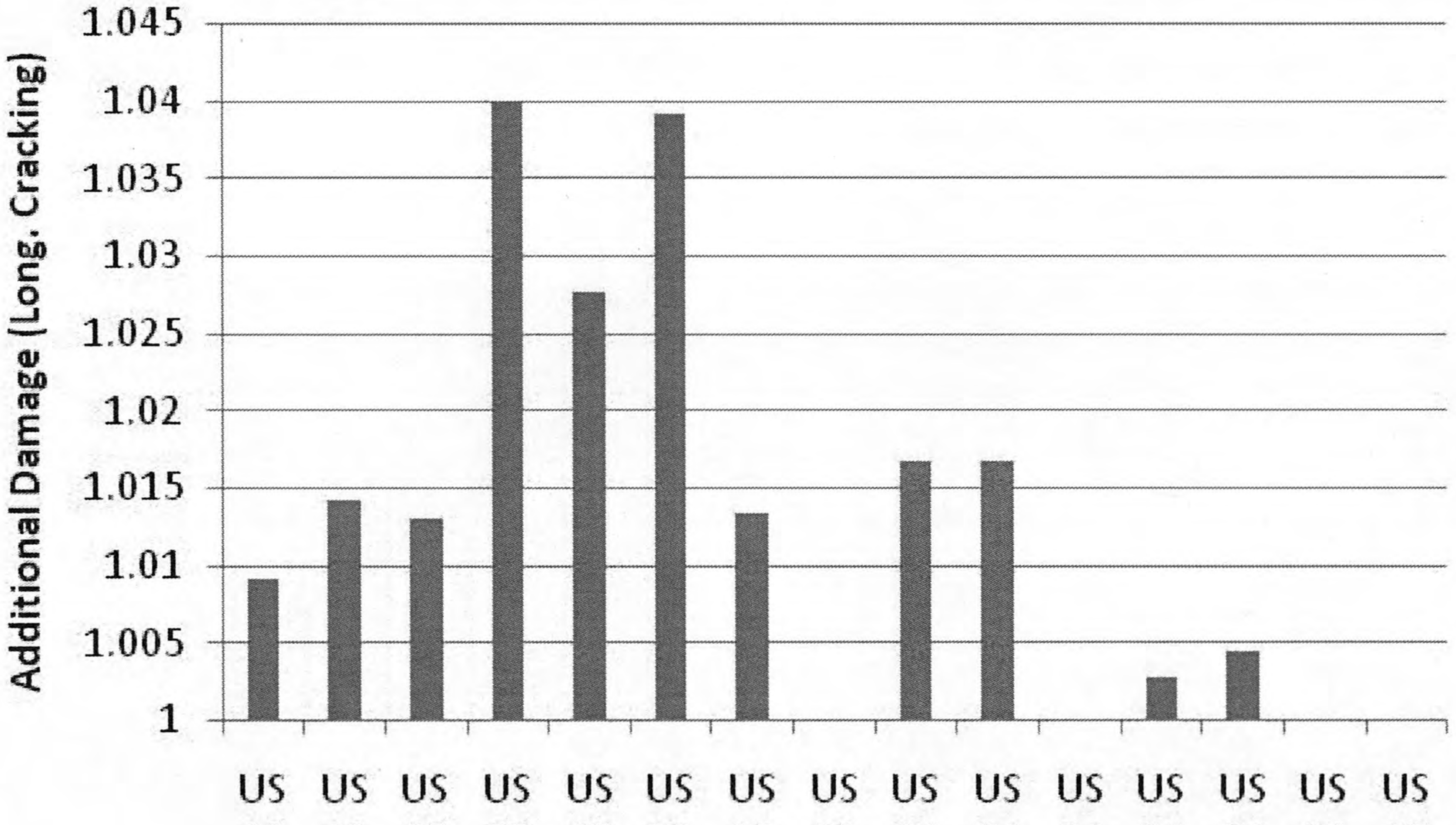


Figure A2.69: Ratio of Longitudinal Cracks on US Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

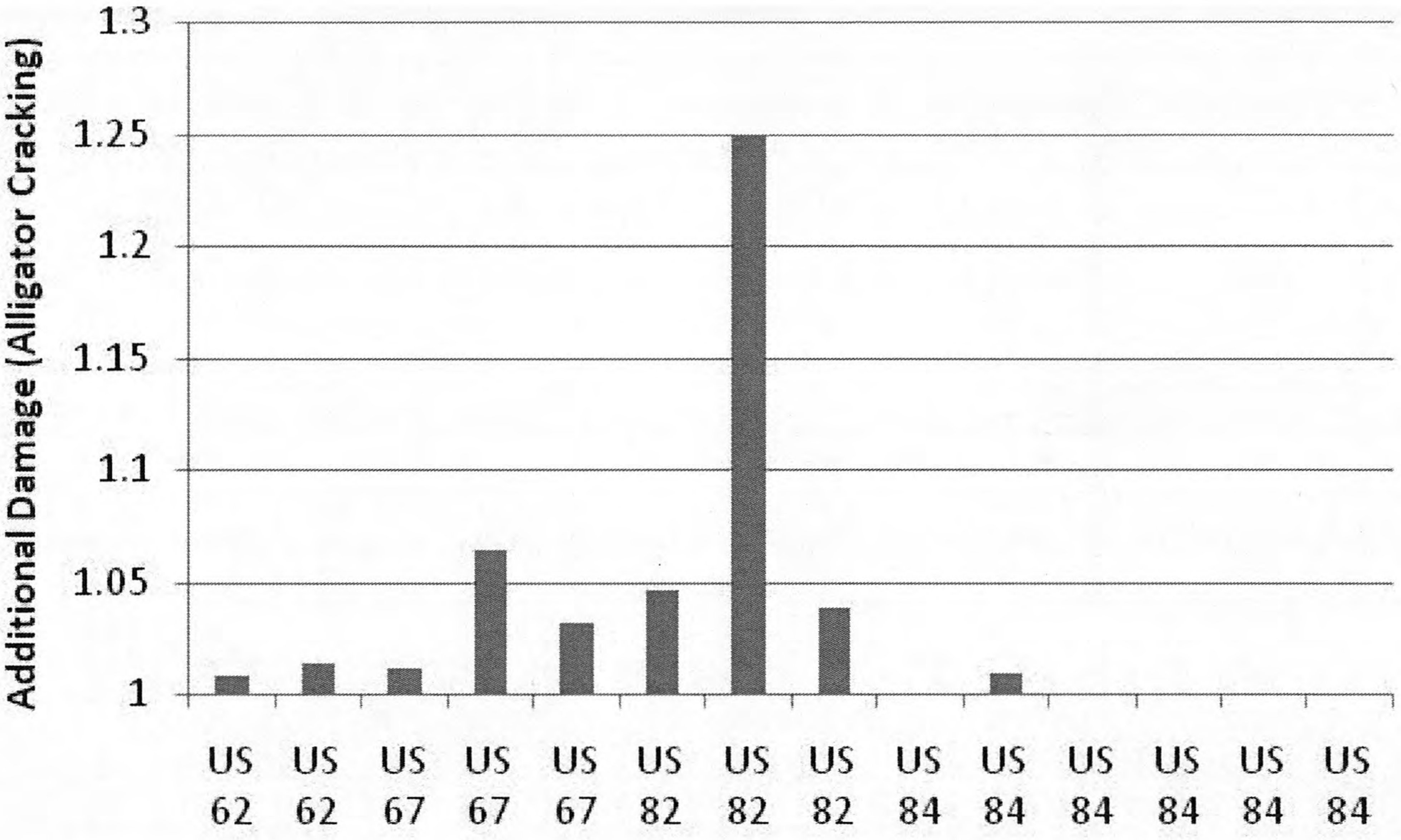


Figure A2.70: Ratio of Alligator Cracks on US Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

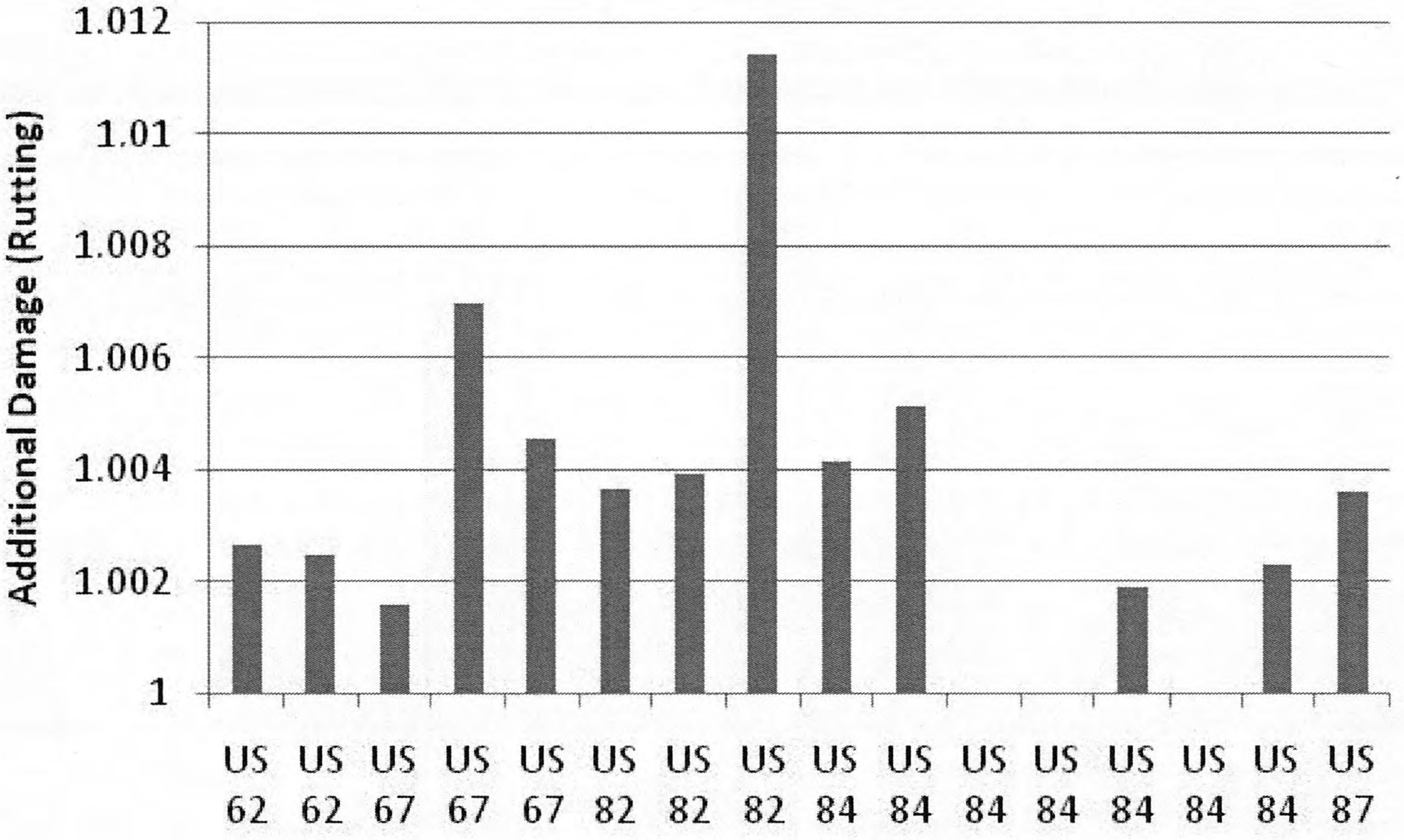


Figure A2.71: Ratio of Rut Depths on US Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

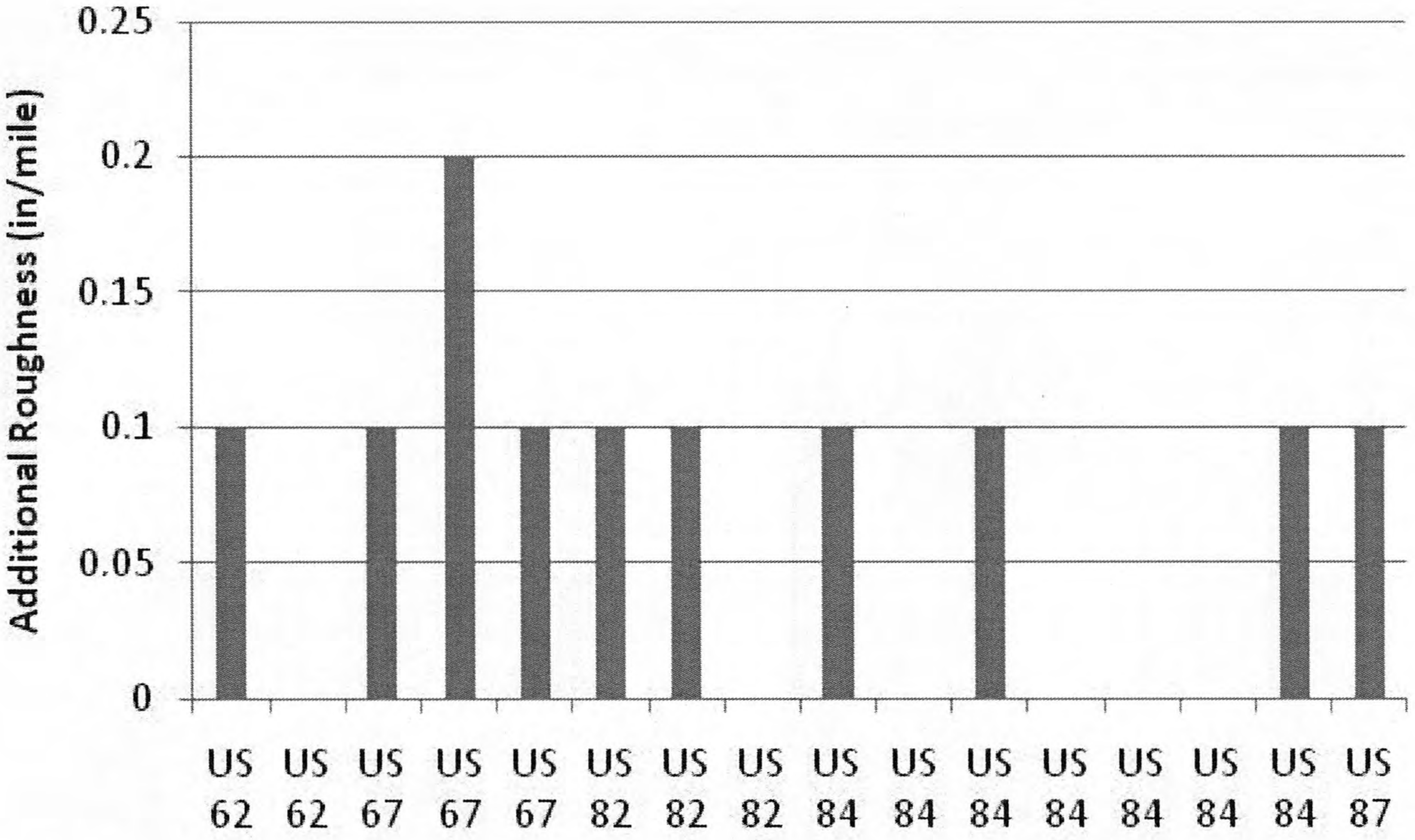


Figure A2.72: Increase in IRI Values for US Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Due to Production Traffic

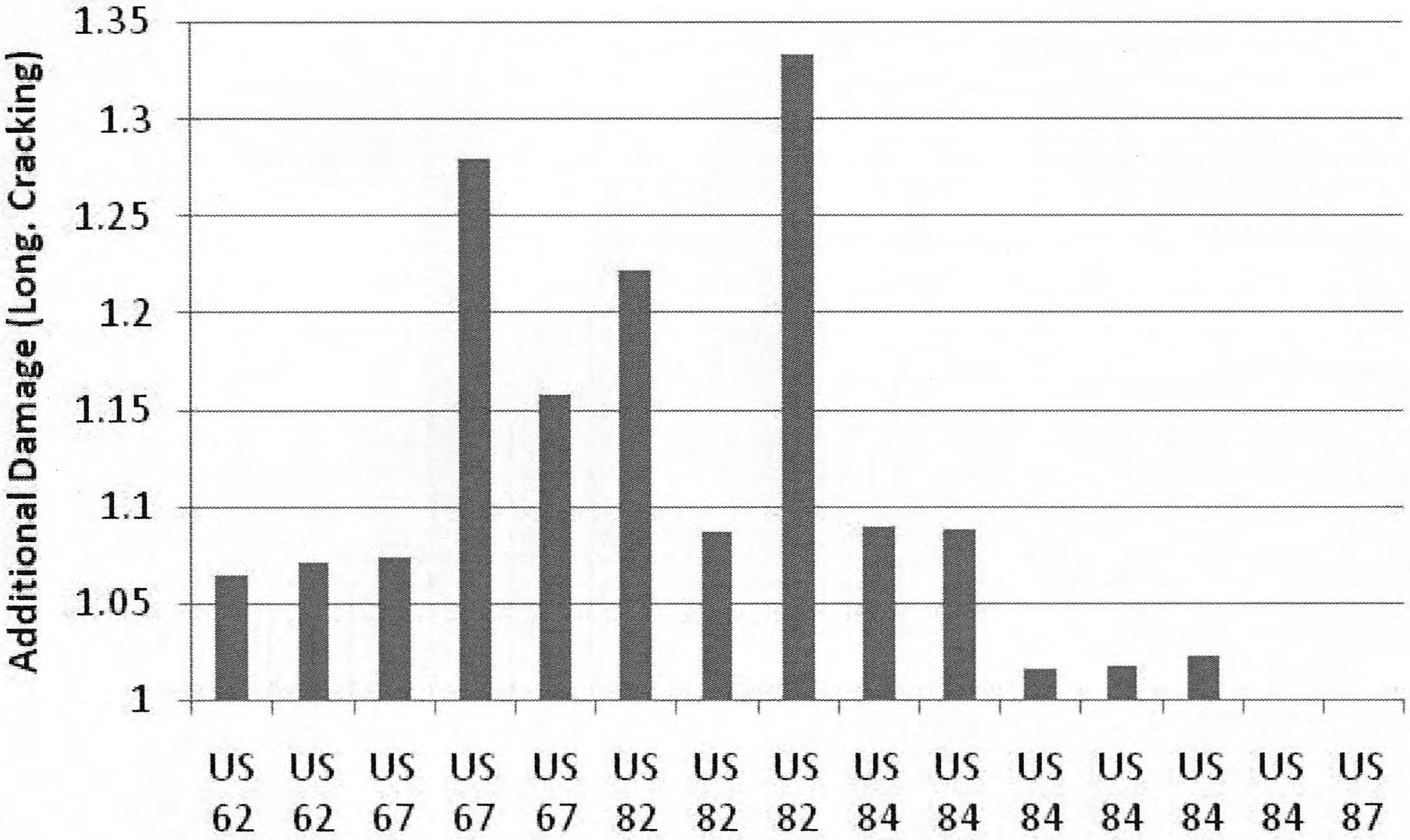


Figure A2.73: Ratio of Longitudinal Cracks on US Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

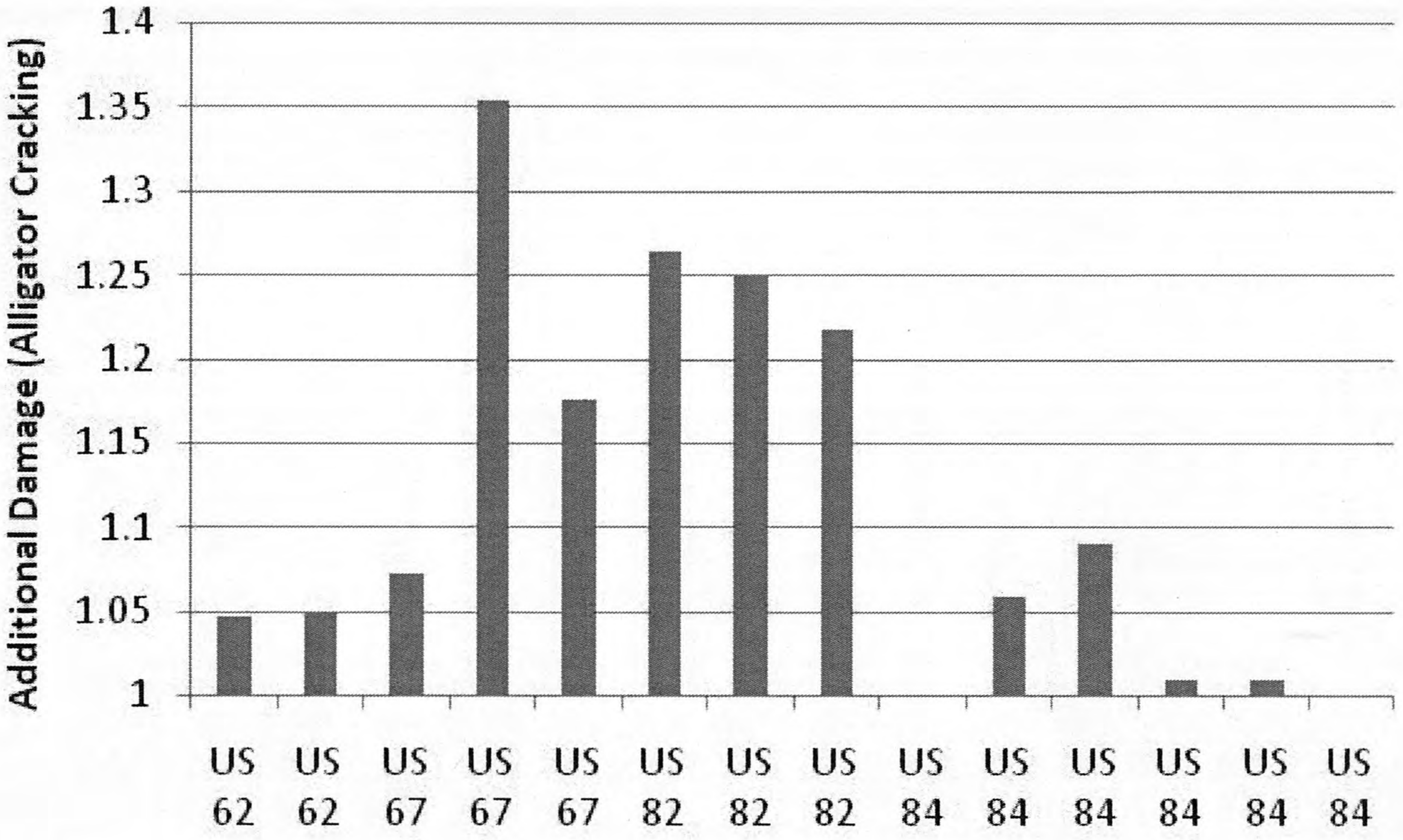


Figure A2.74: Ratio of Alligator Cracks on US Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

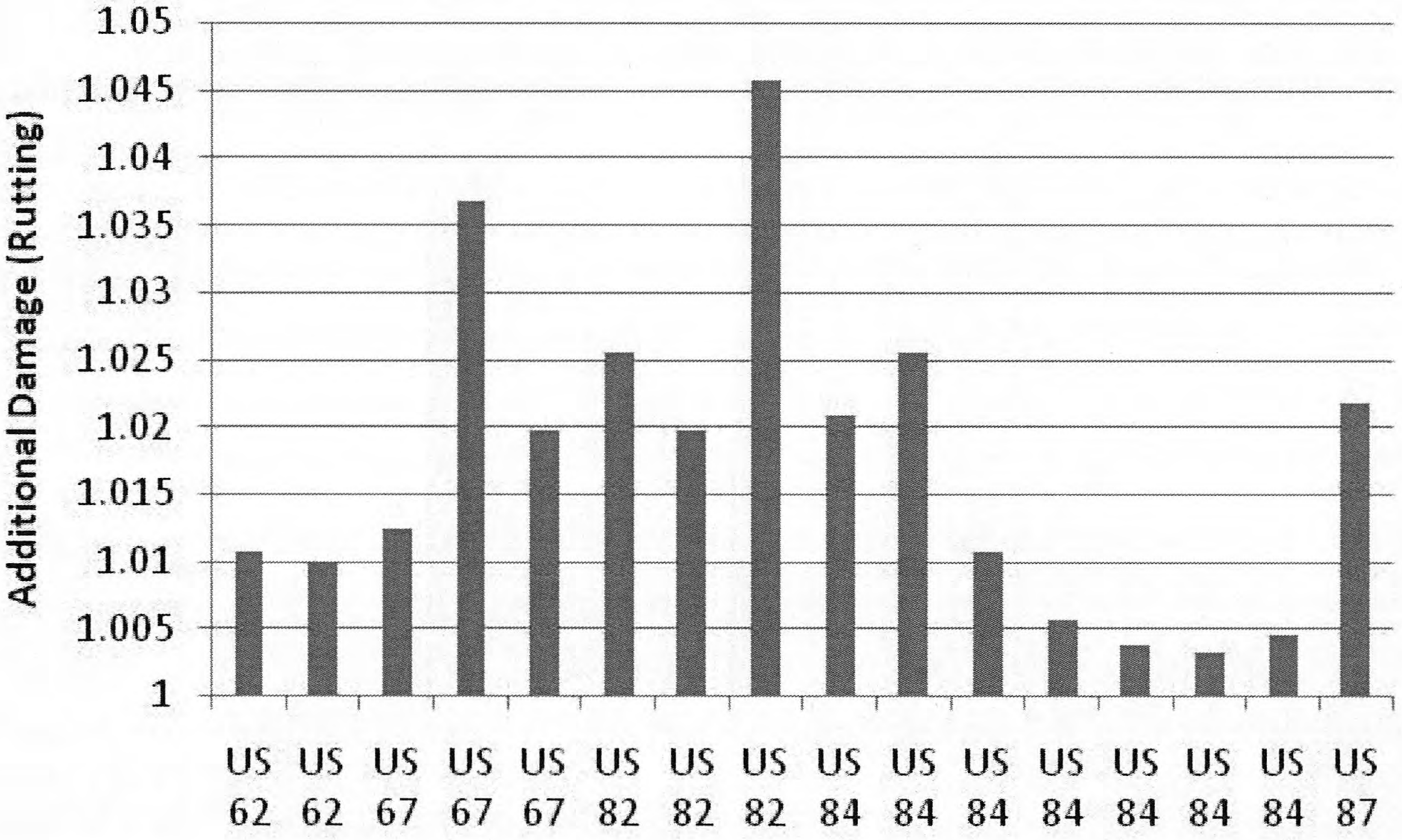


Figure A2.75: Ratio of Rut Depths on US Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

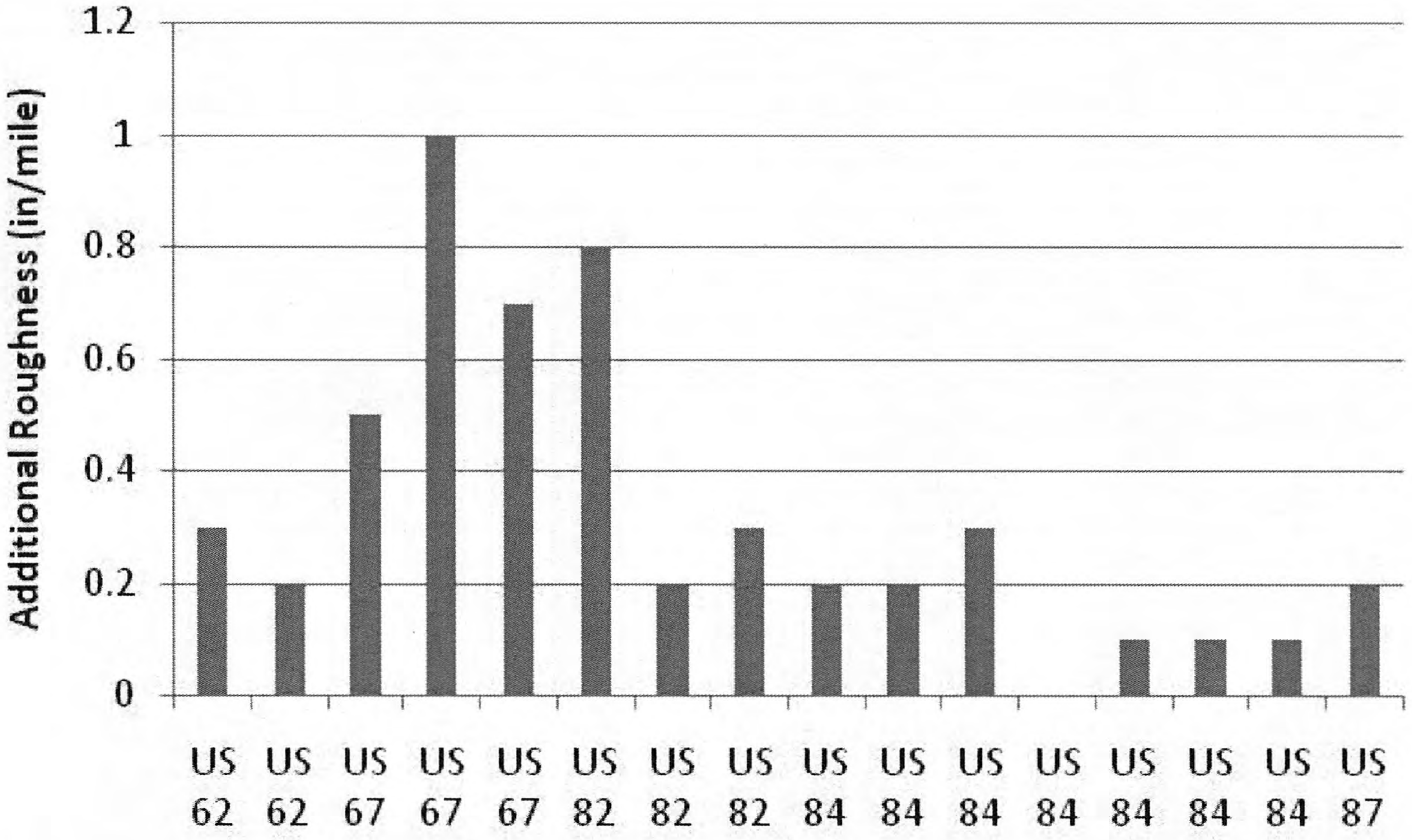


Figure A2.76: Increase in IRI Values for US Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

State Highway Sections

Due to Construction Traffic

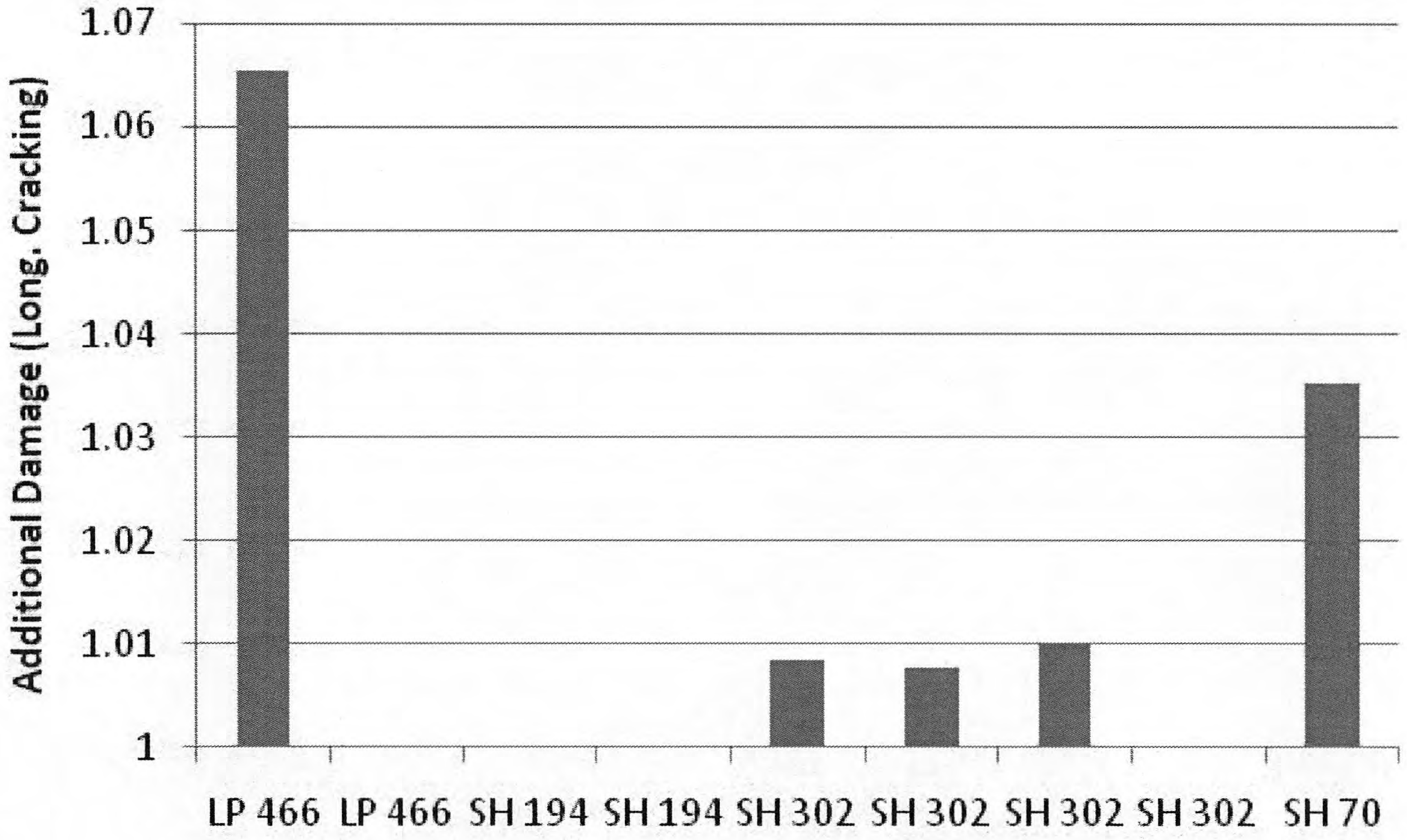


Figure A2.77: Ratio of Longitudinal Cracks on State Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

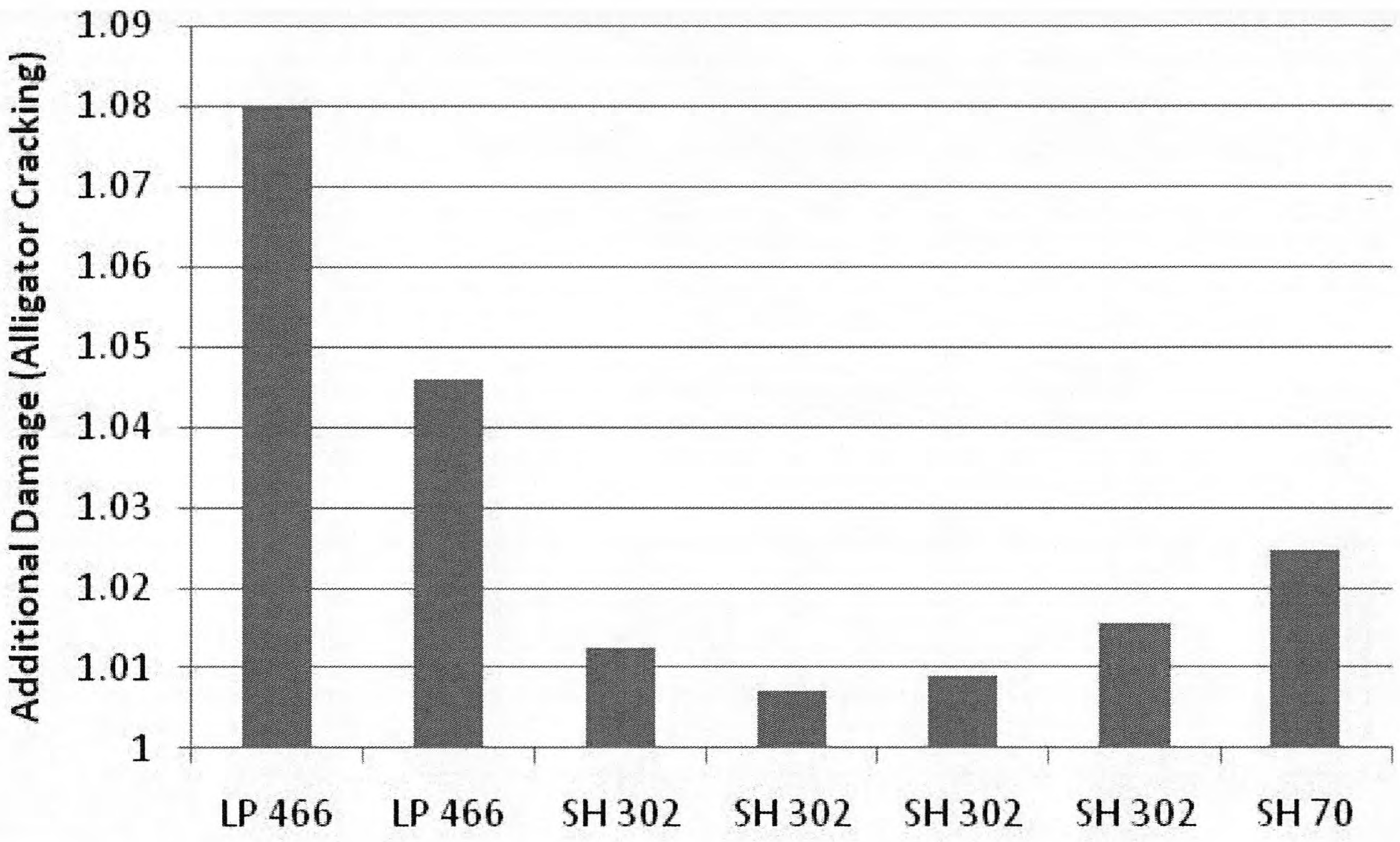


Figure A2.78: Ratio of Alligator Cracks on State Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

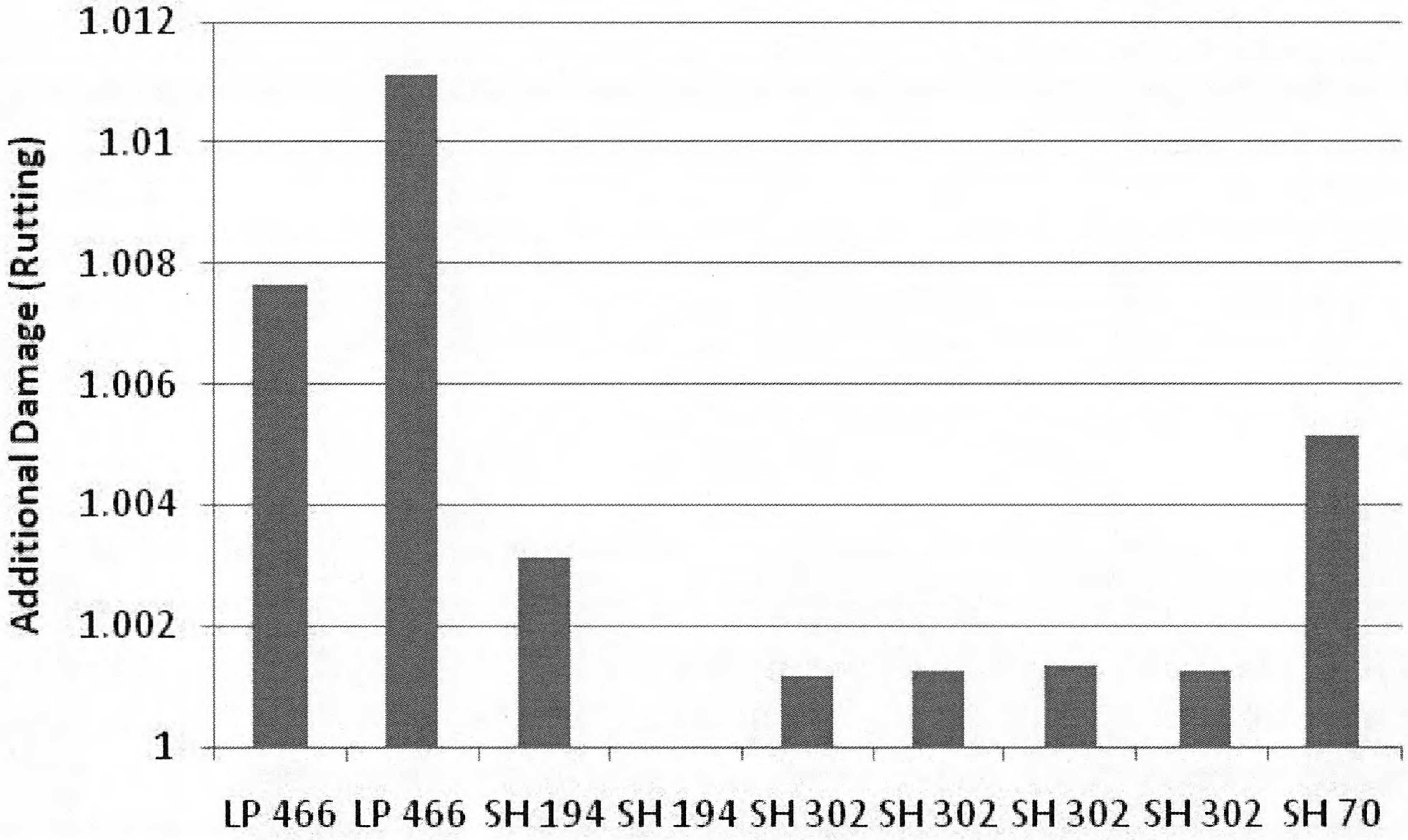


Figure A2.79: Ratio of Rut Depths on State Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

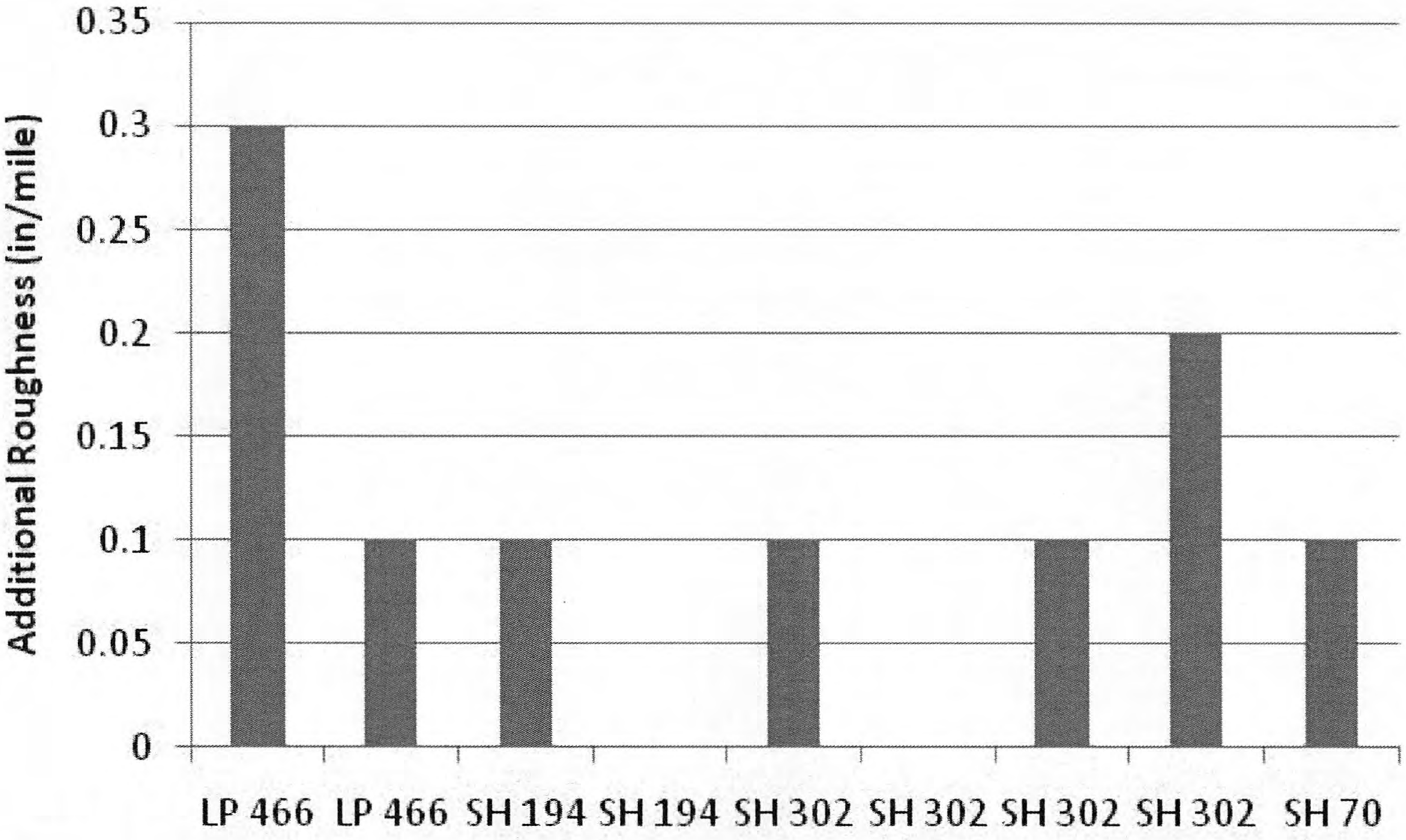


Figure A2.80: Increase in IRI Values for State Highway Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Due to Production Traffic

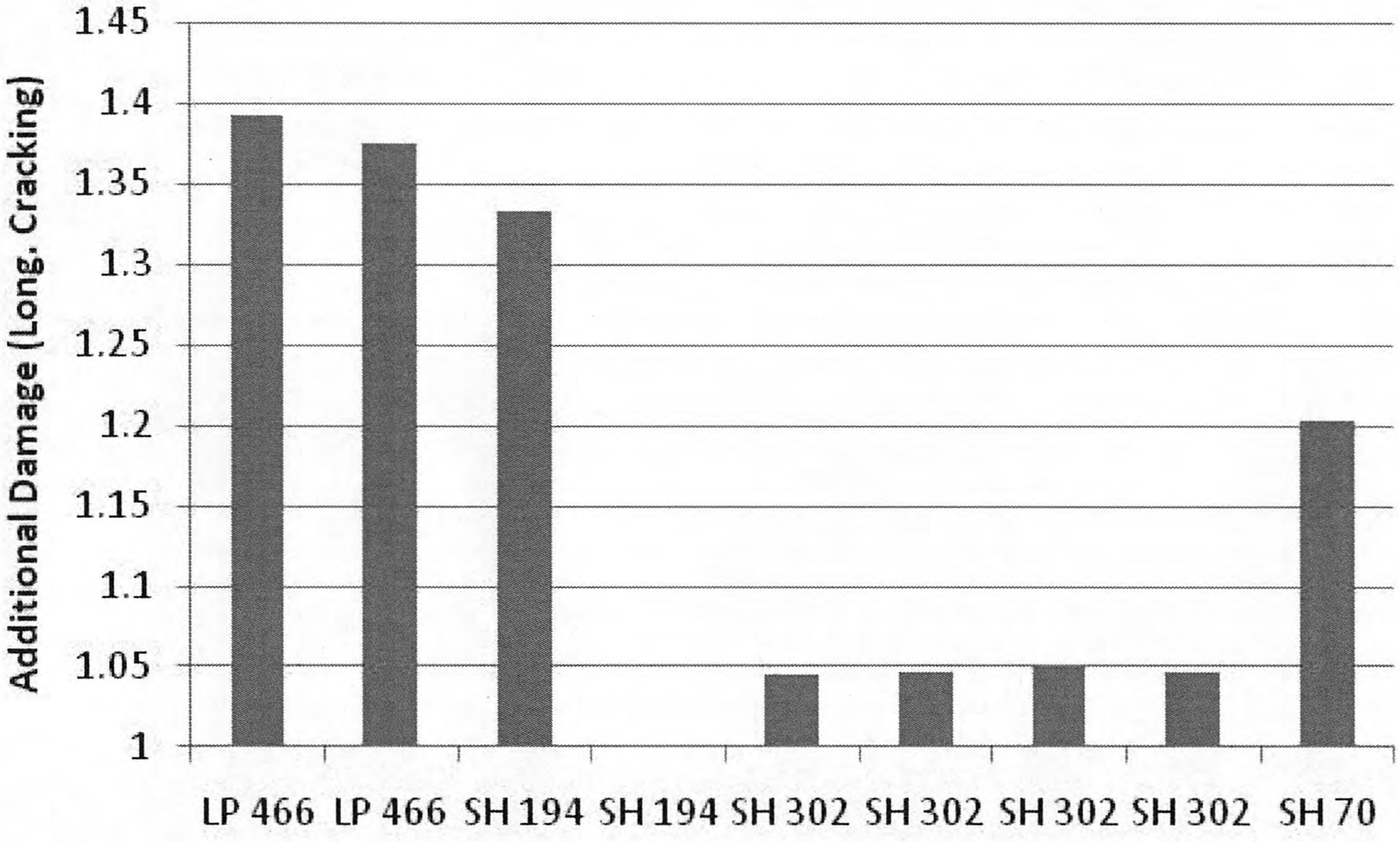


Figure A2.81: Ratio of Longitudinal Cracks on State Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

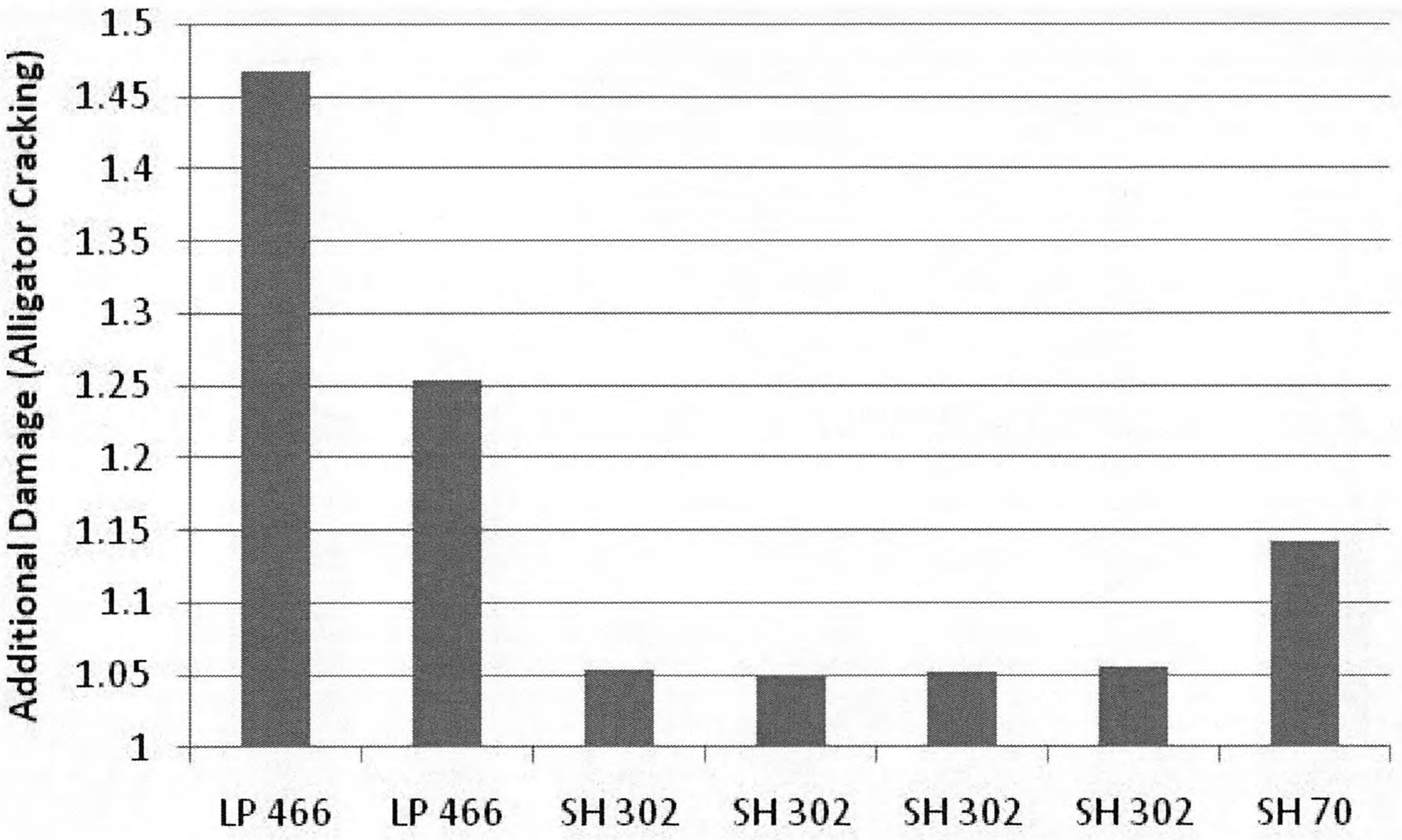


Figure A2.82: Ratio of Alligator Cracks on State Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

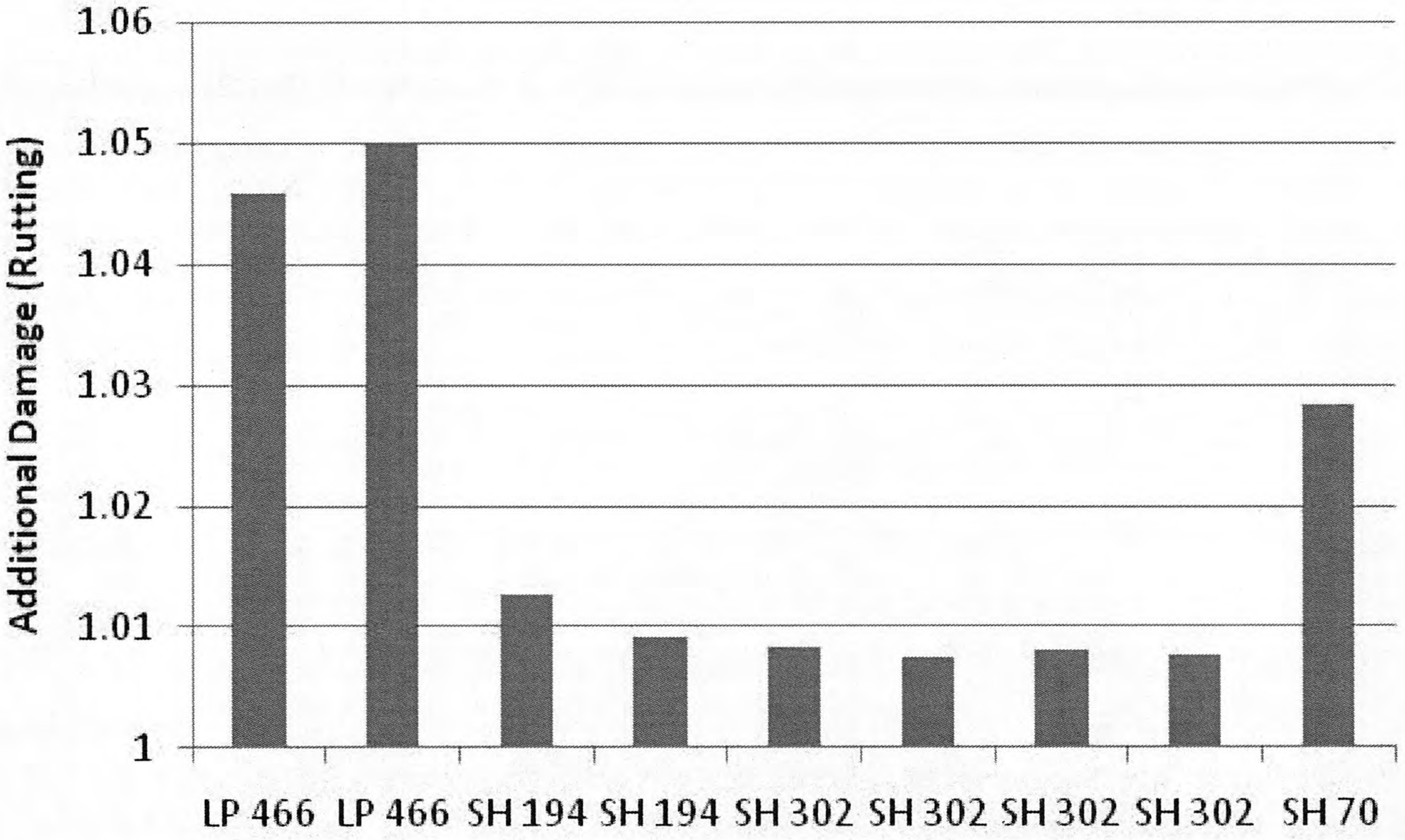


Figure A2.83: Ratio of Rut Depths on State Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

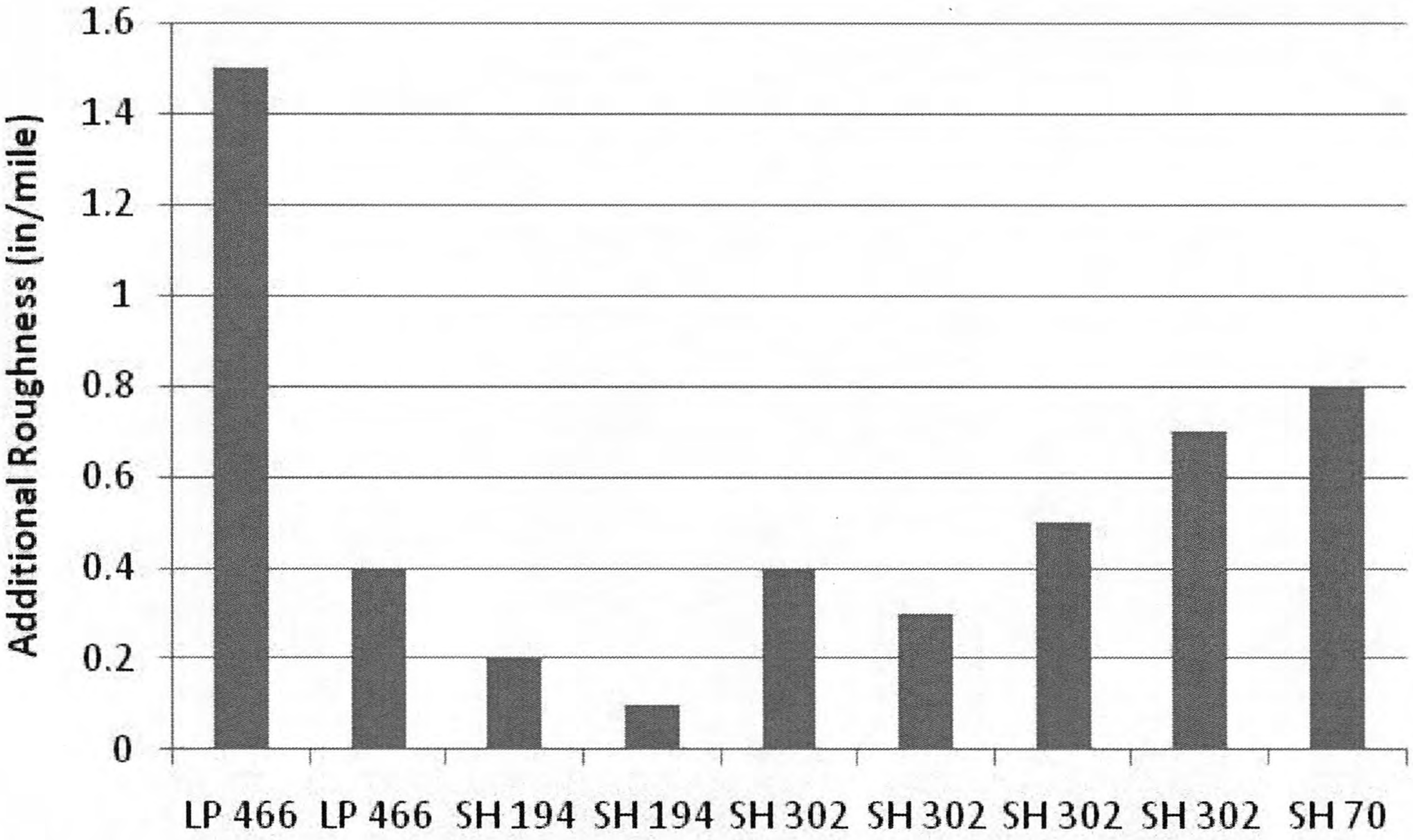


Figure A2.84: Increase in IRI Values for State Highway Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

FM Roads

Due to Construction Traffic

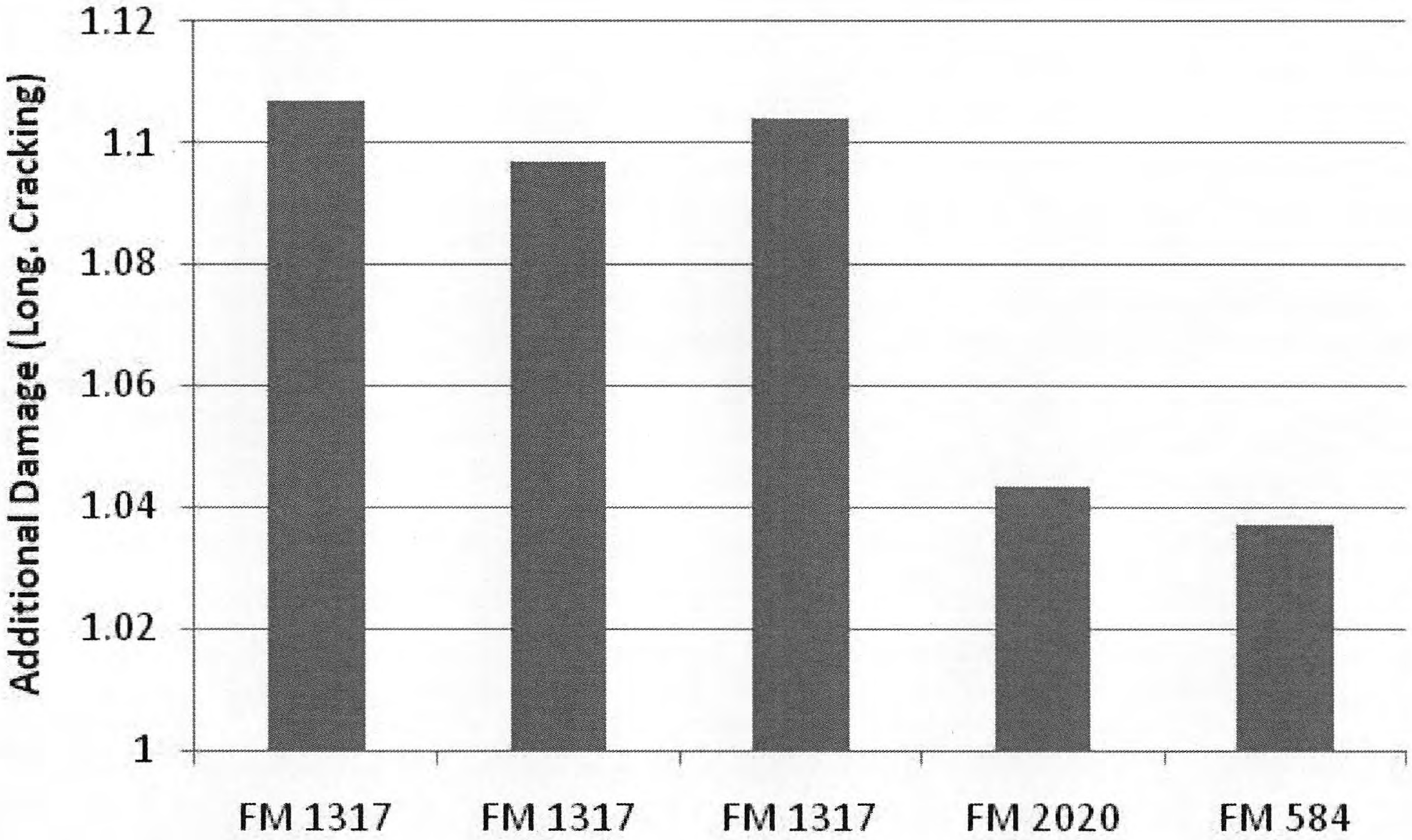


Figure A2.85: Ratio of Longitudinal Cracks on FM Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

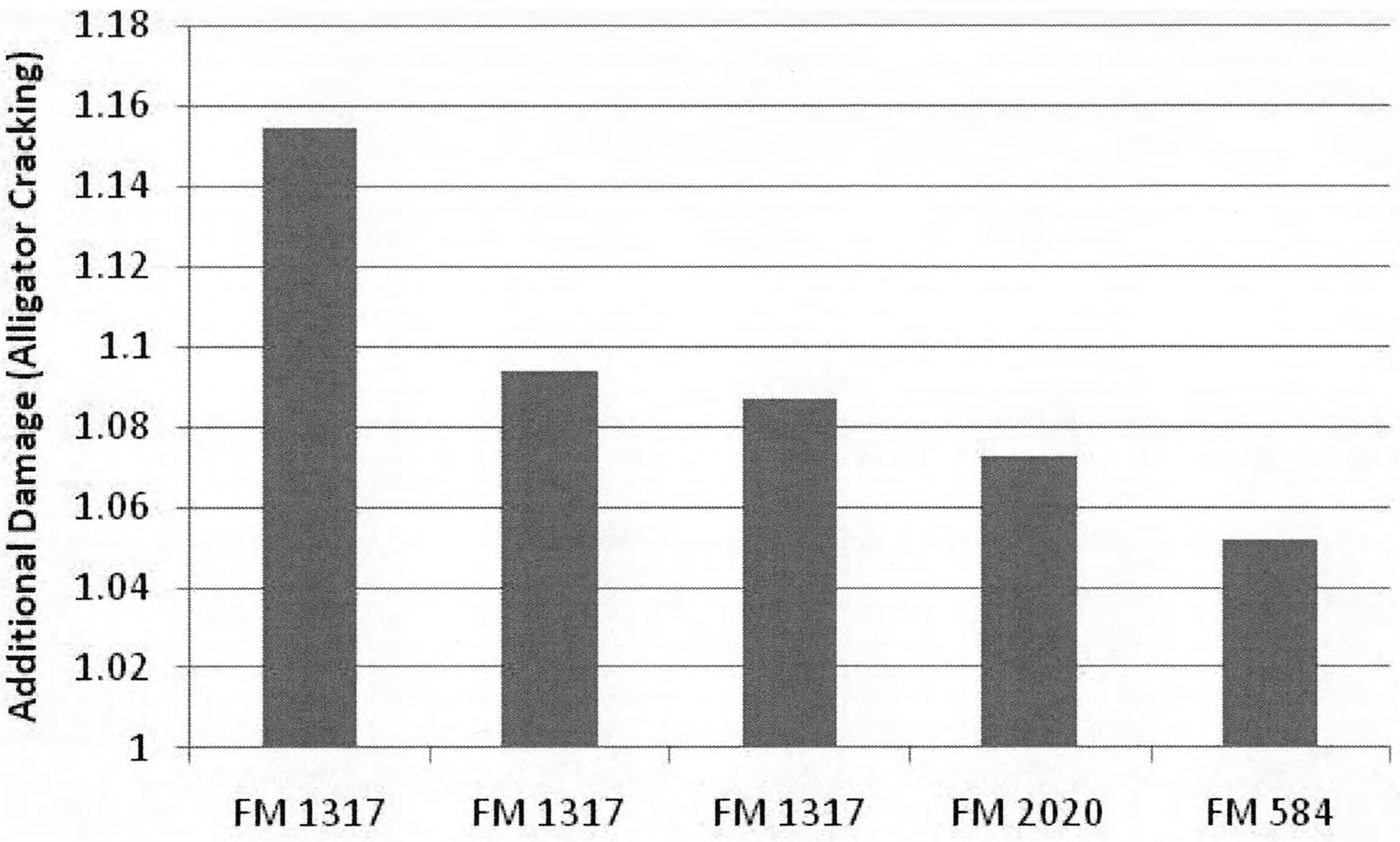


Figure A2.86: Ratio of Alligator Cracks on FM Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

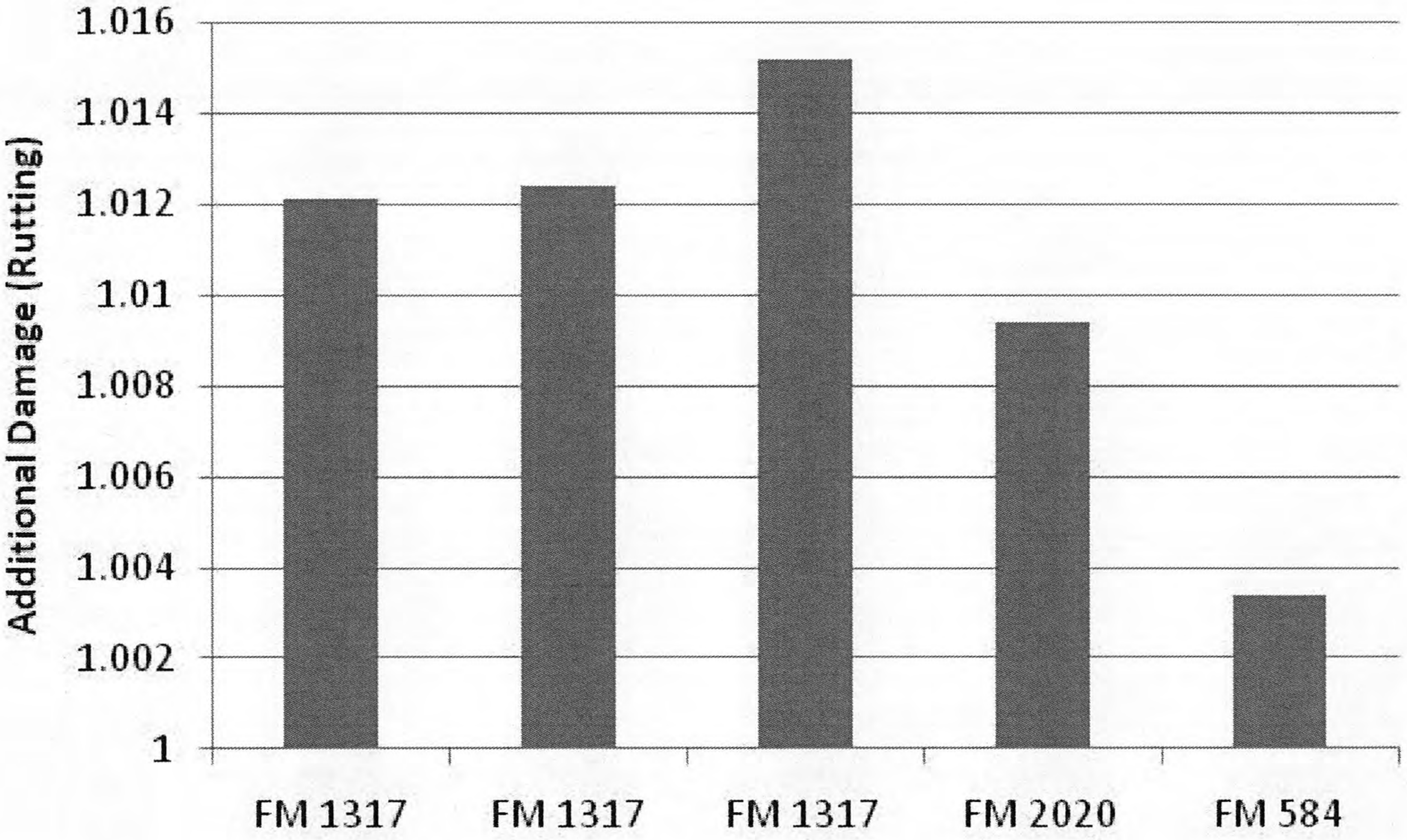


Figure A2.87: Ratio of Rut Depths on FM Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

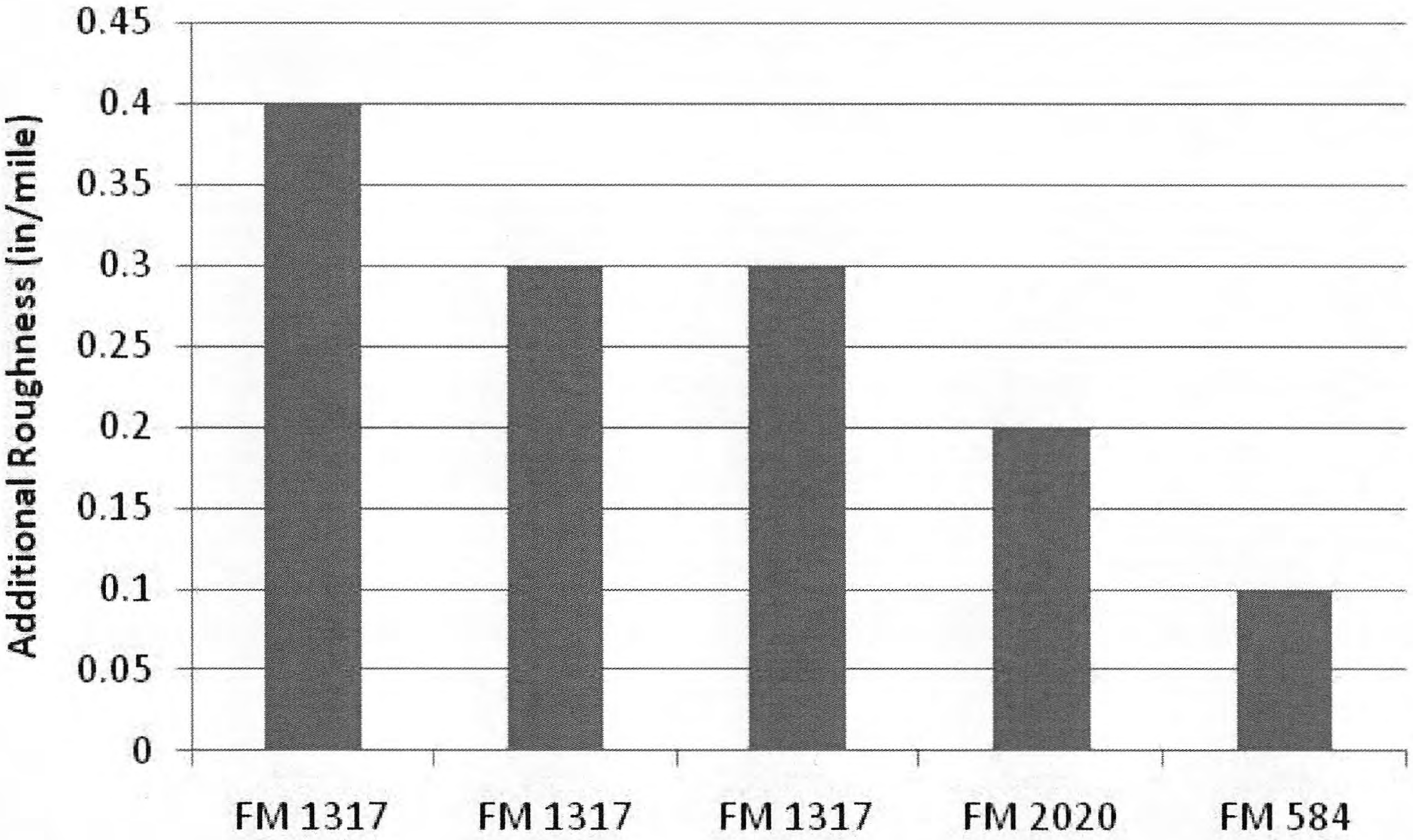


Figure A2.88: Increase in IRI Values for FM Sections due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Due to Production Traffic

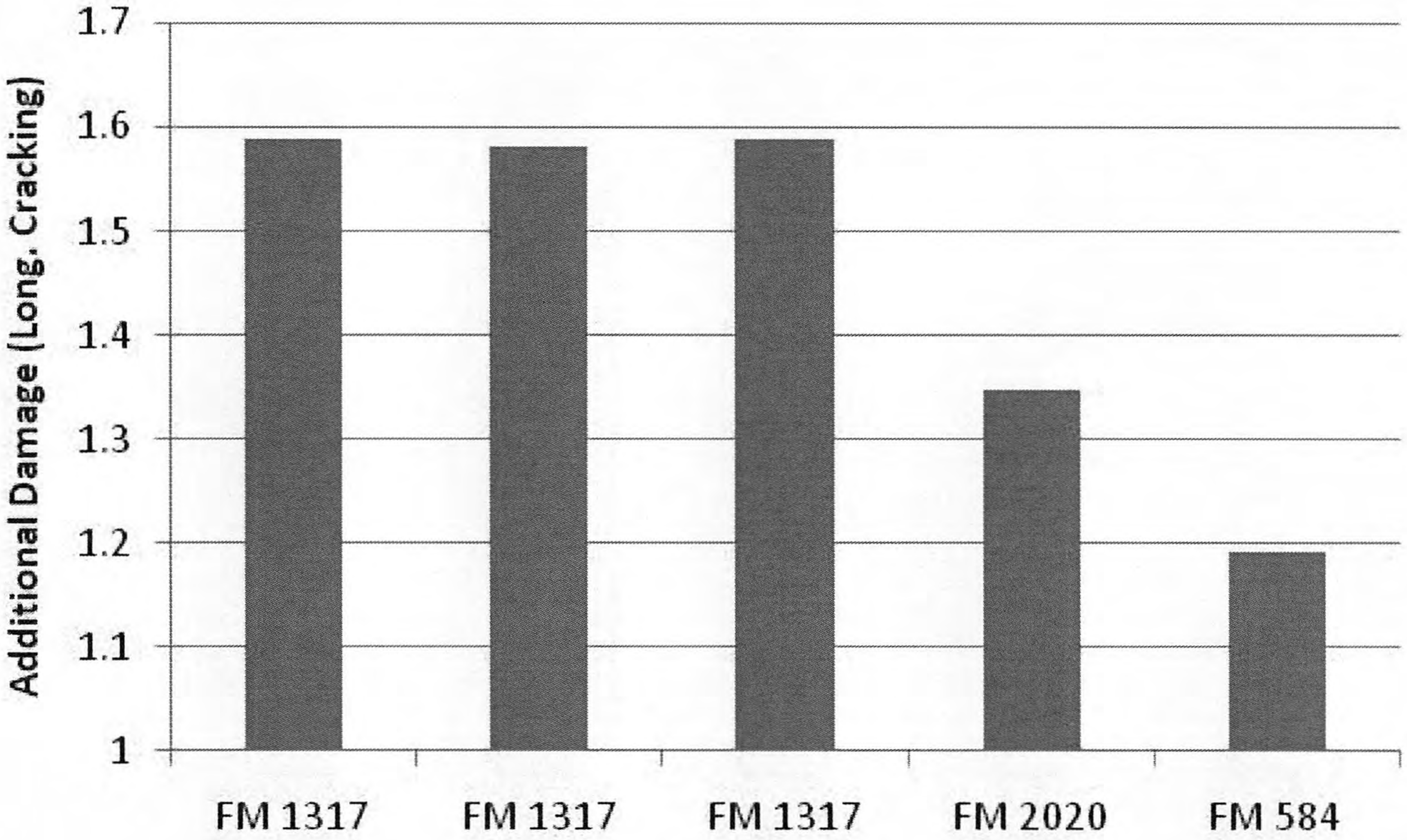


Figure A2.89: Ratio of Longitudinal Cracks on FM Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

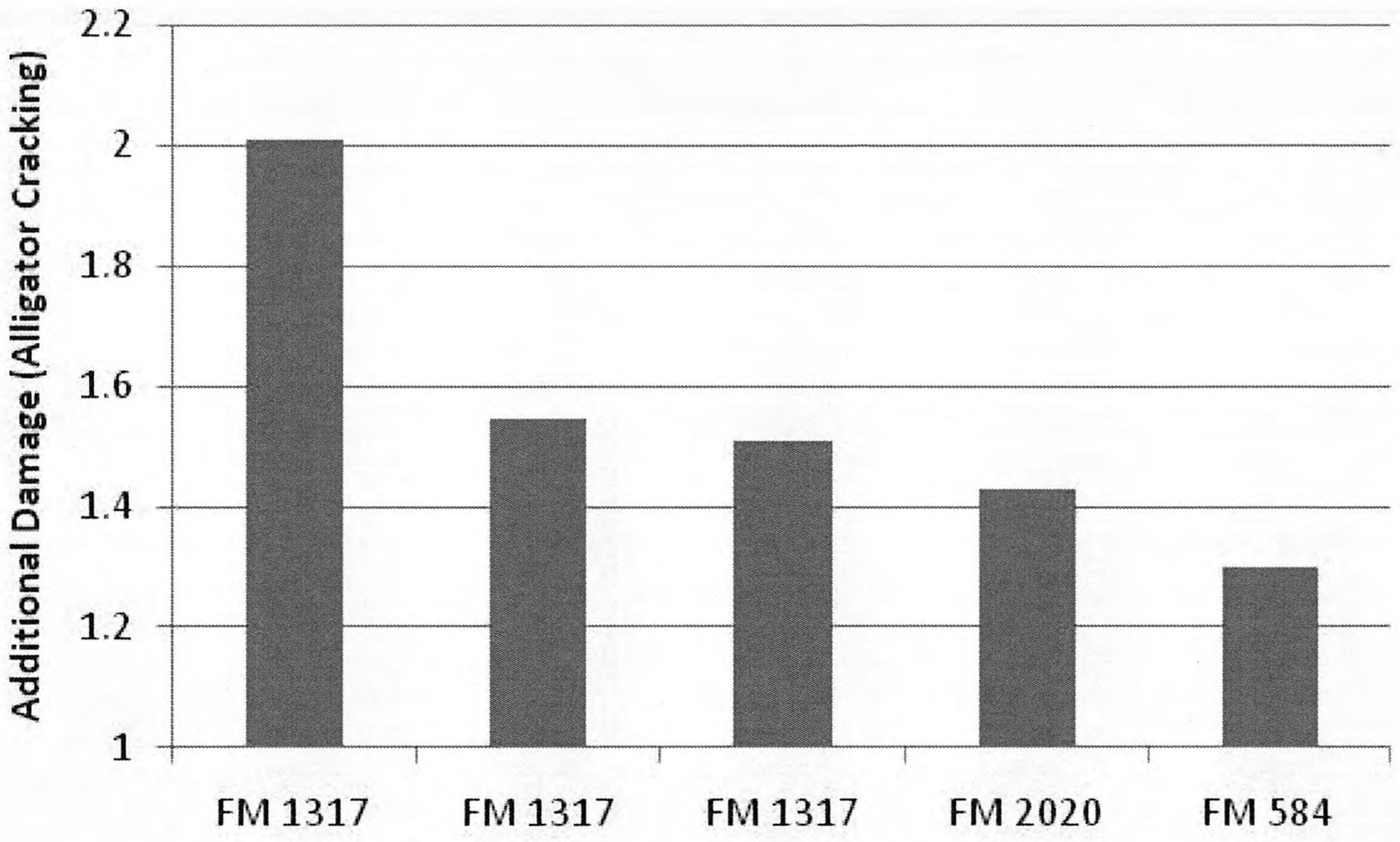


Figure A2.90: Ratio of Alligator Cracks on FM Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

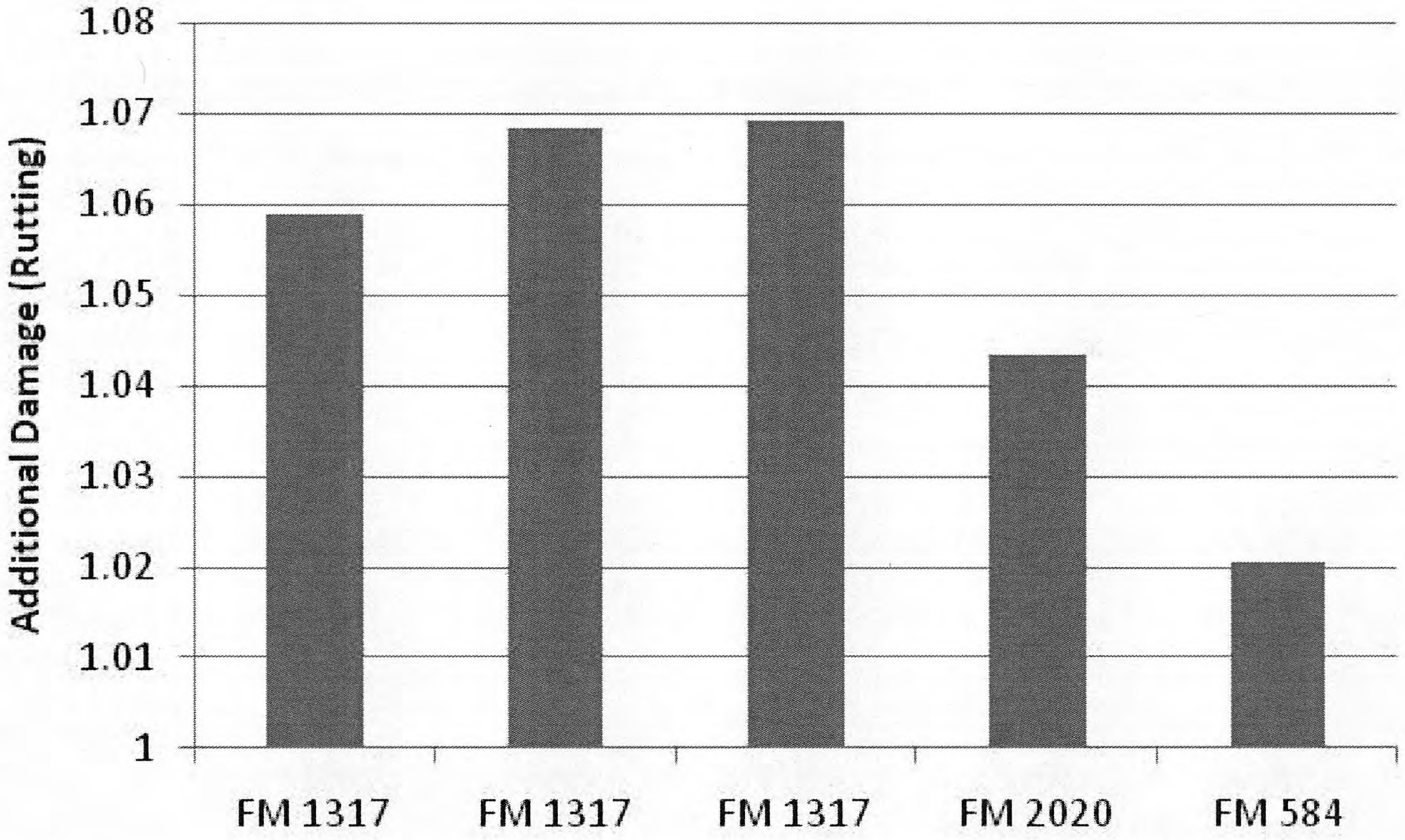


Figure A2.91: Ratio of Rut Depths on FM Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

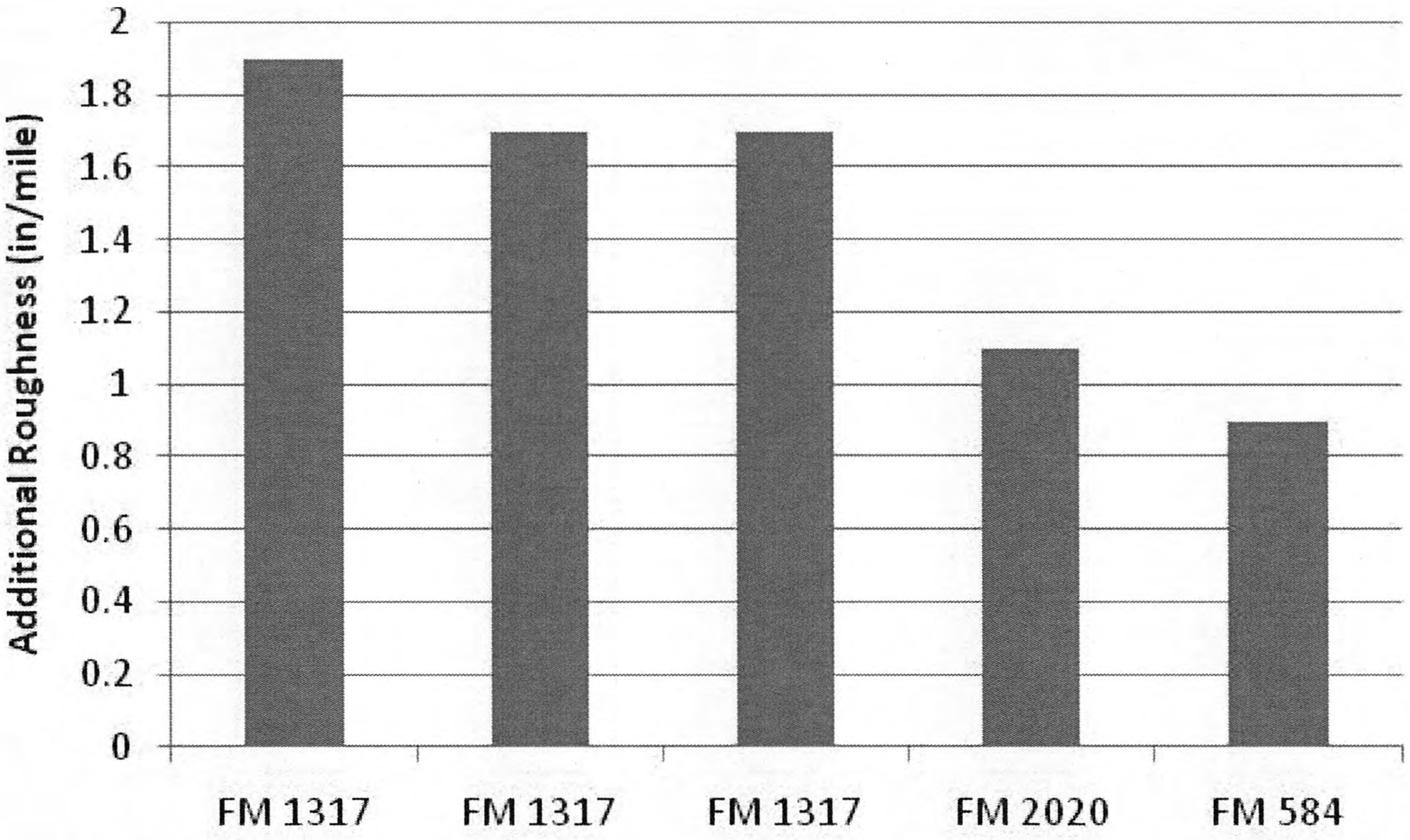


Figure A2.92: Increase in IRI Values for FM Sections due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Appendix A3: Reduction in Service Lives of Pavements due to Wind, Natural Gas, and Crude Oil Energy Developments

Wind Energy Industry

Interstate Highways

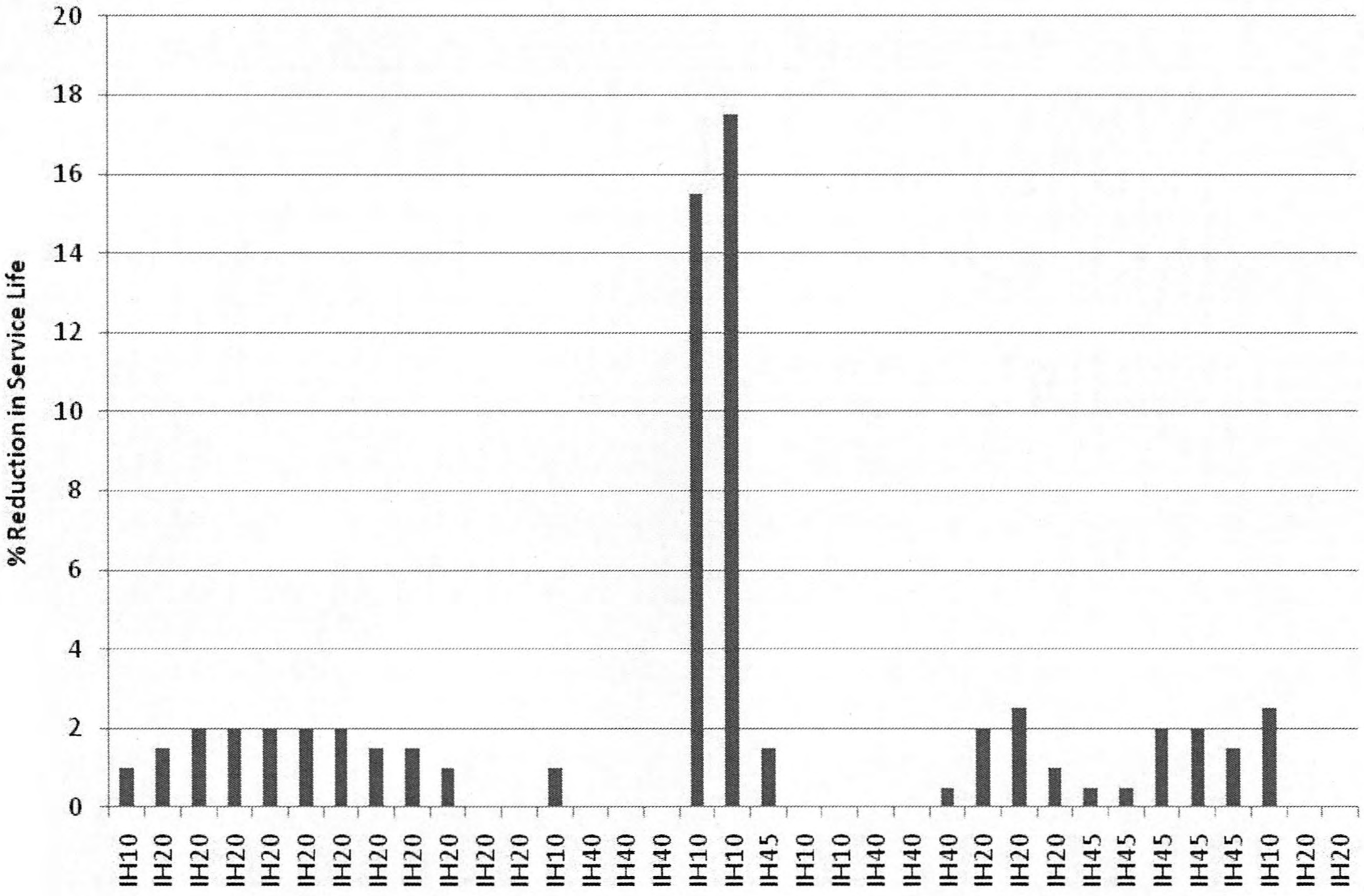


Figure A3.1: Reduction in Service Life of IH Sections due to Wind Turbine Truck Traffic

US Highways

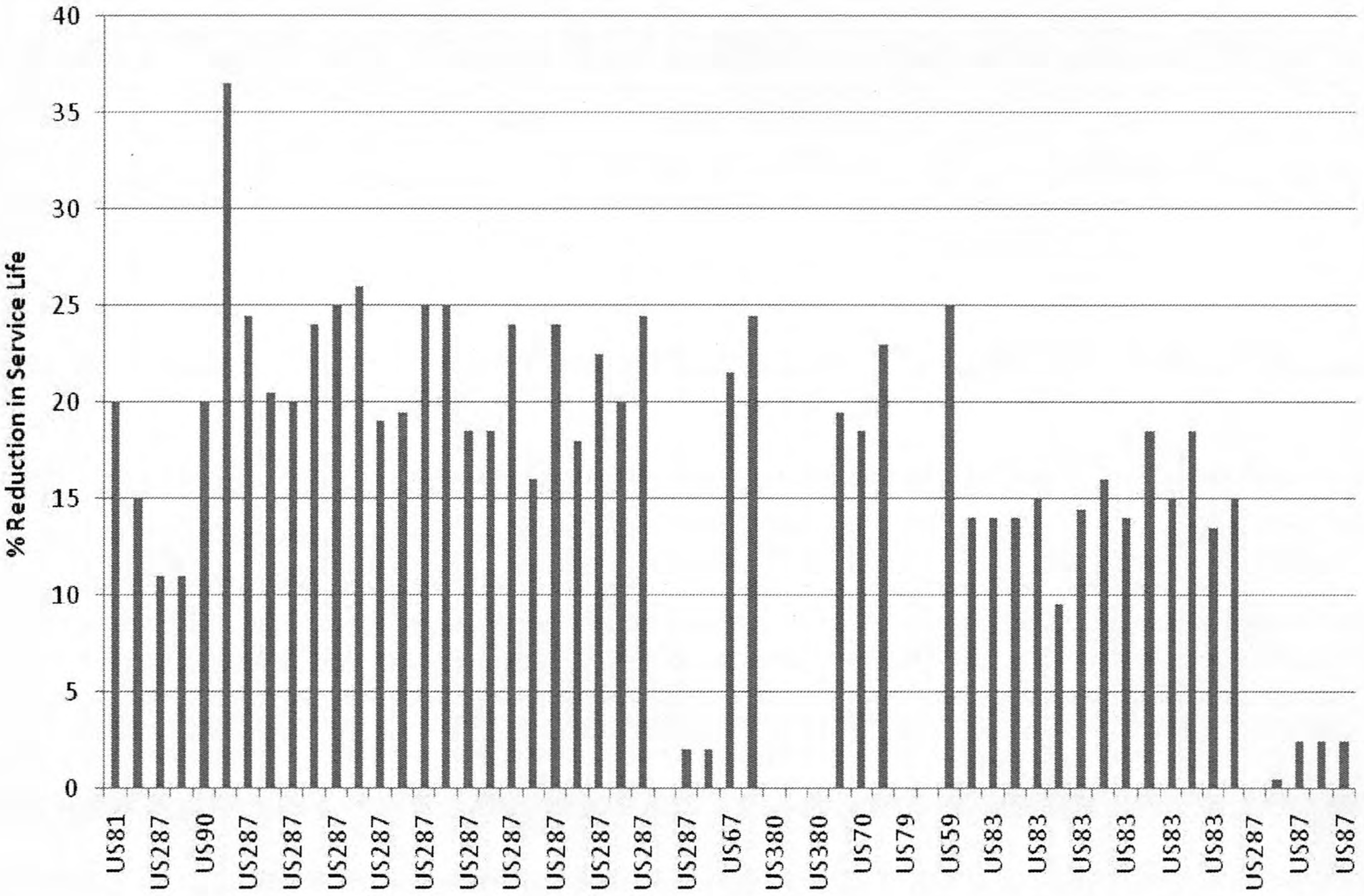


Figure A3.2: Reduction in Service Life of US Highway Sections due to Wind Turbine Truck Traffic

State Highways

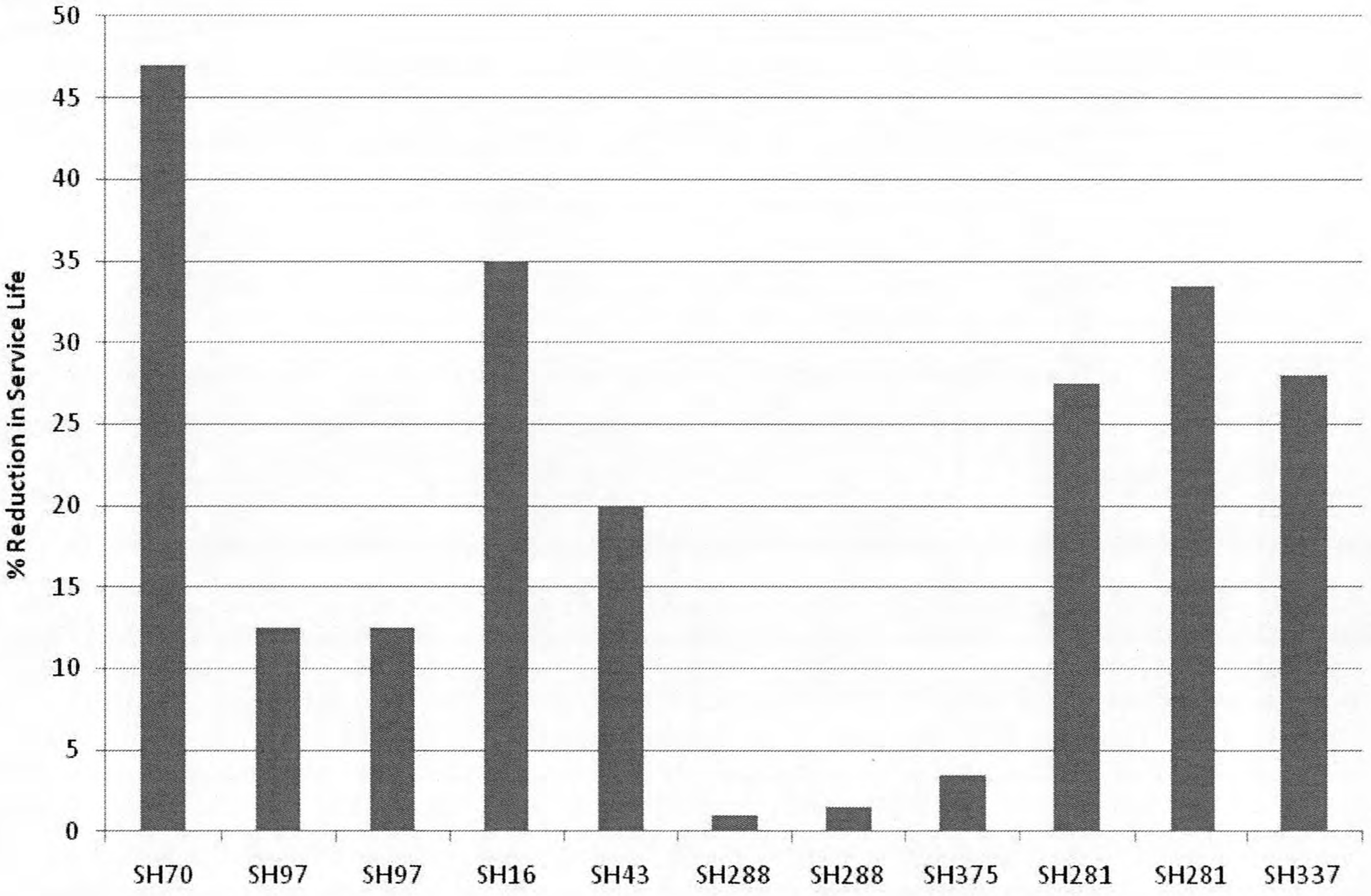


Figure A3.3: Reduction in Service Life of State Highway Sections due to Wind Turbine Truck Traffic

Interstate Highways

Rig Traffic

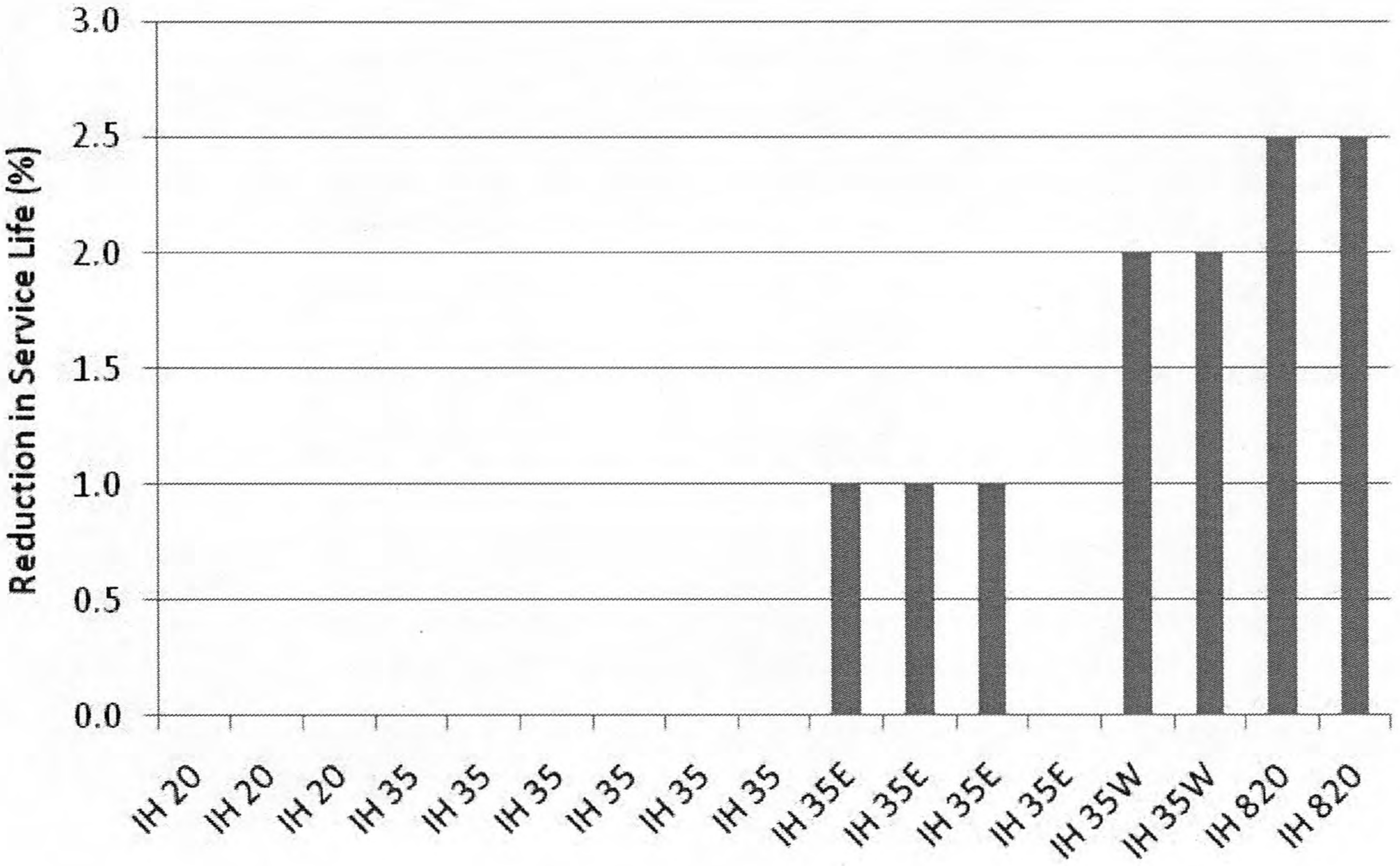


Figure A3.4: Reduction in Service Life of IH Sections in the Barnett Shale Region due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Saltwater Traffic

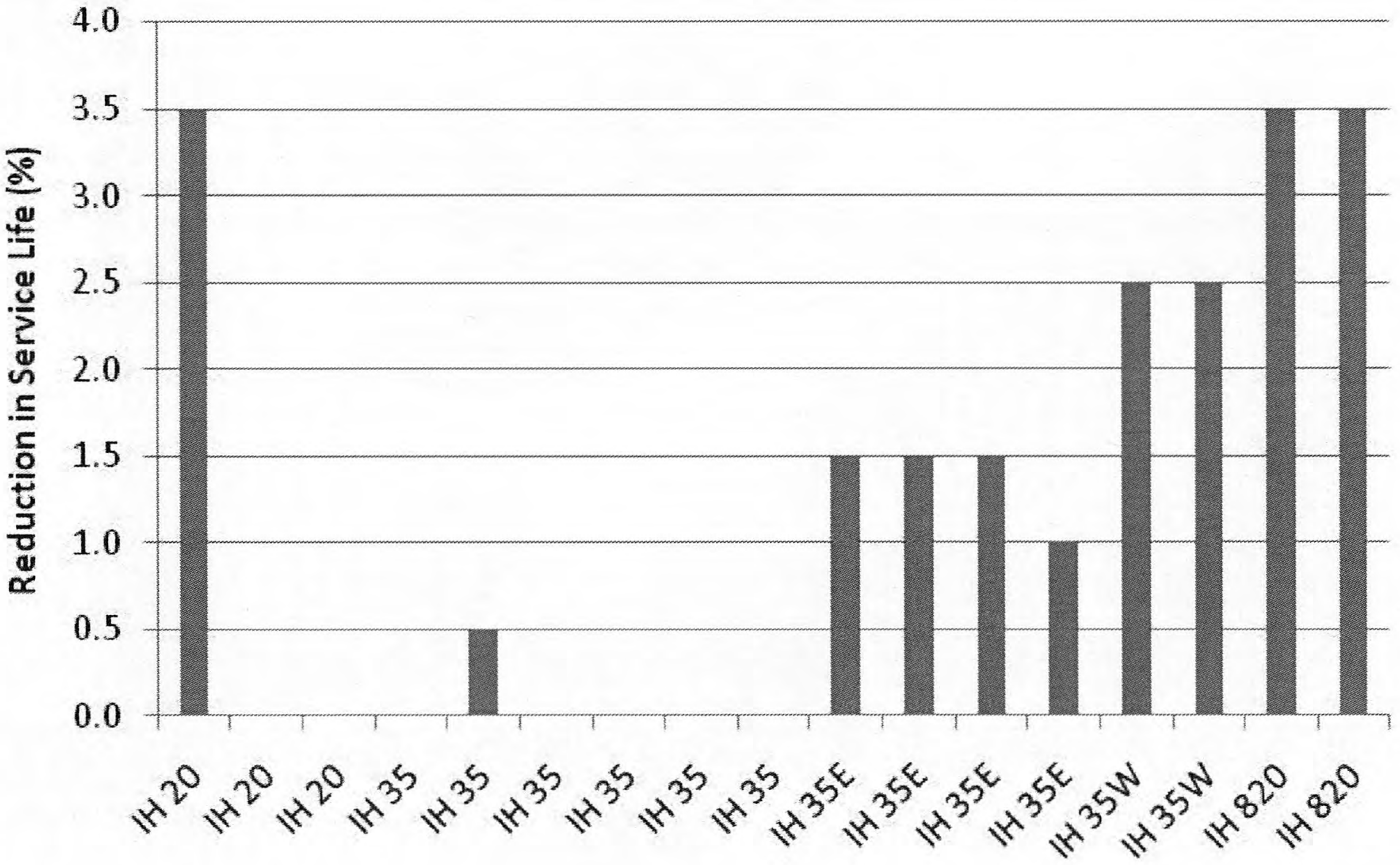


Figure A3.5: Reduction in Service Life of IH Sections in the Barnett Shale Region due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Construction Traffic

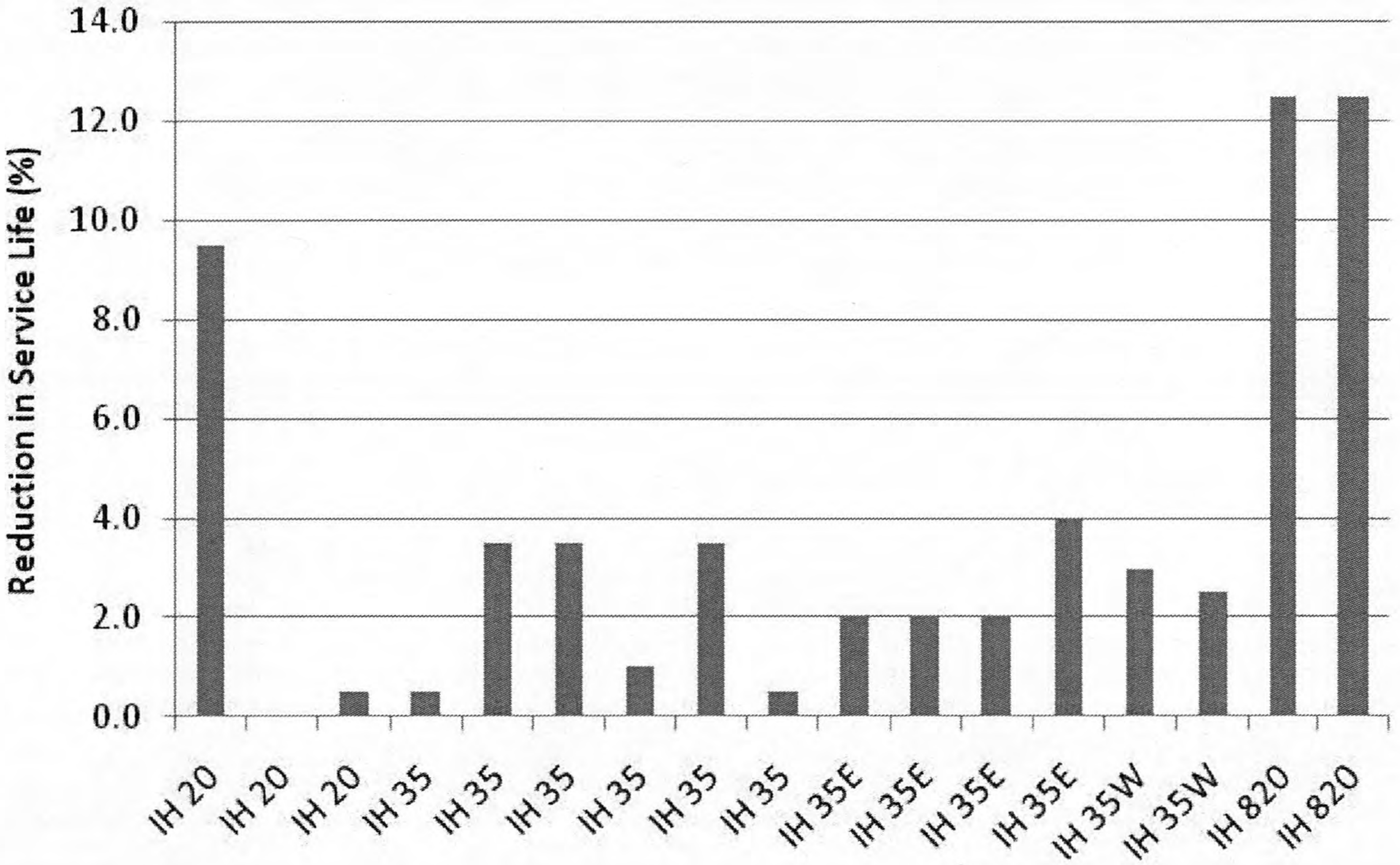


Figure A3.6: Reduction in Service Life of IH Sections in the Barnett Shale Region due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

US Highways

Rig Traffic

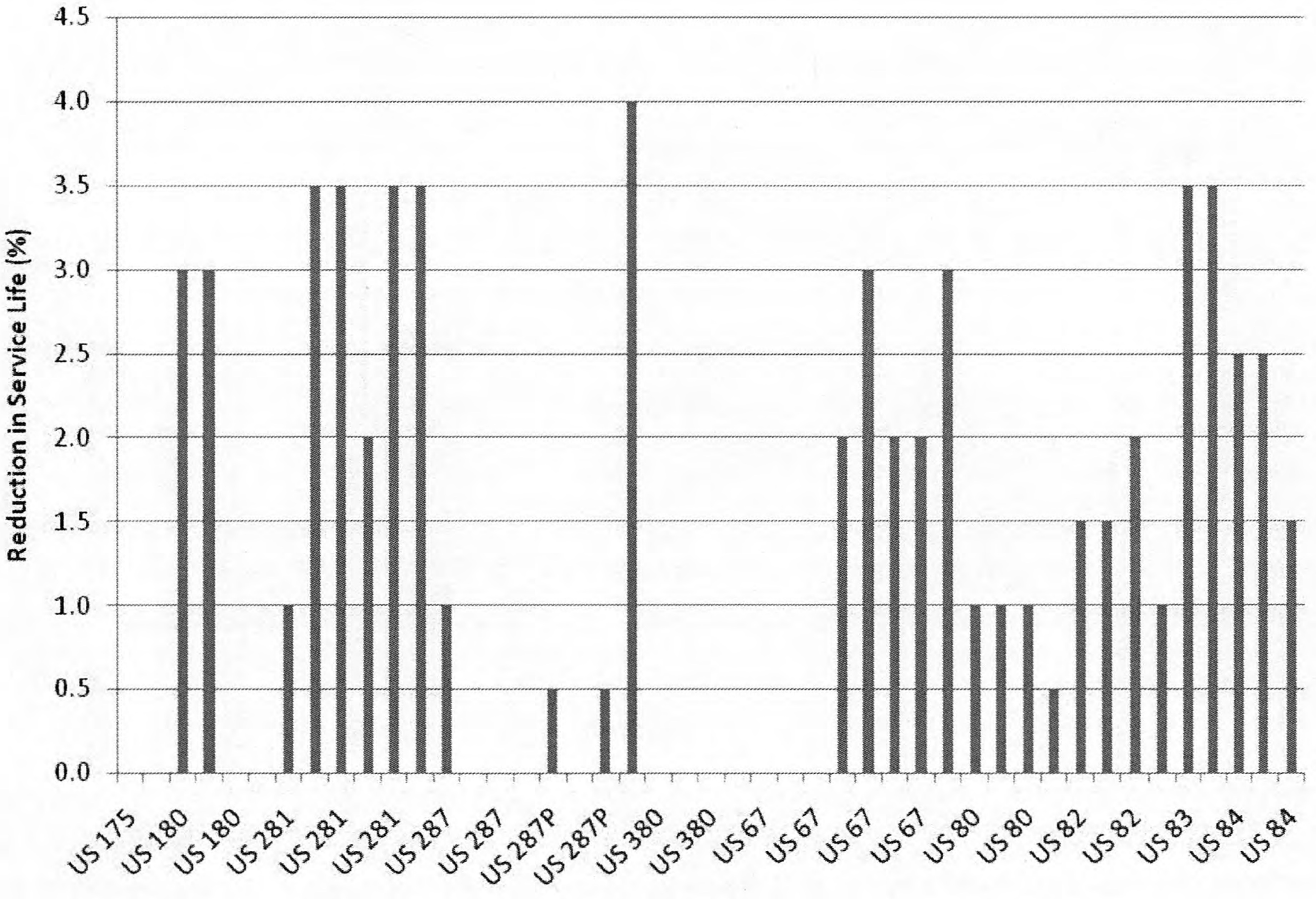


Figure A3.7: Reduction in Service Life of US Highway Sections in the Barnett Shale Region due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Saltwater Traffic

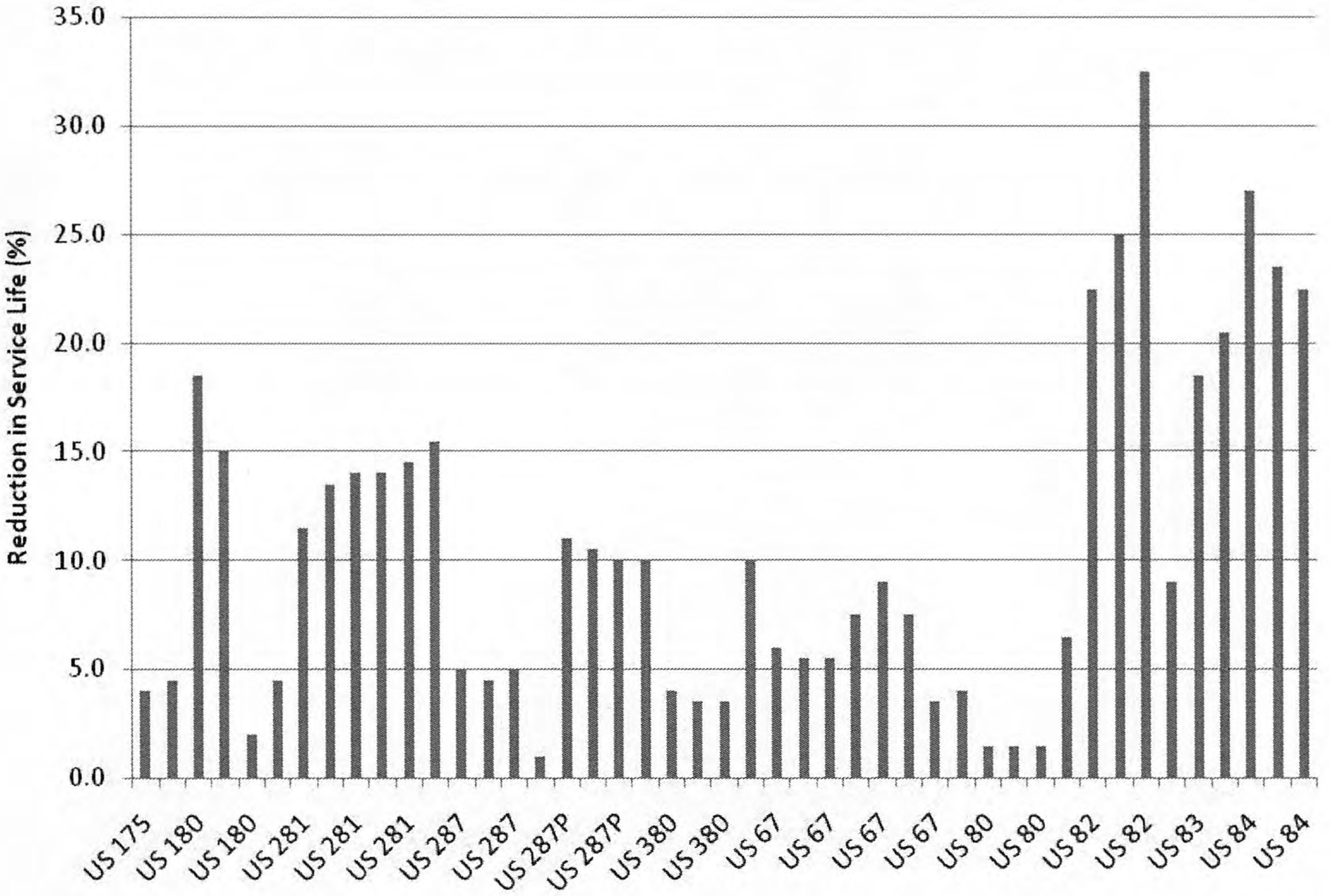


Figure A3.8: Reduction in Service Life of US Highway Sections in the Barnett Shale Region due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Construction Traffic

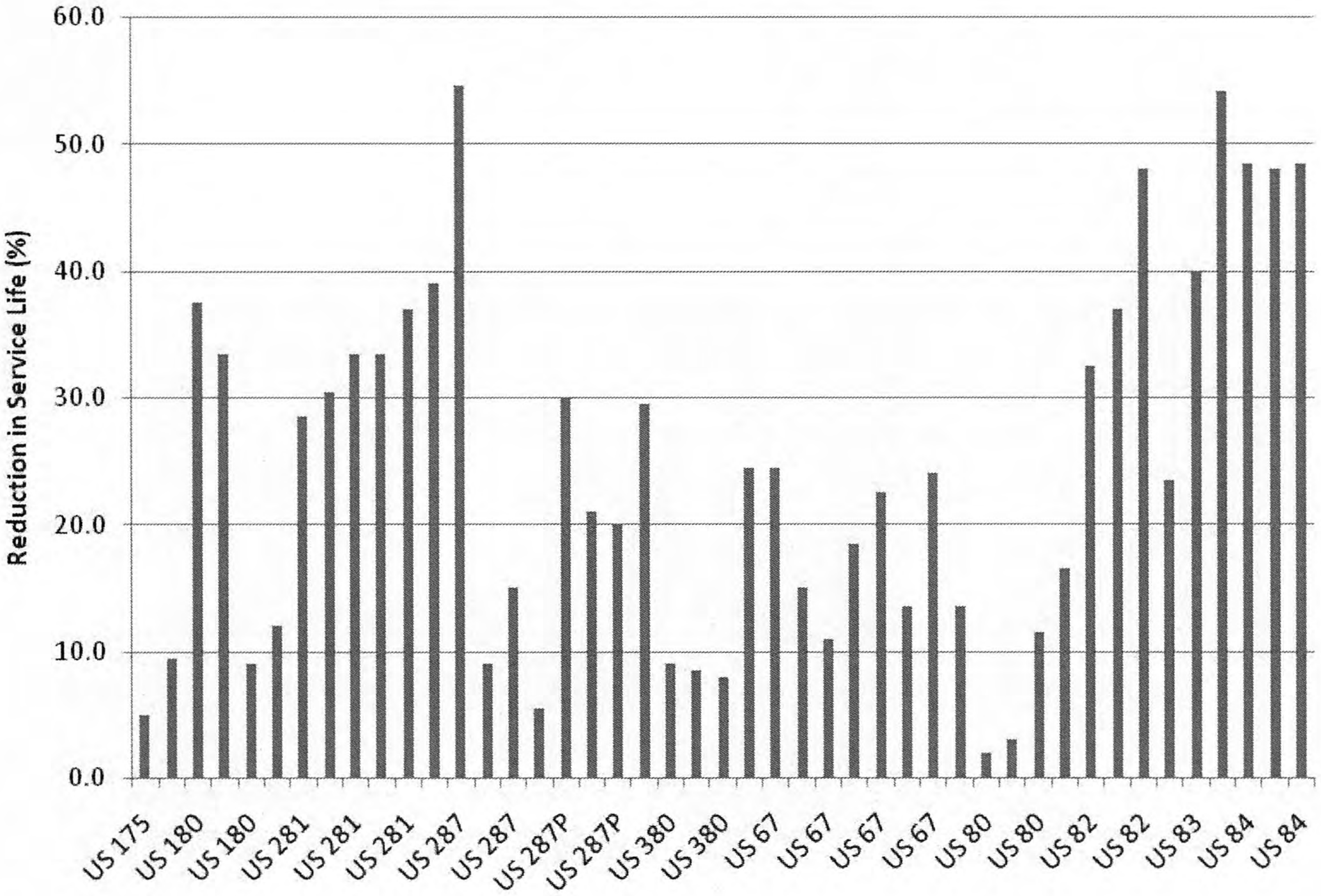


Figure A3.9: Reduction in Service Life of US Highway Sections in the Barnett Shale Region due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

State Highways

Rig Traffic

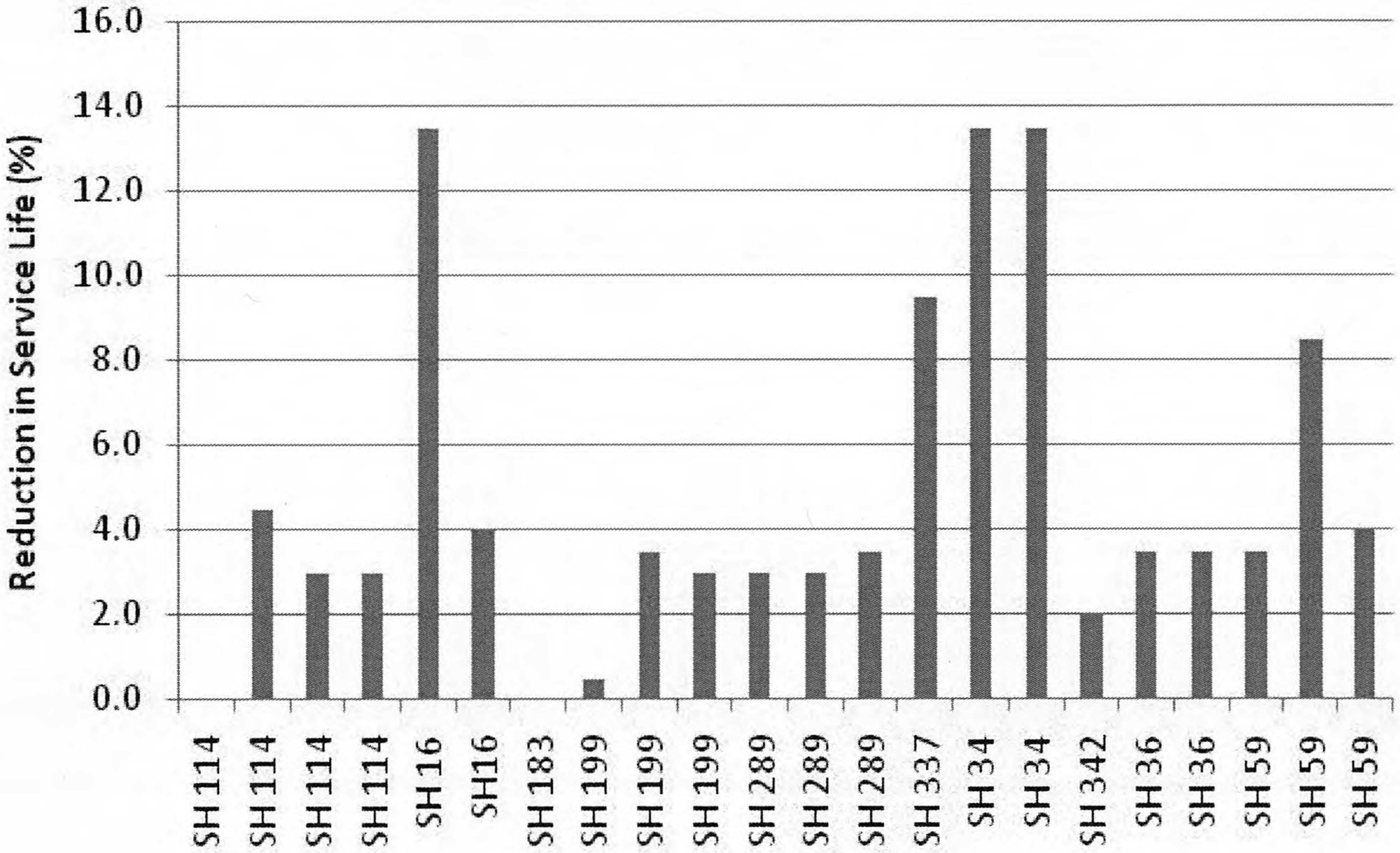


Figure A3.10: Reduction in Service Life of State Highway Sections in the Barnett Shale Region due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Saltwater Traffic

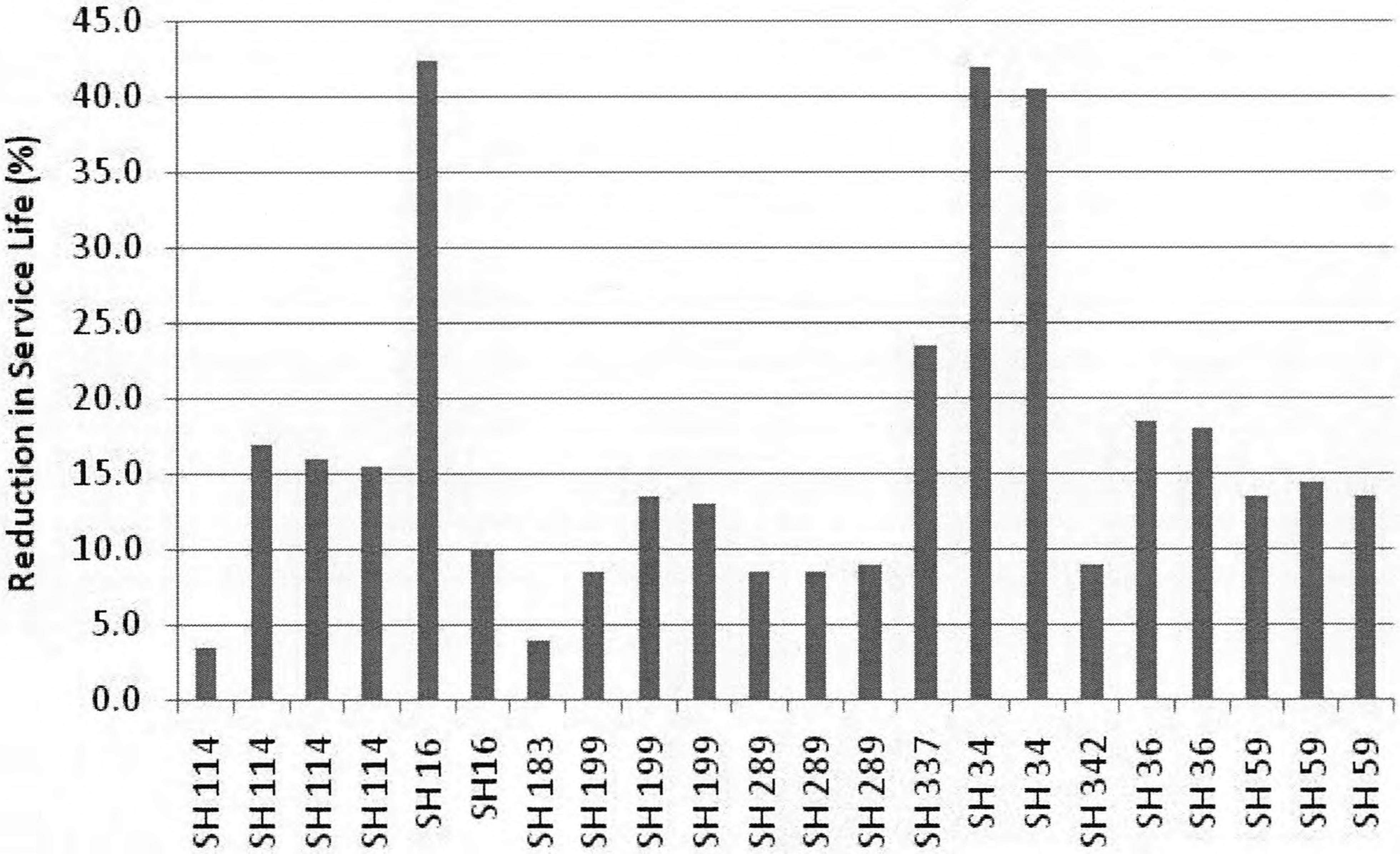


Figure A3.11: Reduction in Service Life of State Highway Sections in the Barnett Shale Region due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Construction Traffic

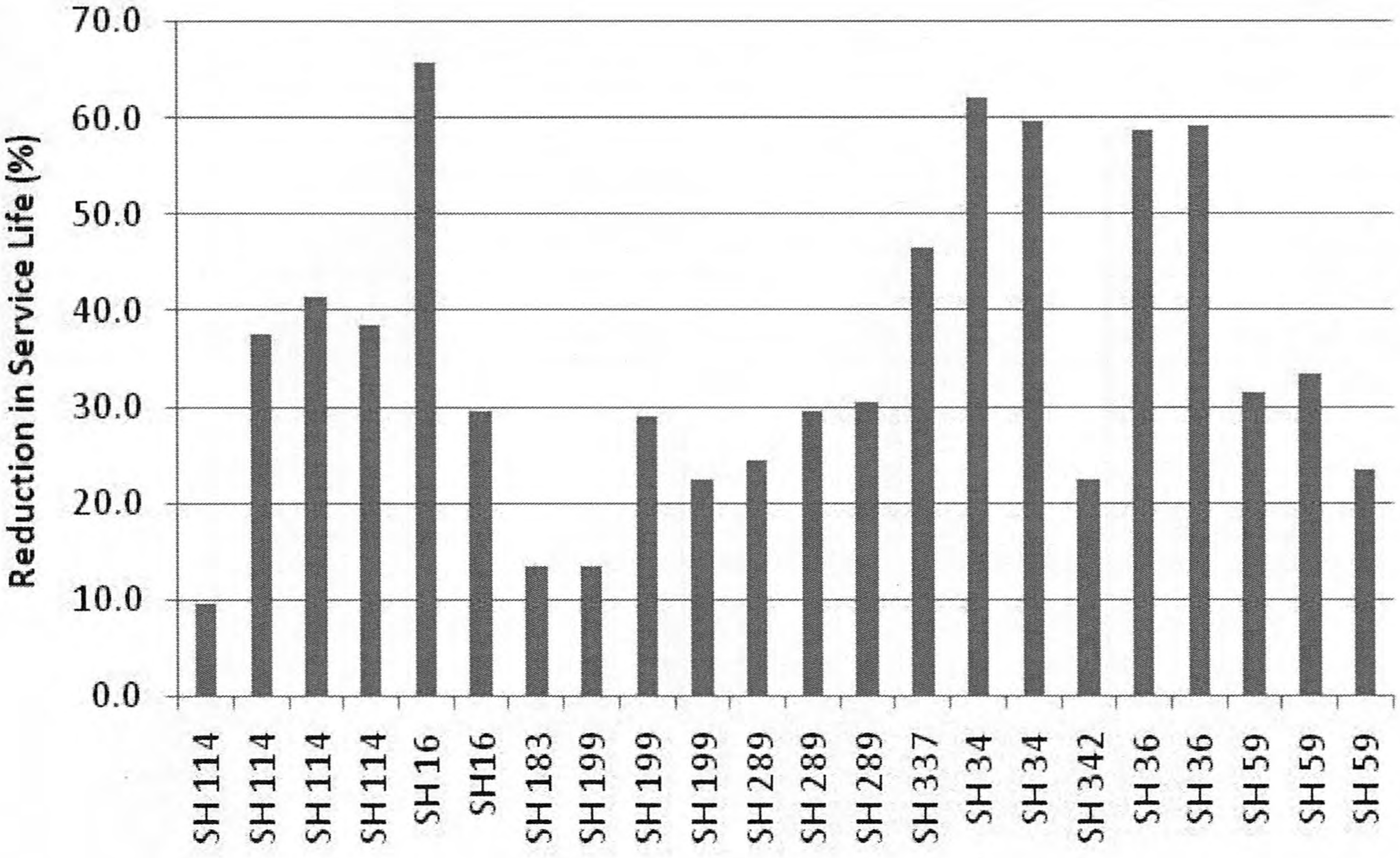


Figure A3.12: Reduction in Service Life of State Highway Sections in the Barnett Shale Region due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

FM Roads

Rig Traffic

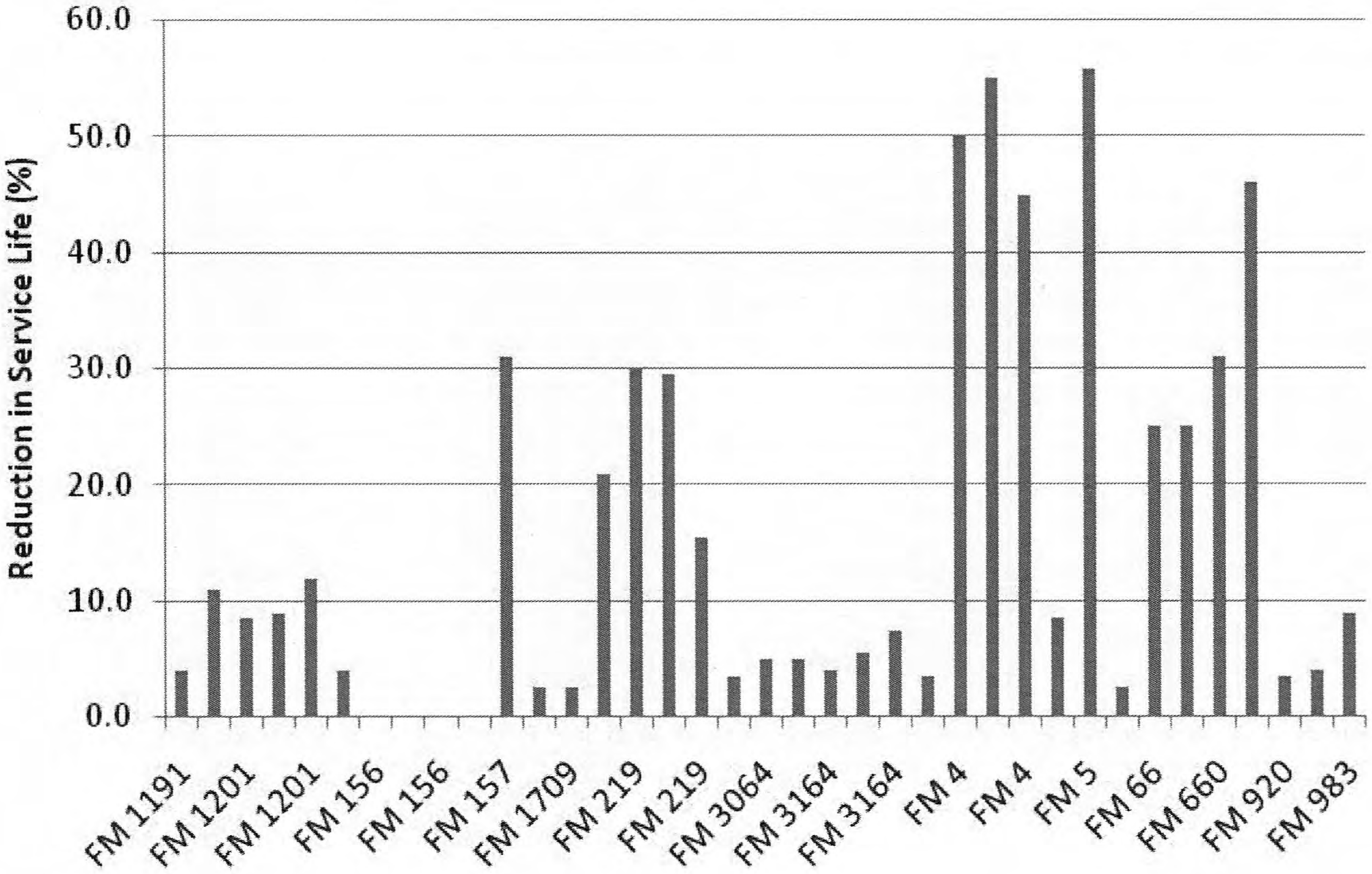


Figure A3.13: Reduction in Service Life of FM Sections in the Barnett Shale Region due to Rig Traffic (for 365 Natural Gas Site Installations over a 20-Year Analysis Period)

Saltwater Traffic

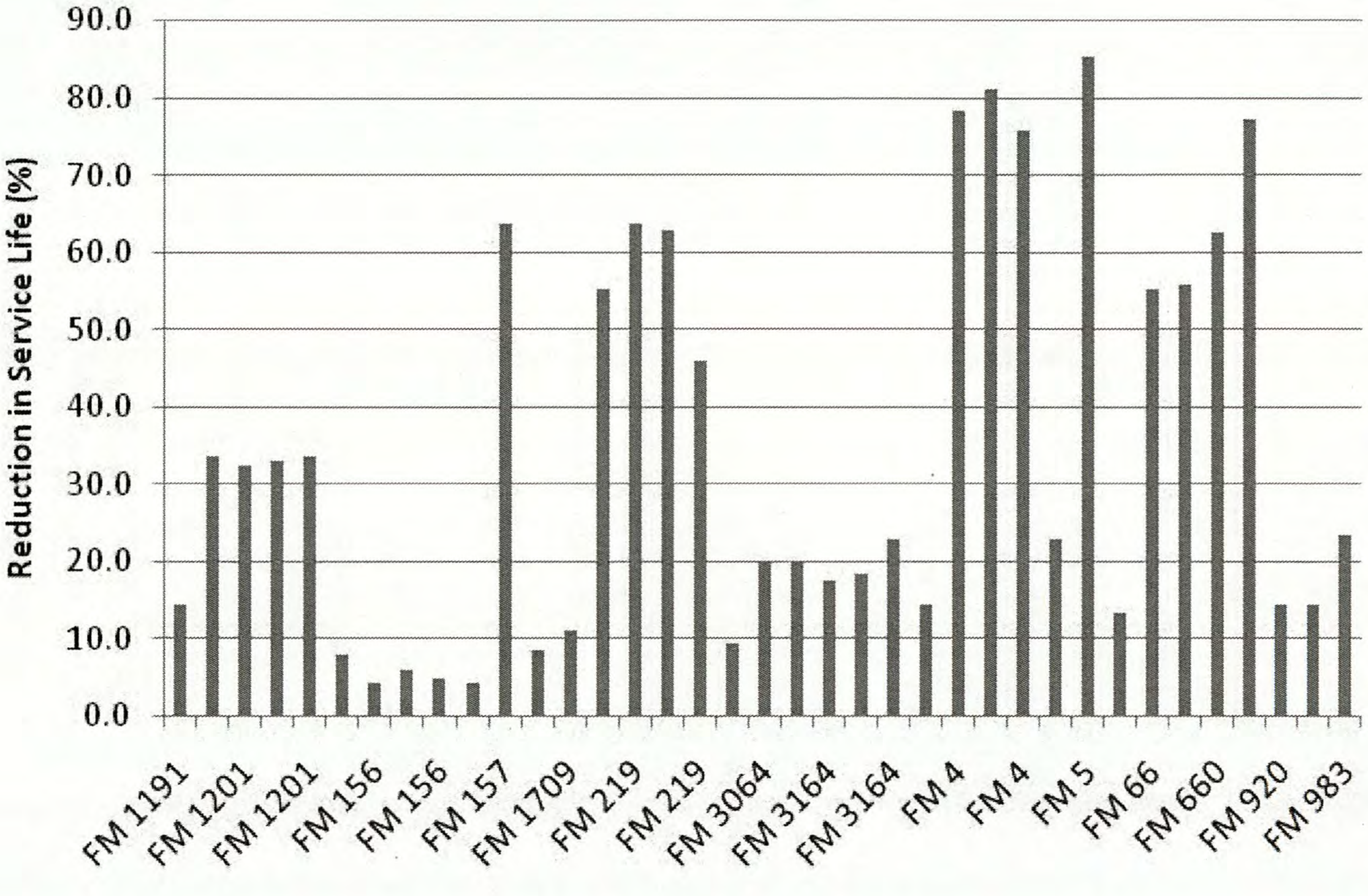


Figure A3.14: Reduction in Service Life of FM Sections in the Barnett Shale Region due to Saltwater Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Construction Traffic

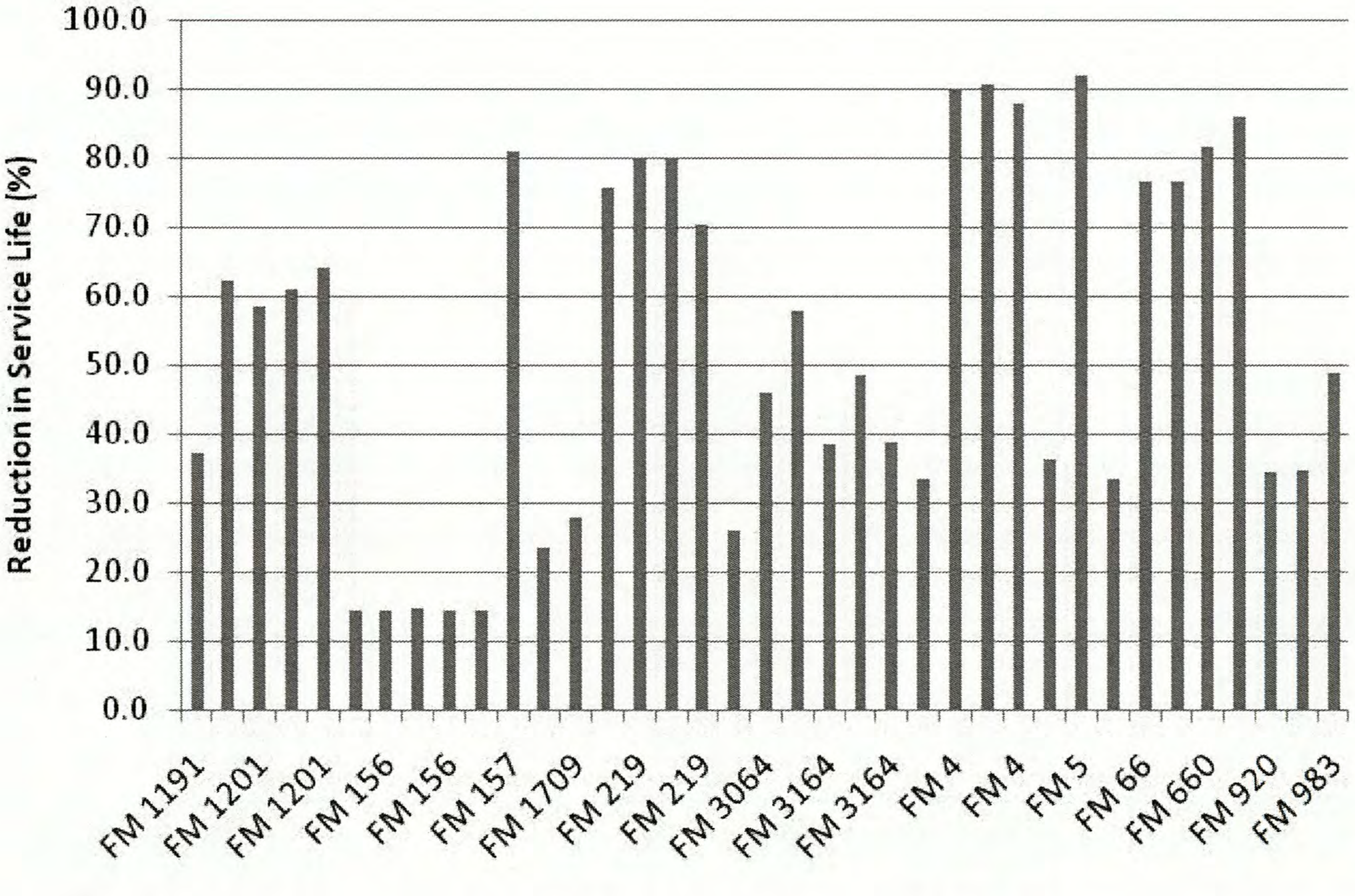


Figure A3.15: Reduction in Service Life of FM Sections in the Barnett Shale Region due to Construction Traffic (for 10 Natural Gas Wellheads over a 20-Year Analysis Period)

Interstate Highways

Construction Traffic

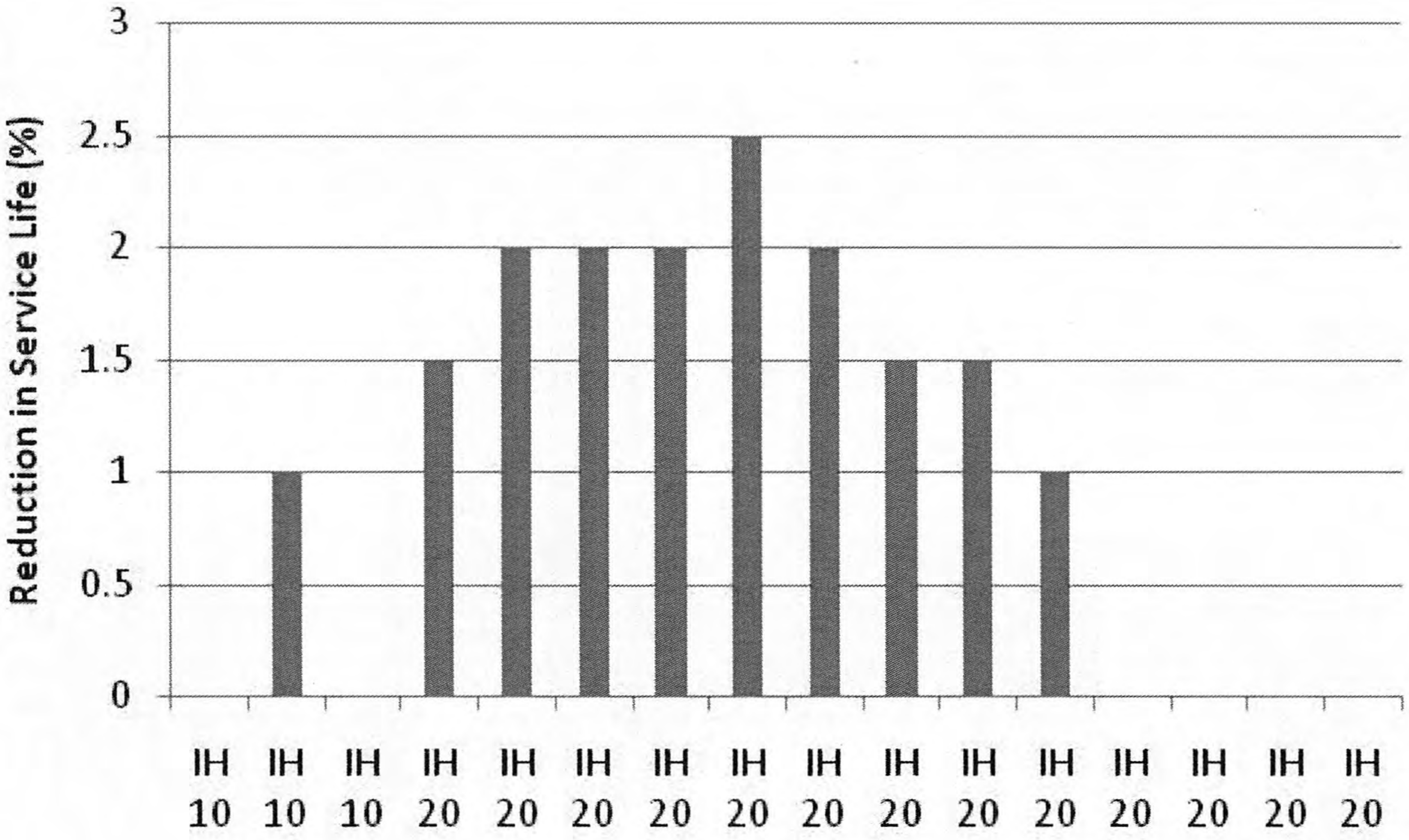


Figure A3.16: Reduction in Service Life of IH Sections in the Permian Basin Region due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Production Traffic

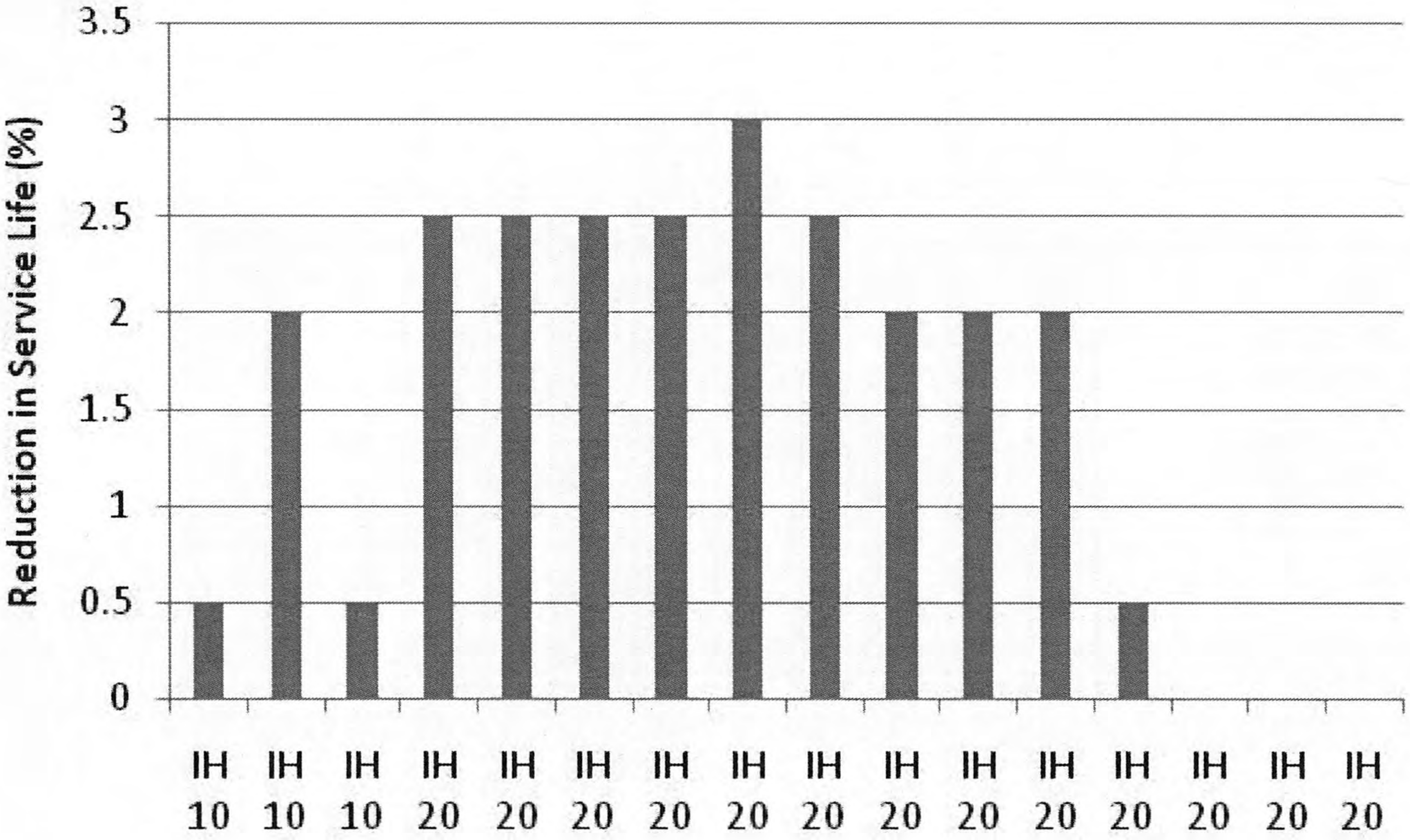


Figure A3.17: Reduction in Service Life of IH Sections in the Permian Basin Region due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

US Highways

Construction Traffic

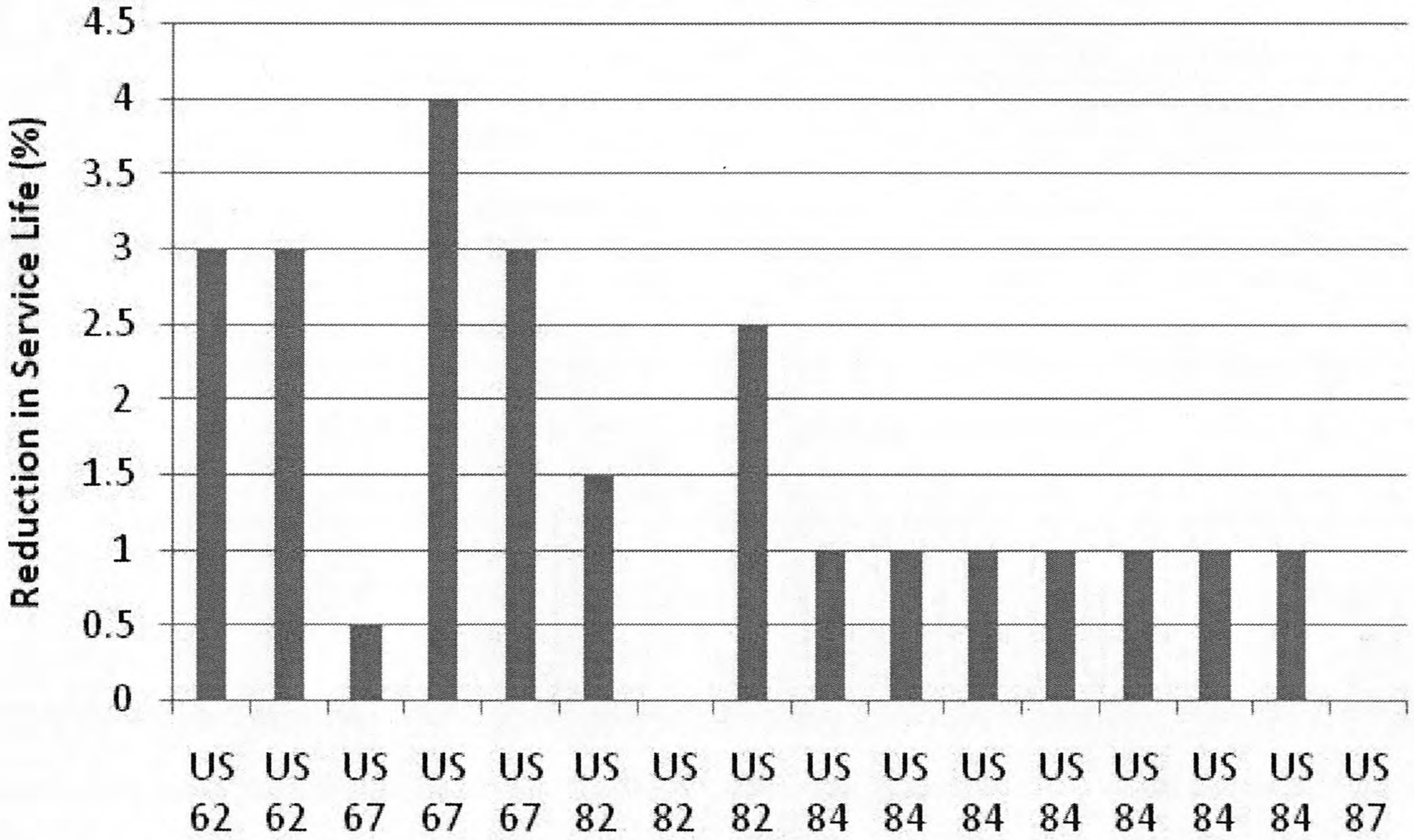


Figure A3.18: Reduction in Service Life of US Highway Sections in the Permian Basin Region due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Production Traffic

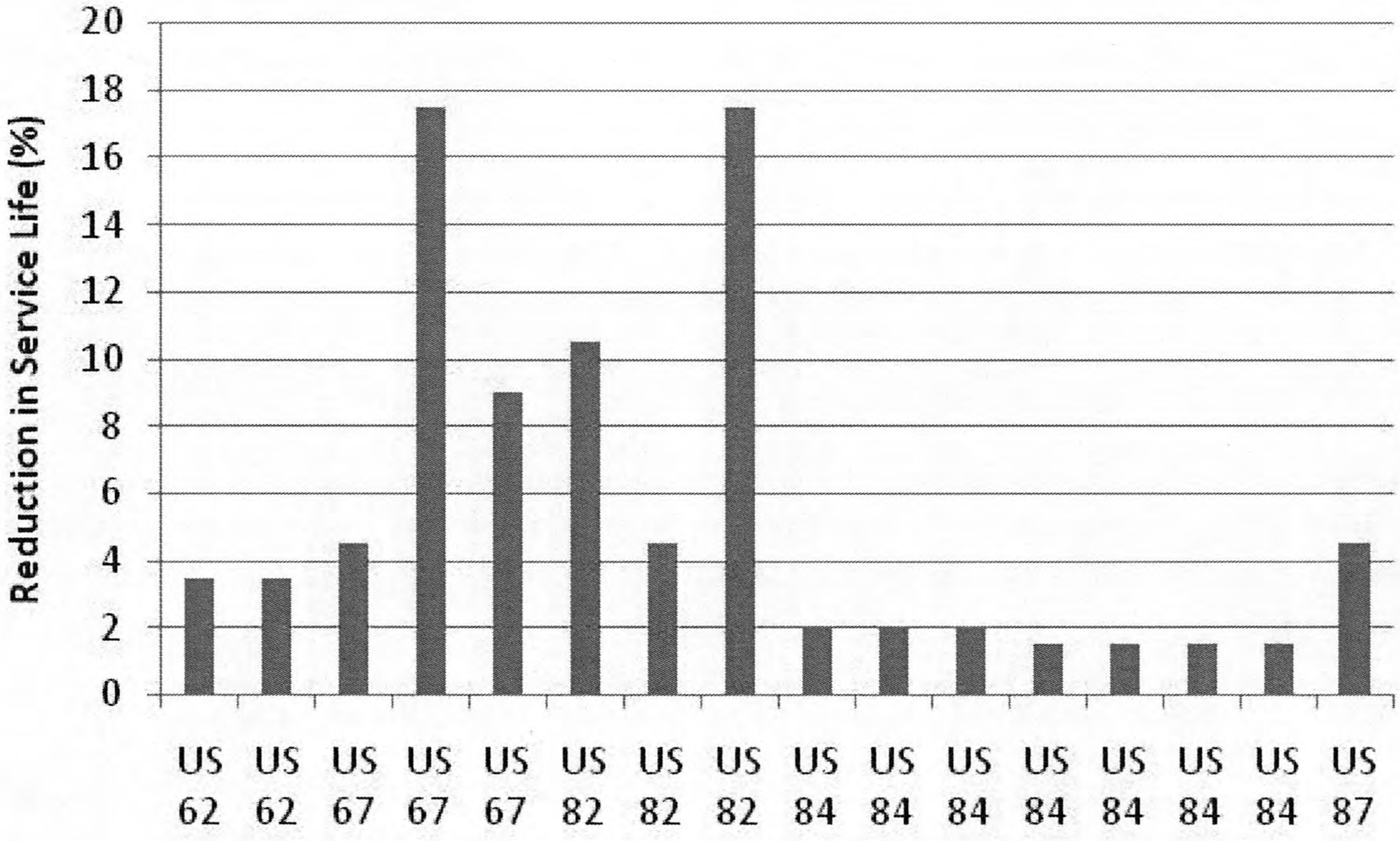


Figure A3.19: Reduction in Service Life of US Highway Sections in the Permian Basin Region due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

State Highways

Construction Traffic

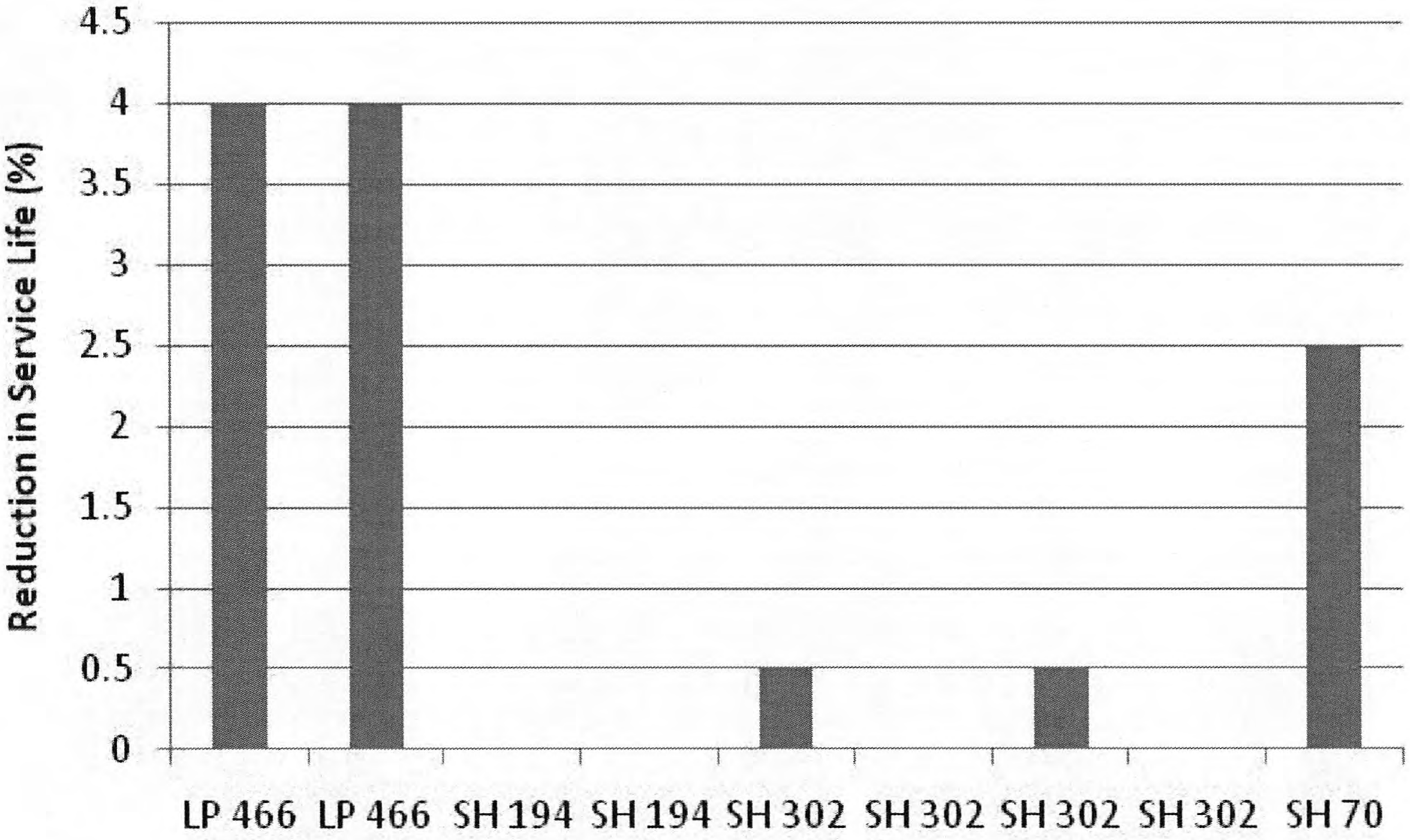


Figure A3.20: Reduction in Service Life of State Highway Sections in the Permian Basin Region due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Production Traffic

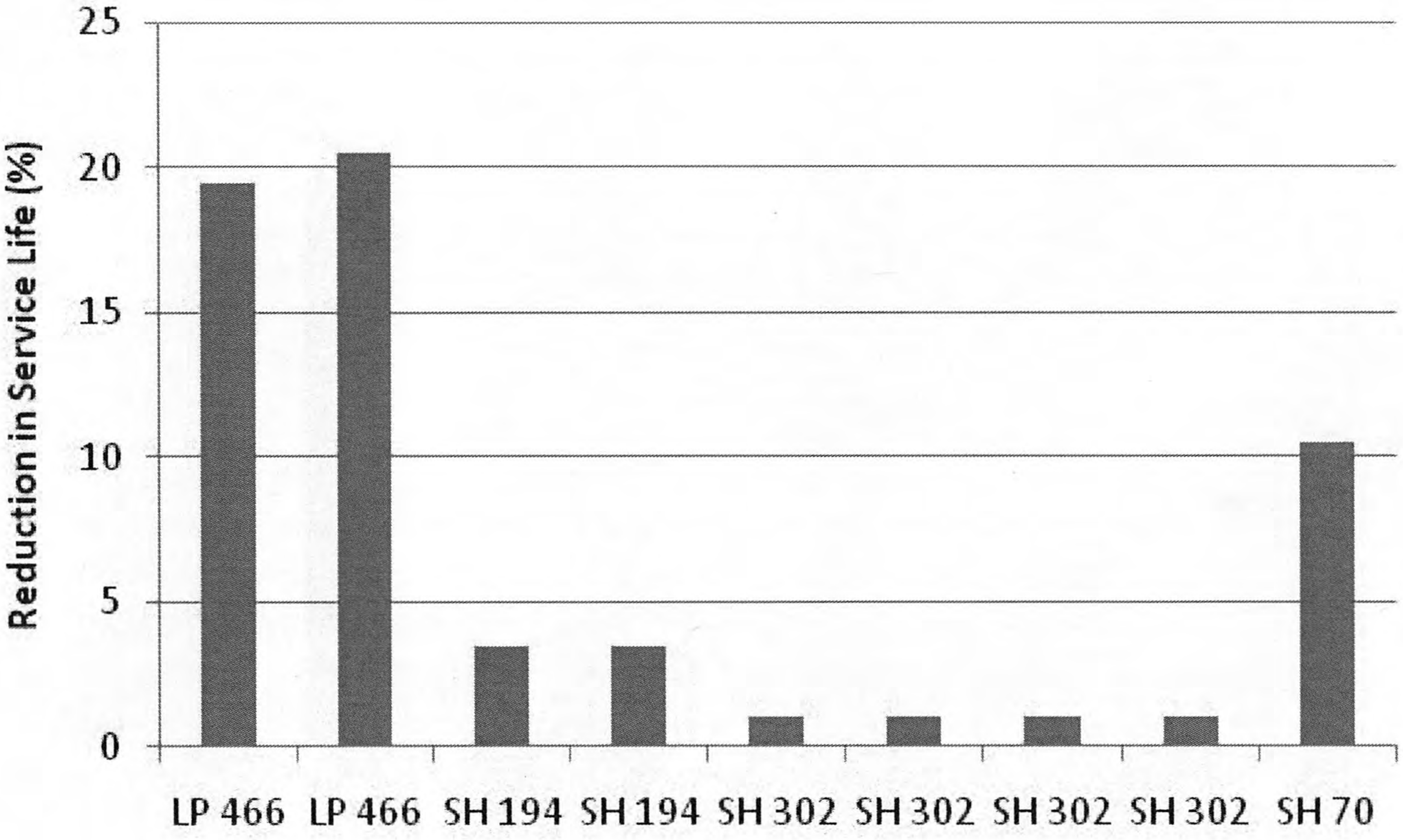


Figure A3.21: Reduction in Service Life of State Highway Sections in the Permian Basin Region due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

FM Roads

Construction Traffic

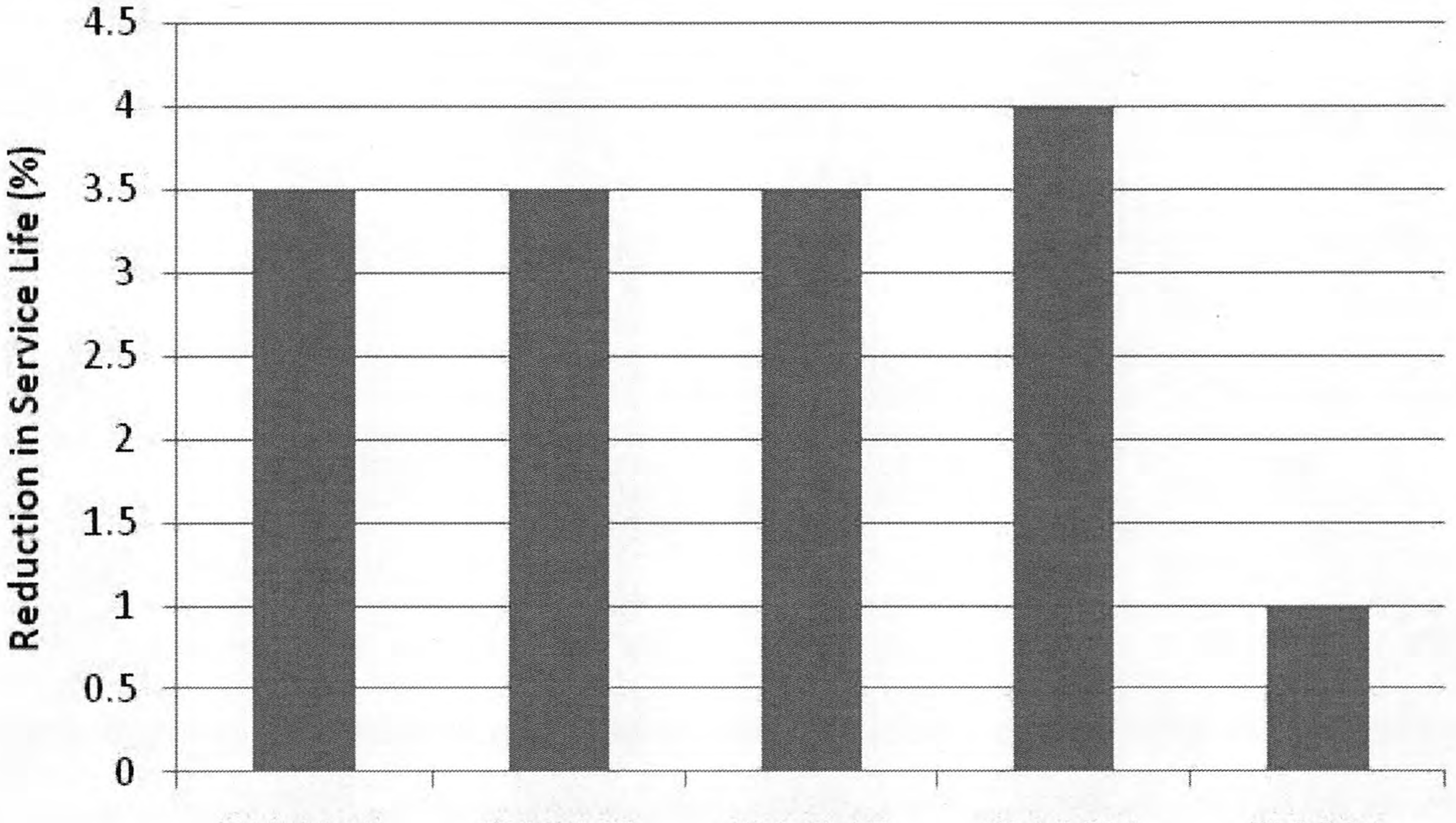


Figure A3.22: Reduction in Service Life of FM Sections in the Permian Basin Region due to Construction Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Production Traffic

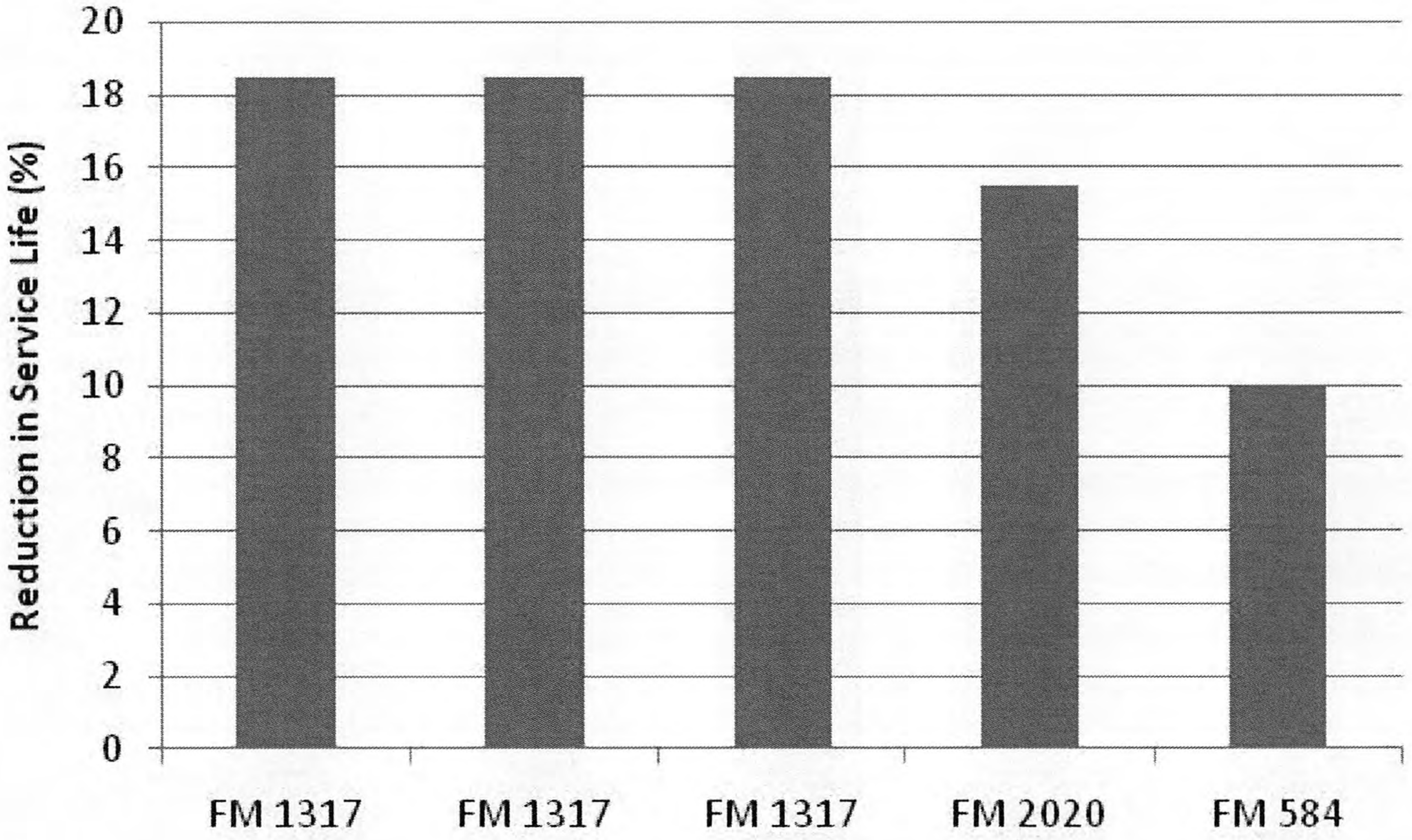


Figure A3.23: Reduction in Service Life of FM Sections in the Permian Basin Region due to Production Traffic (for 16 Crude Oil Wells over a 20-Year Analysis Period)

Appendix A4: The Mechanistic-Empirical Pavement Design Guide

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is a pavement analysis system. In the mechanistic-empirical method, the fundamental pavement responses for flexible pavements under repeated traffic loadings are calculated using a multi-layer linear elastic approach. This approach assumes that a pavement structure is a layered structure and that each of the layers in the pavement structure exhibits an elastic behavior that is linear in nature. The method computes the stresses and strains that are induced in the pavement layers due to traffic loadings. These pavement responses are then related to field distresses using existing empirical relationships. These relationships are known as transfer functions. The MEPDG starts with a trial pavement structure, location, traffic type, weather conditions, existing pavement conditions (in the case of rehabilitation), reliability and failure criteria as design inputs and predicts the pavement performance under the various failure criteria. The MEPDG does not produce a structural design (i.e., layer thickness) but instead analyzes the adequacy of a given design against different failure mechanisms typically seen with flexible or rigid pavements, thus allowing the user to check the sufficiency of the trial design.

Thus, the MEPDG represents a major change from the way pavement design had been done in the past. The designer first considers site conditions (traffic, climate, subgrade, and existing pavement conditions for rehabilitation) and construction conditions in proposing a trial design for a new pavement or rehabilitation. The trial design is then evaluated for adequacy through the prediction of key distresses (cracking and rutting) and smoothness (roughness in IRI). If the design does not meet desired performance criteria, it is revised by changing structural and material properties and the evaluation process is repeated as necessary (Figure A4.1). Thus, the designer has the flexibility to consider different design features and materials for the prevailing site conditions. As such, the MEPDG is not a design tool but a very powerful and comprehensive pavement analysis tool.

The MEPDG was nationally calibrated taking into consideration the various climatic regions across the country. The national calibration of the design guide was based on a wide spectrum of conditions that are too general and different from those normally seen in Texas. For example, materials or weather conditions in Texas are quite different from those found in the northern states of the U.S. Calibrating the MEPDG on a national level implies the performance predicted by the MEPDG will not be accurate enough for a specific region or locality. National calibration reproduces the behavior of a theoretical average American pavement, not any specific one. This approach is due to the fundamental differences in the various design parameters such as climate and materials, because the materials or construction practices used in any given region may differ significantly from the national average, as will regional weather patterns and climate conditions. As a result, predictions will tend to systematically miss the actual in-field observations and the errors so observed will be biased in nature. If the MEPDG with the exact same calibration coefficients were used for pavement design in Texas, the design would either over-estimate or under-estimate the pavement structure because materials, environmental conditions, and construction practices in Texas differ from the national average. The same will apply to any other state or country. The resulting error will be either always positive or negative, meaning that it will never cancel out, thus contributing to the bias in the prediction model. To correct these biases (systematic errors) in the model, the bias correction factors are introduced (also known as the calibration coefficients).

Calibrating the transfer functions in the MEPDG requires many input parameters that are necessary for proper characterization of the individual layers of the entire pavement structure, the geographical conditions, and the traffic. In addition, project-specific performance data is required for each of the distress mechanism for which the transfer function requires calibration. However, in the context of this study, project-level performance data was not available. Thus calibration of the transfer functions was not possible within the timeframe of this research study. Given these limitations, the performance predictions obtained from the MEPDG would therefore be biased. However, obtaining a ratio between two sets of distress measurements would help cancel out the biases in a model where the systematic differences are multiplicative by nature. This happens to be the case for the plastic deformation, alligator cracking, and longitudinal cracking models in the MEPDG. The same procedure could be further extended to other performance predictions models where the systematic differences are additive by nature, the only difference being computing a difference instead of a ratio. This approach was adopted in the case of roughness predictions for the current study.

In order to have a meaningful interpretation of the ratios or the differences that are calculated, it is essential that these indices are calculated with respect to a consistent benchmark. The researchers opted for the distress prediction obtained from the MEPDG with the design traffic level for the specific highway as the baseline for computing the damage parameter. This would not only help obtain an unbiased index for pavement damage but also help estimate the additional damage imposed by the truck traffic associated with a specific energy sector.

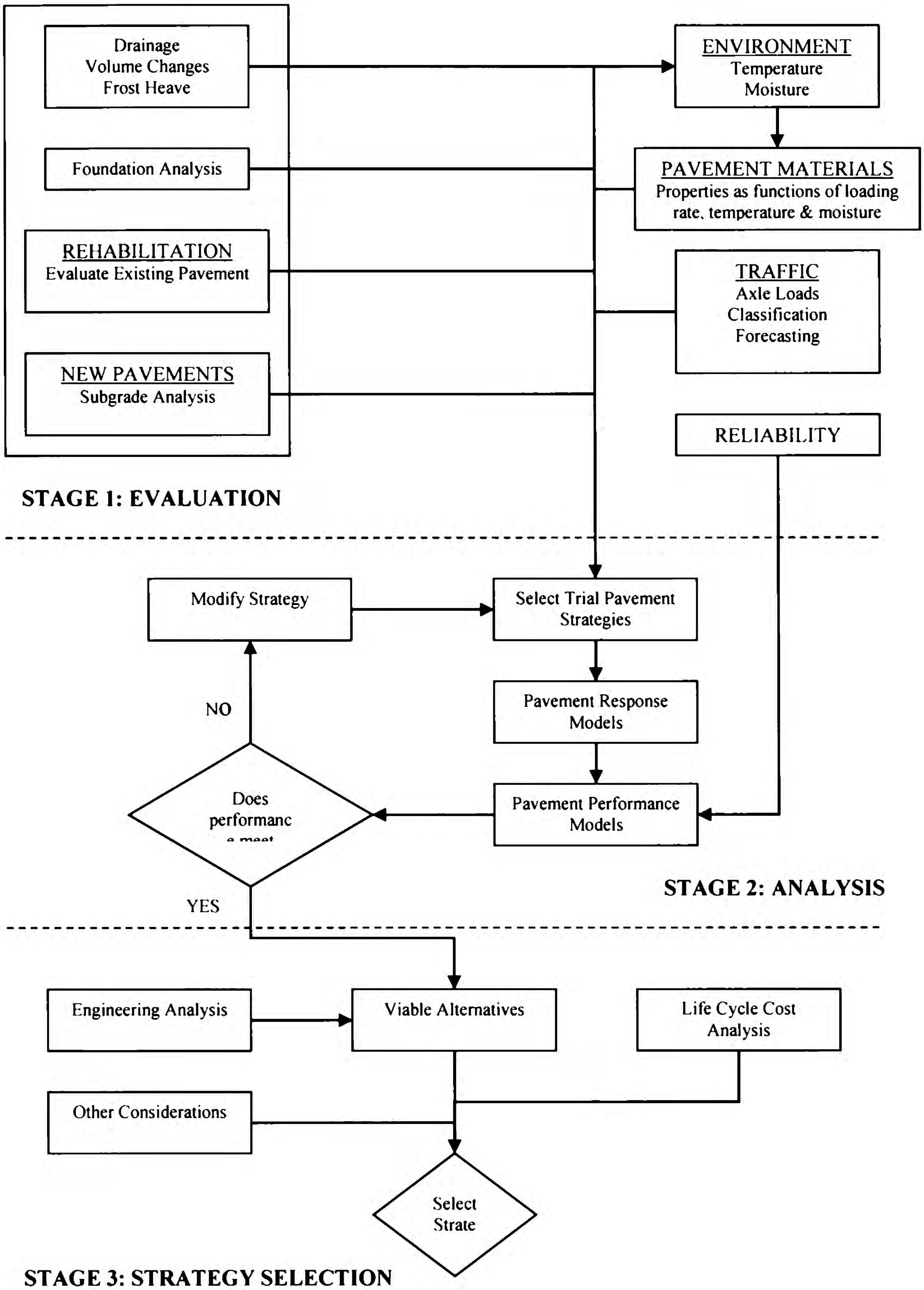


Figure A4.1: MEPDG Design Procedure (ARA, 2004)

Appendix B: Major Gas Well Developers and Operators

As of May 2010, 13,902 gas wells were captured in the RRC records and 220 gas well operators were identified in the Barnett Shale region. Also 139 service companies were identified in the RRC's Oil and Gas Directory. These service companies are involved in activities such as drilling, fraccing, welding, cement services, mud services, and tank services for the natural gas industry. Most of the drilling is, however, done by a select number of companies who own or lease a set number of rotary rigs that they deploy for drilling. Table B.1 presents information on the major drilling companies that operated in the Barnett Shale region in 2008.

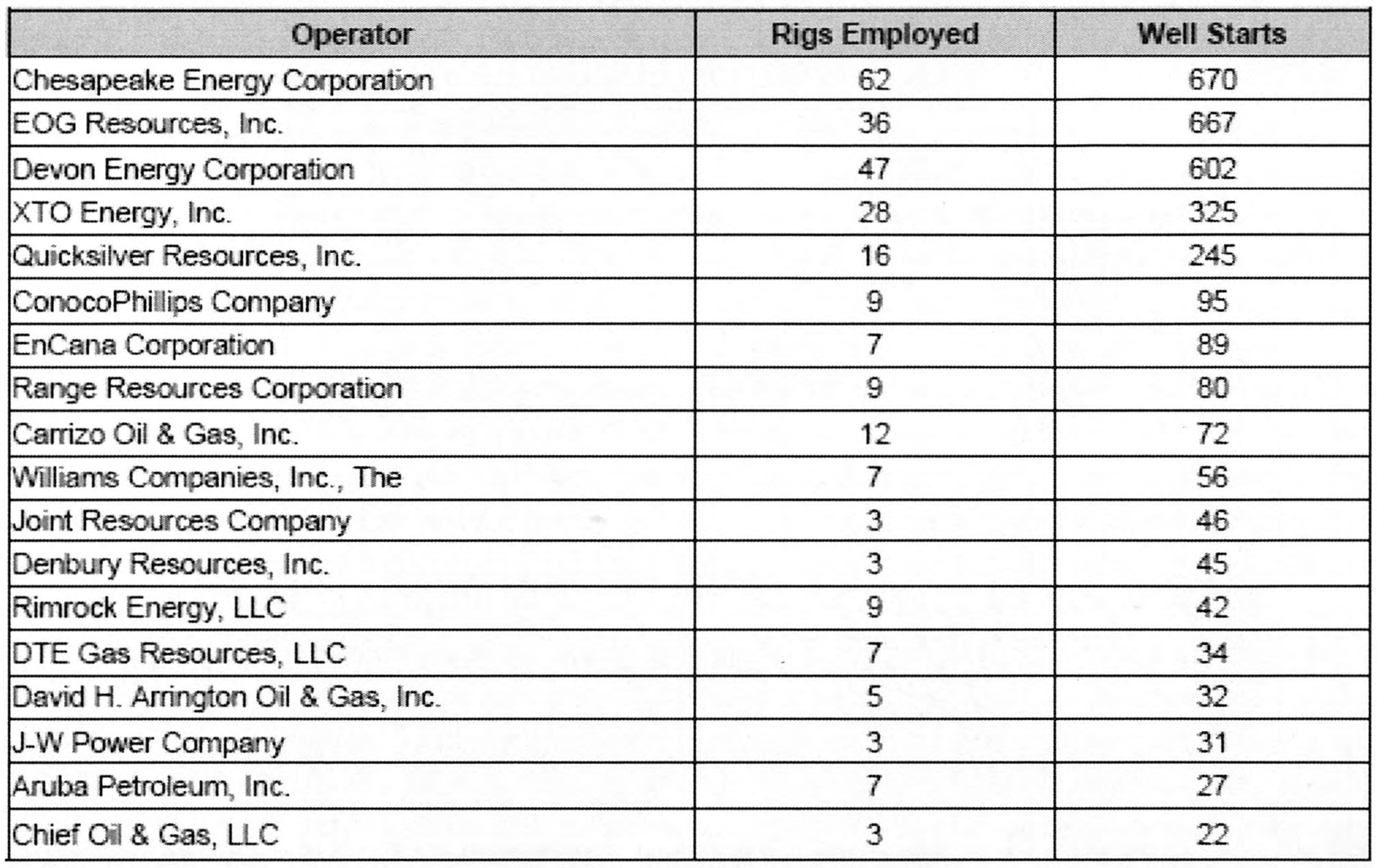
Table B.1: Major Drilling Companies that Operated in the Barnett Shale (2008)

Driller	Rigs Deployed	Well Starts
Patterson-UTI Drilling Company, LP	54	601
Helmerich & Payne, Inc.	34	425
Nabors Industries, Ltd.	24	283
Complete Production Services, Inc.	21	257
Nomac Drilling, LLC	28	222
Saxon Energy Services, Inc.	12	209
Union Drilling, Inc.	16	206
Precision Drilling Trust	12	187
Pioneer Drilling Company	14	177
Trinidad Drilling, LP	7	96
Goober Drilling, LLC	5	87
Grey Wolf, Inc.	8	84
Cactus Drilling Company, LLC	8	79
Mountain Drilling Company	6	51
Steinberger Drilling Company	3	42
Latshaw Drilling & Exploration Company	2	42
HiTex Drilling, LP	5	41
Unit Drilling Company	4	37

Source: RigData, ND

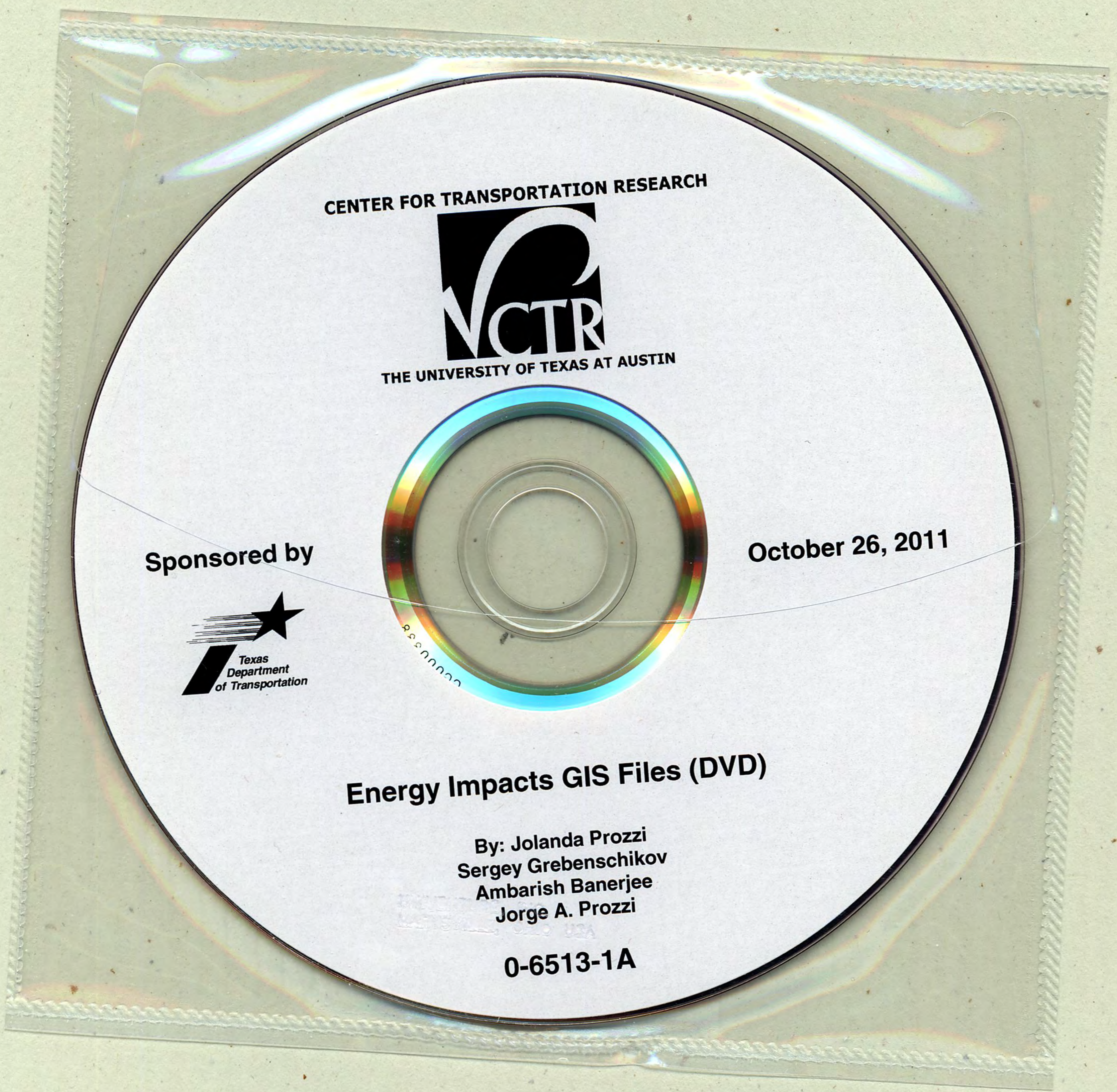
Of the 4,145 permitted well locations on the RRC records in 2008, 75.42% of the sites were drilled by the top 17 drillers listed in Table B.1. This figure implies that most of the drilling in the Barnett Shale is conducted by a few major corporations with the equipment and financial resources to carry out large-scale drilling operations. The operation of natural gas wells is also conducted by several major business entities. Table B.2 presents the top 18 gas well operators in the Barnett Shale area. These businesses operated 76.72% of all permitted well locations in the Barnett Shale area in 2008.

Table B.2: Top Gas Well Operators in the Barnett Shale Region (2008)



Operator	Rigs Employed	Well Starts
Chesapeake Energy Corporation	62	670
EOG Resources, Inc.	36	667
Devon Energy Corporation	47	602
XTO Energy, Inc.	28	325
Quicksilver Resources, Inc.	16	245
ConocoPhillips Company	9	95
EnCana Corporation	7	89
Range Resources Corporation	9	80
Carrizo Oil & Gas, Inc.	12	72
Williams Companies, Inc., The	7	56
Joint Resources Company	3	46
Denbury Resources, Inc.	3	45
Rimrock Energy, LLC	9	42
DTE Gas Resources, LLC	7	34
David H. Arrington Oil & Gas, Inc.	5	32
J-W Power Company	3	31
Aruba Petroleum, Inc.	7	27
Chief Oil & Gas, LLC	3	22

Source: RigData, ND



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