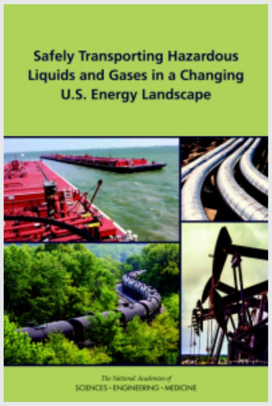

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Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape

Committee for a Study of Domestic Transportation of
Petroleum, Natural Gas, and Ethanol

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Preface

This study was initiated and sponsored by the Transportation Research Board (TRB) Executive Committee in response to the rapid development of domestic sources of energy and questions about the safest ways to move these products. The study charge and origins are explained in Chapter 1. The contents and findings of the report represent the consensus effort of a committee of subject matter experts, who served uncompensated in the public interest. Spanning multiple disciplines, the members applied expertise from transportation systems analysis; energy market analysis; state and local emergency management; transportation safety oversight; risk analysis; and pipeline, rail, and maritime safety and operations. Committee member biographical information is provided at the end of the report.

The study committee met five times over 11 months, including a subcommittee meeting in Texas to visit pipeline, railroad, and waterways facilities. The committee engaged in extensive data gathering during and between meetings. The first two meetings and the Texas site visits included sessions open to the public. At these meetings, the committee heard from government and industry experts on the long-distance transportation of energy liquids (crude oil, ethanol, and natural gas liquids) and natural gas, energy markets, hazardous materials safety research, and emergency response. The appendix includes the agendas of the meetings and the site visits.

ACKNOWLEDGMENTS

The committee thanks the many individuals who contributed to its work.

During data-gathering sessions open to the public, the committee met with the following federal government officials: Karl Alexy, Director of Safety Analysis, Federal Railroad Administration (FRA); Ron Duych, Senior Transportation Specialist, Bureau of Transportation Statistics; Lad Falat, Director of Engineering and Research, Pipeline and Hazardous Materials Safety Administration (PHMSA); CAPT Benjamin Hawkins, Chief, Office of Design and Engineering Standards, U.S. Coast Guard (USCG); Arup Malik, Operations Research Analyst, U.S. Energy Information Administration (EIA); Karen McClure, Industry Economist, FRA; Paul Stancil, Hazardous Materials Investigator, National Transportation Safety Board; and Jeffrey Wiese, Associate Administrator (retired), PHMSA. The contributions of all were appreciated, especially those of McClure, who provided rail traffic data to the committee.

The committee met with and received information from the following representatives of the long-distance carriers and energy sector experts: Terry Boss, Interstate Natural Gas Association of America; E. Russell Braziel, RBN Energy; Peter Lidiak, International Liquid Terminals Association; Robert Fronczak, Association of American Railroads; Robin Rorick, American Petroleum Institute (API); Kelly Davis, Renewable Fuels Association; and Caitlyn Stewart, American Waterways Operators. Additional industry perspectives came from subcommittee meetings with long-distance operators in Texas: Nancy Barton, Gary Buchler, James Holland, Mark Jensen, Ray Miller, and Elizabeth Oakley of Kinder Morgan; James Farley, Jim Guidry, Christian O'Neil, and Matt Woodruff of Kirby Corporation; Stephen Polk of the Seamen's Church Institute Center for Maritime Education; and Pat Brady, Sean Hill, Ryan Miller, Frank Moffitt, and Ryan Ringelman of BNSF Railway. The committee expresses its gratitude for their insight into the transportation of energy liquids and natural gas.

The committee also met with the following individuals with technical expertise in flammable liquid and gas properties, packaging, and emergency response: Christopher Barkan, Rail Transportation and Engineering Center, University of Illinois at Urbana-Champaign; Rick Edinger, International Association of Fire Chiefs; Anay Luketa, Fire Science and Technology Department, Sandia National Laboratories; Debbie French McCay, Applied Science Associates; Frank Reiner, TRANSCAER; Todd Treichel, RSI-AAR Railroad Tank Car Safety Research and Test Project; and David Willauer, Cambridge Systematics. The committee benefited from their assistance in identifying safety assurance challenges posed by energy liquids and natural gas shipments.

Finally, the committee thanks the following individuals who provided briefings or were otherwise helpful in identifying issues and providing data and other information: W. R. "Bill" Byrd and Jenn Lee Randolph, RCP, Inc.; Mindi Farber-DeAnda and Warren Wilczewski, EIA; Suzanne M. Lemieux and Stuart E. Saulters, API; Donna Lepik, TRANSCAER; CAPT Joe Loring, CDR Mike Simbulan, and Kristin A. Williams, USCG; Phani Raj, FRA; Kenneth Ned Mitchell, U.S. Army Corps of Engineers; Serita McKoy, PHMSA; Paul Williams, Norfolk Southern Railway; and Joseph C. Athey, Federal Energy Regulatory Commission. The committee appreciates the expertise shared by Randolph and Byrd to inform its review of pipeline incident data and the access granted by Williams for project staff to attend the Operation Awareness and Response training session on hazardous materials by railroad.

Micah D. Himmel and Thomas R. Menzies were the principal project staff. Himmel managed the study and drafted much of the report under the guidance of the committee and with assistance and supervision from Menzies. Additional technical assistance and oversight were provided by James Zucchetto and K. John Holmes, the Board on Energy and Environmental Systems. The committee also acknowledges the work and support of Karen Febey, Senior Report Review Officer, who managed the report review process. Amelia Mathis provided extensive support to the committee in arranging its meetings and managing documents. The committee acknowledges Rachel D'Agostino, who edited the report.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report: Kevin Book, ClearView Energy Partners, LLC, Washington, D.C.; Julie Carey, NERA Economic Consulting, Washington, D.C.; Stacey Gerard, PHMSA (retired), Berryville, Virginia; Barbara Ivanov, University of Washington, Seattle; Michael Kavanaugh, Geosyntec Consultants, Oakland, California; Jan Schilling, Advanced Products General Electric Aviation (retired), Liberty Township, Ohio; George Tenley, Consultant, Hedgesville, West Virginia; Frits Wybenga, Dangerous Goods Transport Consulting, Inc., Rockville, Maryland; and Mary Lou Zoback, Stanford University, Stanford, California.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by the review coordinator, John F. Ahearne (National Academy of Engineering), Sigma Xi, The Scientific Research Society (retired), and Susan Hanson (National Academy of Sciences), Clark University (*emerita*). They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Summary

This report reviews the response of the U.S. pipeline, rail, and barge industries to the marked increase after 2005 in the domestic production of crude oil, fuel ethanol, and natural gas. The growing demand to move these new energy supplies economically and safely from new origins, across new routes, and by new means of conveyance was largely unanticipated by transportation providers and the federal authorities that regulate their safety. To the credit of both, the vast majority of these hazardous liquids and gas shipments are transported without incident, enabling the country to capitalize on its energy resources while reducing imported supplies and the safety risks associated with their transportation to the United States. However, some incidents have had severe consequences that attracted the attention of the public, and policy makers are intent on preventing similar incidents in the future.

When this study began in 2015, a debate was under way about whether the domestic energy revolution was creating demands on the transportation system that were sacrificing safety. Railroad tank cars and river and coastal tank barges were being used to haul oil and fuel ethanol in increasingly larger volumes, over longer distances, and often through communities that had little, if any, previous experience with hazardous materials traffic. Some serious tank car derailments occurred, and there was skepticism about whether more high-capacity pipelines could be built to provide a safer means of transport, in part because of highly publicized opposition to the construction of new pipelines on grounds that their safe operation could not be assured.

In retrospect, skepticism about the ability of the pipeline sector to add capacity in response to the increasing and changing geographic demand for energy transportation was unwarranted. The country's hazardous liquid and gas transmission pipeline network has expanded dramatically in a relatively short period for such an infrastructure-intensive mode. Since 2015, the domestic energy revolution has taken new turns in response to volatility in oil and natural gas prices, which has led to sharp reductions in the demand for the transportation of these energy liquids and gases by rail and by barge. Even the demand for transporting fuel ethanol, which is met largely by railroads, has passed from a period of growth to one of stability as ethanol production has reached levels targeted by federal policy. Because the domestic energy revolution is still playing out, the potential remains for additional, unanticipated impacts on the energy transportation system that present new safety challenges.

In sponsoring this study, the Transportation Research Board Executive Committee sought a review and comparison of how the pipeline, rail, and barge industries have fared to date in safely transporting the new domestic energy liquids and gas traffic. For several reasons—including the difficulty of accounting for infrequent, high-consequence events in incident statistics and the secondary safety effects of more barge and rail traffic activity (e.g., train crashes at highway grade crossings)—direct statistical comparisons of the safety performance of the different transportation modes can be difficult to make. Furthermore, such safety comparisons can be of questionable value in situations when the modes are not viable substitutes for one another, such as when the traffic served by a train or a barge is too light or irregular to justify the investment in a high-volume transmission pipeline.

Nevertheless, several insights can be gleaned from a comparative review of the safety assurance systems in each of the three long-distance transportation modes. Based on the following observations from its review of these systems, as well as efforts to strengthen the response capacity when emergencies do occur, the committee offers several recommendations to the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) and the Federal Railroad Administration (FRA). The recommendations are made in the spirit of developing a safety assurance and emergency response capability that is even more robust in the face of safety challenges that may arise in the future.

OBSERVATIONS

Expansion of Oil and Gas Transmission Pipelines Will Require Added Safety Vigilance

Dedicated almost exclusively to the transport of hazardous liquids and gases, U.S. pipelines have long transported a large majority of the country's domestic and imported crude oil and natural gas supplies. Pipeline operators, who have a high degree of familiarity with oil and gas shipments, have made substantial investments in new capacity to serve the growing domestic oil and gas sector. The U.S. pipeline industry has accommodated the increasing volumes of domestic oil and gas traffic without creating major new safety concerns and within the basic framework of a longstanding regulatory and safety assurance process.

Unintended pipeline releases have not increased with the higher traffic volumes, and most large year-to-year fluctuations in total release volumes have been the result of occasional major incidents with no discernible pattern. Nevertheless, the addition of substantially more pipeline mileage and traffic volume can be expected to result in more total pipeline releases than would have occurred in the absence of these developments. Time-dependent release mechanisms such as corrosion and cracking, as well as outside-force damage such as from excavation strikes, will undoubtedly lead to releases from some of the newer pipelines over time. While the use of advanced pipeline construction methods and technologies may limit these releases, vigilance in pipeline maintenance, integrity management, and leak monitoring will be essential to suppressing an increase in total incidents and the likelihood of major events. In cases when existing pipelines have undergone flow reversals or been repurposed from carrying other commodities to transport the new domestic oil and gas traffic, an inventory of these pipelines may be warranted to allow for closer monitoring of potential problems that may arise from changes in their stress and operating profiles.

Marine Transportation System Offers a Model for a Robust Safety Assurance System

Tank barges have a long history of transporting crude oil and other energy liquids with improved safety performance as a result of extensive readiness planning and response training informed by lessons learned more than 30 years ago. Although the increase over the past decade in barge movements of crude oil has not attracted much public attention, the total volumes of oil transported by barge have exceeded those of rail. A possible reason for the lack of public attention is the exemplary safety record of this mode, which has had no reports of significant ethanol releases from tank barges during the past 10 years and only rare reports of unintended releases of crude oil.

The highly sensitive nature of the marine environment has long demanded vigilance in preventing, containing, and mitigating oil releases from tank barges. A series of catastrophic oil spills from tanker ships and tank barges nearly 30 years ago caused the federal government to revamp the safety assurance system in ways that have fundamentally altered the industry's safety profile. In addition to requiring the use of double-hulled tankers and tank barges for carrying oil and refined products, several new statutory and regulatory requirements have created a safety assurance system that has proven to be robust in enabling the maritime industry to safely accommodate unanticipated changes in demand for the movement of oil and other energy liquids. Designated by law as the responsible party for oil spills, barge and other vessel operators must make preparations for responding to releases over the length of their transportation routes and immediately notify the U.S. Coast Guard of any observed oil in water regardless of quantity or the possibility of another party being the source of the release. These reforms have been credited with not only fundamentally changing the set of safety incentives that maritime carriers and shippers face, but also with creating a safety culture and assurance system that is anticipatory so that safety is reasonably assured in the face of unforeseen changes in traffic levels, technology, and operating practices.

Railroads Have an Opportunity to Create a More Robust Safety Assurance System

Railroads had little experience carrying crude oil and ethanol in large quantities until after 2005 when they started transporting these flammable liquids in blocks of tank cars and eventually in unit trains of 100 or more tank cars. Unlike in the pipeline and marine transportation sectors in which the carrier has primary responsibility for all major factors affecting safety, railroads share this responsibility with shippers who own or lease, load, and secure the tank cars. In response to early derailments of trains carrying ethanol and crude oil, the focus of railroad and shipper safety assurance efforts was on designing a tank car that is more crashworthy and resistant to thermal failure in the event of a derailment.

New tank car designs intended to improve crashworthiness and thermal resistance, including the newest DOT-117 specification, were informed largely by the historical performance of tank cars that had derailed in mixed-car trains. Experience with unit trains of tank cars was too limited to know how the dynamics of their derailments would compare. As this derailment experience increases over time, the safety performance of the DOT-117 design will become clearer. For a transitional period, however, tank cars built to the older specifications that are less crashworthy and less resistant to thermal failures may continue to be used for flammable liquids traffic. Preventing derailments of this traffic is imperative.

Investigations of train derailments indicate that track wear and defects are common causal factors. FRA regulations that establish maximum failure rates per track mile are performance based so as to encourage innovation in the identification, assessment, and repair of defects. Questions remain, however, about the technical basis for the allowable failure rate, the prioritization that should be given to repairing certain defects, and whether this rate and prioritization should be adjusted for routes with significant flammable liquids traffic. Likewise, questions remain about the technical basis for regulatory requirements that establish maximum speed limits for this traffic, which were established based on speed limits imposed on other types of hazardous materials that are seldom transported in unit trains.

Emergency Response Preparedness Has Improved but with Geographic Inconsistency

Because crude oil and ethanol unit trains are a relatively new phenomenon, many of the communities traversed had no previous experience preparing for and responding to emergencies involving this traffic. Emergency preparedness has improved as knowledge of crude oil and ethanol behavior in tank car derailments has grown and as emergency responder resources, information, and procedures have been enhanced as result of the research, training, and educational efforts of industry and government safety agencies. Transportation providers have strengthened their connections with state and local officials, developed new communications tools to aid emergency responders, and increased offerings of emergency response training.

Despite these noteworthy accomplishments, opportunities remain for further improvement in emergency response capabilities and resources. Industry and government authorities face a continuing challenge in ensuring that the best practices for preparing for and responding to incidents are widely known and that training opportunities are fully exploited, especially among rural communities served by volunteer fire departments. In addition, there is little in the way of guidelines on the kinds of traffic information that carriers should be providing to state emergency response planning agencies, nor assurance that the recipient agencies are transmitting the information to the local responders who may need it.

RECOMMENDATIONS

A decade after the start of the domestic energy revolution, it is difficult to know whether the impacts on the pipeline, rail, and barge industries have stabilized or temporarily reached a steady state. However, while the pace of change has slowed, it is an opportune time to review the functioning and performance of each mode's safety assurance system with a strategic focus on its ability to handle future safety challenges. To this end, the committee recommends that PHMSA, which has primary federal responsibility for overseeing and regulating hazardous materials transportation safety, takes the following actions:

1. Undertake a comprehensive review of the successes and failures during the past decade in responding promptly and effectively to the transportation safety challenges presented by the domestic energy revolution for the purpose of informing the development of more anticipatory and robust safety assurance systems, including regulatory approaches.
2. Consult regularly with industry on developments impacting energy liquids and gas transportation and report annually on steps that are being taken to monitor and assess these developments for safety implications.
3. Evaluate the utility of existing incident- and traffic-reporting data for the purpose of identifying and assessing public safety and environmental risks associated with transporting energy liquids and gases, determine whether new and improved incident- and traffic-reporting systems are needed, and ensure that these data and risk metrics are being shared with state emergency preparedness agencies and with industry for safety assurance purposes.
4. Consult shippers and carriers on the kinds of data that are available and needed to improve incident- and traffic-reporting systems for the purpose of developing risk metrics.
5. Consult with state emergency preparedness agencies on opportunities for presenting and sharing these data and metrics with local communities and their emergency responders.
6. Coordinate with the other modal safety regulators in encouraging pipeline, rail, and barge operators to make greater use of quantitative risk analysis tools to inform decisions about the routing of energy liquids and gases and about priorities for maintenance and integrity management of equipment and infrastructure.
7. Work with FRA in regularly and systematically assessing the risk-reduction impacts of new regulations to ensure the safety of flammable liquids shipments, perhaps starting with a review of the crash and thermal performance of the new DOT-117 tank car design.
8. Systematically model the full array of factors that can give rise to and affect the severity of flammable liquids train derailments and crashes, giving attention, for instance, to the propagation of internal rail defects and the kinetics that arise from multicar derailments.
9. Make a concerted effort to ensure that federal emergency preparedness grants are being used to meet the planning, training, and resource needs of communities that are facing new and unfamiliar risks as a result of the changes that have occurred in the routing and volume of energy liquids and gas shipments. As a starting

point, PHMSA should review the extent to which emergency responders in such communities, especially in rural areas served by volunteer fire departments, are taking advantage of relevant training opportunities, and then use this information to tailor programs that will enable and incentivize higher levels of participation.

In addition to working with PHMSA on the actions recommended above, the committee recommends that FRA:

10. Enable and incentivize more frequent and comprehensive inspections of rail routes that have regular energy liquids traffic, particularly by enabling railroads to exploit new inspection capabilities that are being made possible by advances in sensor, imaging, and autonomous systems technologies.

CONCLUDING COMMENTS

The committee believes, as reflected in the actions recommended above, that industry and regulators should strive to make the safety assurance system for energy liquids and natural gas transportation more anticipatory, responsive, and risk informed. Based on its review of responses to the safety challenges arising from the domestic energy revolution, the committee is optimistic about the ability of industry and government to achieve such an outcome, especially through increased collaboration. Working together, industry, regulators, and the emergency response community will be in a better position to reduce the occurrence and the severity of incidents involving transportation of energy liquids and natural gas. To do so, however, they will need to share information and develop more robust risk analytics, create and apply incentives to further the use of automation and other technological innovations for monitoring the safe operation and condition of equipment and infrastructure, and regularly review the effectiveness of safety regulations. The actions recommended in this report represent first steps in meeting these needs.

1

Introduction

For more than a decade, the United States has been experiencing what is often called a domestic energy revolution. The increased use of hydraulic fracturing and horizontal drilling has led to a dramatic increase in U.S. production of crude oil, natural gas, and natural gas liquids from the country's shale and other mudstone basins. During roughly the same period, domestic production of corn-based ethanol has risen sharply in response to federal mandates for the use of renewable fuel in gasoline. Often sourced from regions that were once minor producers of energy liquids and gases, these new supplies have created many unforeseen demands on long-distance energy transportation.

Home to some of the country's most productive hydraulic fracturing fields, North Dakota, Pennsylvania, and their neighboring states are located far from many established markets for oil and natural gas, such as refinery and petrochemical centers. Having limited access to an in-place network of transmission pipelines, producers of oil and natural gas liquids from these regions have turned to trains and barges to transport their products to distant markets. Likewise, ethanol plants in Illinois, Iowa, Nebraska, and other corn-producing states in the Midwest are located far from some of the country's largest consumers of gasoline, the major population centers on the East and West Coasts and in the Southeast and the Southwest. These producers too have turned to trains and barges to access distant markets.

The country's new oil, natural gas, and ethanol supplies have added to what was already a large volume of hazardous liquids and gases, including gasoline, diesel, and propane, moving in pipelines, railroad tank cars, and tank barges. Assuring the safety of these hazardous shipments has therefore been a concern of industry and government for decades. The additional energy liquids and gas supplies, however, have presented some new and, in many cases, unanticipated safety assurance challenges. For instance, negligible amounts of crude oil, and relatively little ethanol, were transported by rail a decade ago. When traffic demand increased abruptly, general purpose tank cars were enlisted to transport the oil and ethanol, first in blocks of a dozen or fewer tanks cars and later in unit trains consisting of 100 or more tank cars. Traversing new routes, these tank car unit trains attracted the attention of the communities unfamiliar with this traffic. This attention soon turned to concern as some trains derailed with serious consequences.

Meanwhile, increasingly larger quantities of crude oil and ethanol were being transported by barge, carried southbound on the Mississippi River, on the intracoastal waterways in the Gulf of Mexico, and in combination with trains to waterborne transshipment points, such as the Port of Albany on the Hudson River, to serve refineries on the Atlantic Coast. Unlike rail, the waterways have a long history of moving crude oil and other petroleum products in large quantities by tank barge and ship. Longstanding concern over oil movements on the nation's waterways has led to a well-established system for spill prevention, containment, and mitigation, including requirements for double-hull designs, spill notification, and emergency response preparation. By no means a novice transporter of crude oil and other flammable liquids, the waterways can nevertheless be a controversial mode because of the environmentally sensitive nature of the rivers and coastal waters that compose the marine transportation system.

The transportation mode that is most specialized to hazardous liquids and gases, and thus inherently well-equipped to handle the new domestic shipments of oil and natural gas, is the transmission pipeline system. In the case of natural gas and natural gas liquids, pipelines offer the only practical option for high-volume, domestic transportation. In the case of crude oil, the building of more long-distance pipelines is often proposed as a way to move this product to markets more efficiently and safely than by other modes. Inasmuch as transmission pipeline incidents have been responsible for some of the country's largest and most costly onshore oil releases, these safety advantages can be questioned, or at least scrutinized. A more fundamental issue, however, is whether the three modes—rail, barge, and pipeline—are practical and economical substitutes for one another such that comparisons of their safety record are material. Concentrated in the middle of the country, the U.S. crude oil pipeline network lacks direct connections to many East Coast and West Coast refineries, which do have access to rail or water transportation or both. The prospect of connecting these refineries to the transmission pipeline network is limited for economic, technical, and political reasons. Therefore, in those instances when the modes are not practical substitutes, comparisons of their safety performance can lack decision-making relevance.

In recent years, additional pipelines have been built to accommodate more of the oil, natural gas, and natural gas liquids produced from hydraulic fracturing, thereby enabling supplies from once-stranded fields to reach a larger number of markets. Typically more economical than other modes, the growing pipeline network, coupled with the lifting of the crude oil export ban, has increased markets for the once-trapped domestic supplies of crude oil and reduced the price gap that had made its transportation by rail and by barge more attractive to shippers.

The transportation safety impacts of the domestic energy revolution are much clearer today than they were when the traffic volume of energy liquids and gases started to escalate a decade ago. In response to derailments of trains carrying crude oil and ethanol, industry and government regulators have taken action, including the development of new rules governing the design of the tank cars eligible to carry these products, the routing and operating speeds of trains moving these tank cars, and the provision of traffic data to states and local communities for emergency response planning purposes. At that time, these regulatory measures and other steps to ensure the safety of shipments had to be developed quickly without the benefit of prior experience or an empirical basis to gauge potential impacts. With those heady days having passed, there is time to develop this basis, both to evaluate the measures that have been taken and to identify additional actions that may be needed to address any newly understood or residual risks. As discussed next, an important aim of this study is to spark such a follow-on process—not to second-guess past decisions but rather to ensure that the systems for assuring the safe transportation of energy liquids and gases are responsive to changes in shipping trends and sufficiently robust to accommodate further changes in the domestic energy landscape.

STUDY ORIGINS, SCOPE, AND CHARGE

As the domestic energy revolution's many effects on the U.S. transportation system were becoming evident, the Transportation Research Board (TRB) Executive Committee decided in 2015 to sponsor this study, which focused on the safety of the modes used for long-distance movement of energy liquids and gases. Often referred to as the "midstream" portion of the energy supply chain, these long-distance modes consist primarily of transmission pipelines, railroads, and waterways. They move crude oil, natural gas, natural gas liquids, and ethanol in bulk quantities from "upstream" production and processing facilities to distant "downstream" locations, where the shipments are refined, stored, and/or delivered to end customers by barge, truck, or pipeline.

A reason for focusing on the midstream modes is that they have been affected most by the growth in the domestic energy supplies and by the changes in where the supplies are produced, how they are transported, and the routes they traverse. While downstream-refined products such as gasoline and diesel are often transported long distances between refineries and customers, the locations of refinery centers and their customer bases have remained fairly fixed over time, and therefore so too has the pattern of downstream-transportation activity. The fact that refineries are receiving more of their crude oil supplies from domestic production sources has had little bearing on the downstream modes, including trucks, that transport the refinery output. Likewise, the utilities and local distribution companies that receive natural gas from new domestic sources continue to distribute the gas through the same pipeline distribution systems.

All three segments of the logistics chain—upstream, midstream, and downstream—face transportation safety challenges. As new oil and gas fields using hydraulic fracturing have been developed far from traditional energy-producing regions, local roads have had to be upgraded, both to accommodate higher truck volumes and to ensure traffic safety. This upstream segment, however, is characterized by the movement of oil and gas over short distances, often in low-volume gathering pipelines or by tank trucks operating on rural roads.[1] At the other end of the logistics chain, the downstream transportation segment can be especially challenging because of the need to move flammable liquids and gases through populated areas, often by tank trucks operating in mixed traffic and in pipelines serving commercial and residential users. However, even though these safety challenges can be vexing, they have not changed fundamentally as a direct result of the domestic energy revolution.

Although affected the most by the domestic energy revolution, the midstream transportation system was in many ways well prepared for the resulting safety challenges. Crude oil and natural gas liquids have been moved by transmission pipeline and on the nation's waterways for decades. The operators of these modes are familiar with transporting these commodities, and have long been subject to regulatory requirements to prevent, contain, and mitigate releases through means such as corrosion prevention, double-hull vessels, and leak-monitoring systems. For these two midstream modes, the added traffic volumes and new routings have, at the very least, added marginally to an already significant task of ensuring the safe transport of energy liquids and gas shipments. The safety challenge has been substantially greater for railroads, because they did not transport large

[1] The safety of gathering lines has raised concern in recent years, especially because of the construction of some larger, higher-pressure gathering pipelines to move natural gas; Government Accountability Office. 2015. *Pipeline Safety*. http://www.gao.gov/assets/680/672809.pdf.

quantities of crude oil and ethanol before the domestic energy revolution. For this mode, the new locations, quantities, frequencies, and properties of this added traffic have created several new safety challenges.

Observing the many changes taking place in the country's midstream energy transportation sector, the TRB Executive Committee called for a study—as detailed in Box 1-1—that would focus specifically on this part of the logistics chain. In so doing, the Executive Committee requested a comparison of the three midstream modes in safely transporting the new energy liquids and gas traffic. The comparison would go beyond a review of incident rates, the results of which can have little decision-making value when the modes are not realistic substitutes for one another. Instead, the comparison would be undertaken with an eye to the regulatory and other means by which each mode has responded to the safety challenges created by the dramatic changes in the location, frequency, and quantity of this added traffic. Because an important aspect of this safety assurance challenge is to ensure an effective emergency response, the study charge calls for an examination of the resources needed by the emergency preparedness community to plan for and respond to these incidents.

The TRB Executive Committee was not interested in a study that examines safety interventions and initiatives that have been required by regulatory agencies or adopted by industry in recent years in response to safety concerns arising from developments other than the domestic energy

Box 1-1
Statement of Task

This study will focus on the transportation safety issues associated with changes in the long-distance movement of crude oil, natural gas, and ethanol resulting from sharply increased domestic production of these hazardous materials in recent years. To inform federal, state, and local officials, the committee will:

- Review and compare the performance of the long-distance modes in safely transporting these shipments with minimal harm to people, property, and the environment;
- Examine the safety risks and assurance challenges arising from changes in the routing, frequency, quantity, and properties of the long-distance shipments;
- Critically review strategies to reduce the likelihood and severity of incidents;
- Examine the resources needed by the emergency preparedness community to plan for and respond to these incidents; and
- Determine whether changes in public policy could reduce the likelihood of these incidents and their adverse safety and environmental impacts.

revolution. Such a review would have been unwieldy for modes such as marine and rail transportation that move many different products that present a diverse set of safety demands. While a discussion of past initiatives is needed to provide context, the focus of the study is on examining the more recent response to the specific challenges arising from the domestic energy revolution. Moreover, the TRB Executive Committee was not interested in a study that second-guesses these recent responses, but rather one that is forward-looking and helpful for the development of an increasingly robust safety assurance system—one that enables a more effective response to the energy transportation challenge. It is in this spirit that the study charge calls for recommendations on changes in public policy that could reduce the likelihood of incidents and their adverse safety and environmental consequences.

ORGANIZATION OF THE REPORT

This report is organized into five chapters. This chapter provides the introduction. Chapter 2 describes the revolutionary changes that have been taking place in U.S. energy supply and demand during the past decade. It begins with a general review of the country's energy supply and demand circumstances before 2008, and then describes more recent developments in the domestic crude oil, natural gas, and ethanol markets since the domestic energy revolution. Chapter 3 describes how the midstream transportation modes have accommodated the increasing volumes of domestic energy. Background is provided on the size and scope of each mode's network and the specific means of conveyance used for these energy commodities. Trends in the amount of crude oil, ethanol, and natural gas shipped by these three modes are reviewed from the start of the domestic energy revolution to today.

Chapter 4 reviews the safety performance of the three long-haul modes when transporting crude oil, ethanol, and natural gas. The discussion focuses on the number, severity, and causes of incidents during the past decade and on safety issues that have been identified following investigations of the most serious incidents. Consideration is also given in Chapter 4 to key policies that have been put in place since the domestic energy revolution to assure the safety of the midstream modes and to strengthen emergency response capacity. Chapter 5 contains the study findings and recommendations.

2

The Domestic Energy Revolution

Dramatic changes have been taking place in U.S. energy supply and demand over the past decade. While their specific impacts on the transportation sector are discussed later in the report, this chapter provides background on the major developments in the oil, natural gas, and ethanol markets that spawned these impacts. The chapter begins with an overview of circumstances before 2009 when energy producers using hydraulic fracturing and horizontal drilling technologies started extracting increasingly larger quantities of oil and gas from the country's interior at about the same time that federal policies were spurring growth in the production and use of ethanol as a motor fuel. The implications on domestic crude oil, natural gas, and ethanol markets since these transformative developments are then described.

Most data in the chapter are for the period 2005 to 2015 and 2016. When the chapter was written in early 2017, it was by no means clear that the country's energy landscape had reached a semblance of a steady state. Domestic oil markets are tied to global oil markets that have been historically volatile and rattled by technological developments, as exemplified by the transformative effects of hydraulic fracturing and horizontal drilling. Government policies also matter and are prone to change. The desirability of federal and state efforts to promote ethanol fuel, for example, continues to be the subject of policy debate. Furthermore, the demand for transportation is often described as being "derived" from the demand for other goods and services. Accordingly, suppliers of pipeline, rail, barge, and other transportation services must remain ready to serve an energy sector that, as demonstrated over the past decade, can undergo dramatic and unpredicted changes.

HISTORICAL PERSPECTIVE

By the turn of the century, it was already the conventional view that domestic production of oil and natural gas would continue to decline and be outpaced by growth in demand to necessitate greater reliance on energy imports. Any other view would have seemed implausible in light of decades of stable or declining domestic oil and gas production and expanding consumer demand for these energy supplies. Between 1985 and 2005, U.S. production of crude oil fell by about 40 percent, while the trend in natural gas production was essentially flat.[1] To meet the country's increasing demand for gasoline, diesel, and other refined products, the importation of crude oil was continually growing. By 2005, the United States was importing 10 million barrels of oil per day[2] while producing only 5 million barrels.[3] Over the same period, U.S. production of natural gas increased slightly from about 16 trillion to 18 trillion cubic feet per year.[4] However, to meet growing demand, these gas supplies were increasingly supplemented by imports from Canada.[5] Flattening domestic production contributed to rising natural gas prices and to uncertainty about the future availability of key gas-derived compounds such as ethane and butane. The U.S. petrochemical manufacturers that relied on this hydrocarbon feedstock were facing increasing prices so as to make investing in domestic manufacturing capacity less attractive.[6]

Over the course of decades, the growth in energy imports had come to shape the country's energy transportation system. Tanker ships bringing crude oil from overseas offloaded at coastal refineries and terminals, where a network of transmission pipelines moved the commodity to inland refineries. In the case of natural gas, pipeline systems were built to accommodate Canadian imports. By 2005, large investments were being contemplated for specialized port facilities to handle imports of liquefied natural gas (LNG) by tanker ship to meet supply shortfalls. Indeed, many energy analysts were

[1] U.S. Energy Information Administration, "U.S. Field Production of Crude Oil," *Petroleum & Other Liquids*, accessed September 14, 2017, https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mcrfpus2&f=m.

[2] U.S. Energy Information Administration, "Annual Energy Outlook" (Washington, D.C., January 7, 2017), https://www.eia.gov/outlooks/aeo.

[3] U.S. Energy Information Administration, "U.S. Field Production of Crude Oil."

[4] U.S. Energy Information Administration, "U.S. Dry Natural Gas Production," *Natural Gas*, accessed September 14, 2017, https://www.eia.gov/dnav/ng/hist/n9070us2a.htm.

[5] U.S. Energy Information Administration, "U.S. Natural Gas Imports and Exports: Issues and Trends 2005," February 2007, https://www.eia.gov/naturalgas/importsexports/annual/archives/2007/ngimpexp05.pdf. Canadian gas exports to the United States grew from 1 trillion cubic feet in 1985 to about 3.5 trillion cubic feet in 2005; https://www.eia.gov/naturalgas/importsexports/annual/archives/2007/ngimpexp05.pdf.

[6] Alexander H. Tullo, "Petrochemicals: A North American Recovery Was Elusive in 2003, but Producers Hope They Will Make Some Progress in 2004," *Chemical & Engineering News*, March 15, 2004, http://pubs.acs.org/cen/coverstory/8211/print/8211petrochemicals.html.

predicting that imports of LNG would meet about 20 percent of the country's natural gas demand by 2020.[7,8] Meanwhile, concern over the country's growing dependence on oil imports had led federal and state policy makers to strengthen incentives for the production and use of corn-based ethanol. While these efforts had yielded only modest national impacts on the demand for ethanol by the early 2000s, they were leading to more truck and rail movements of this fuel in the corn-growing states of the Midwest.[9]

The waning of domestic oil and gas supplies and their replacement by imports and alternatives such as ethanol remained the dominant narrative as late as 2011, even as many casual observers were beginning to take notice of contrary developments in the field. It was around this time that *The New York Times*, *CNN*, and other news media began reporting that rural communities across eastern Montana, western North Dakota, Oklahoma, Pennsylvania, and western Texas had become oil and gas boomtowns, experiencing burgeoning demand for workers, housing, equipment, materials, transportation, and public services.[10] Their observations coincided with market evidence of increasingly larger supplies of oil and gas originating in these regions—a development that signaled the prospect of the United States not only becoming less dependent on imports but potentially a net exporter of oil and gas in the years ahead.[11,12]

The U.S. Energy Information Administration (EIA) reported in 2014 that domestic natural gas production was nearing an all-time high.[13] Having issued a forecast in 2006 that oil imports would account for two-thirds

[7] Liquefied natural gas is natural gas that has been cooled to a liquid state at –160 degrees Celsius. Liquefaction reduces its volume more than 600 times, making it more practical for storage and transportation by ship.

[8] National Petroleum Council, *Balancing Natural Gas Policy—Fueling the Demands of a Growing Economy*, vol. 1, Summary of Findings and Recommendations (Washington, D.C.: National Petroleum Council, 2003), http://www.npc.org/reports/NG_Volume_1.pdf.

[9] U.S. Energy Information Administration, "Increasing Ethanol Use Has Reduced the Average Energy Content of Retail Motor Gasoline," *Today in Energy*, October 27, 2014, https://www.eia.gov/todayinenergy/detail.cfm?id=18551. Biofuel's share of the motor fuel supply had reached barely 3 percent by the early 2000s.

[10] Monica Davey, "North Dakota Has Jobs Aplenty, but Little Housing," *The New York Times*, April 20, 2010, http://www.nytimes.com/2010/04/21/us/21ndakota.html.

[11] Blake Ellis, "Six-Figure Salaries, but Homeless," *CNNMoney*, October 26, 2011, http://money.cnn.com/2011/10/21/pf/america_boomtown_housing/index.htm.

[12] Robert J. Samuelson, "The U.S. May Become Energy-Independent after All," *The Washington Post*, November 14, 2012, https://www.washingtonpost.com/blogs/post-partisan/post/the-us-may-become-energy-independent-after-all/2012/11/14/ef8624e4-2e7d-11e2-89d4-040c9330702a_blog.html?utm_term=.7ce9e5011e50.

[13] U.S. Energy Information Administration, "U.S. Weekly Supply Estimates," *Petroleum & Other Liquids*, accessed September 14, 2017, https://www.eia.gov/dnav/pet/pet_sum_sndw_dcus_nus_w.htm.

of U.S. oil consumption during the next decade,[14] EIA was issuing updated forecasts that domestic oil production would surpass imports for the first time in 30 years.[15] Meanwhile, even as domestic gas and crude oil supplies were surging, production of ethanol was also on the rise, as policies instituted in the 2000s to mandate the greatly increased use of biofuel had taken effect. The 350 million barrels of ethanol produced in 2015 were nearly four times higher than volumes produced 10 years earlier, and nearly equal to 10 percent of the country's total gasoline sales.[16]

It is difficult to overstate the extent to which U.S. energy markets had been transformed in a few short years, or to exaggerate how this transformation caught energy analysts by surprise. In retrospect, the transformation's central causes are now clear—the most important being the widespread exploitation of new drilling technologies and methods that enabled economic recovery of oil and gas from the country's many basins of porous rock (e.g., shale and other types of mudstone) (see Figure 2-1). In the case of ethanol, of course, the cause of its marked growth was an increasingly ambitious federal policy to increase the use of biofuels.[17]

The impact of this energy transformation was felt well beyond U.S. oil and gas markets. The population of North Dakota grew by 13 percent between 2010 and 2015 as hydraulic fracturing activity ramped up.[18] The counties of northern Pennsylvania, site of the Marcellus basin, became new employment centers in a region that had been slowly recovering from high unemployment during the Great Recession.[19] In the rural mudstone basins of Kansas, Oklahoma, and northern Texas, many new oil and gas jobs were being created. Meanwhile, to meet ethanol supply mandates, more and more of the country's corn crop (up to 40 percent) was being devoted to the production of this fuel, which had become an important source of employment in the rural counties of Illinois, Indiana, Iowa, and

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[14] U.S. Energy Information Administration, "Annual Energy Outlook 2006." Table A1.

[15] U.S. Energy Information Administration, "U.S. Weekly Supply Estimates."

[16] U.S. Energy Information Administration, "Monthly Energy Review: Table 10.3 Fuel Ethanol Overview," n.d., http://www.eia.gov/totalenergy/data/monthly/query/mer_data_excel.asp?table=T10.03.

[17] The standards are intended to comply with the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007.

[18] "North Dakota Population Could Top 1 Million by 2040," *The Bismarck Tribune*, January 19, 2016, http://bismarcktribune.com/news/state-and-regional/north-dakota-population-could-top-million-by/article_d4f75d95-669e-5dc3-8bc8-453cd1b65390.html.

[19] Jennifer Cruz, Peter W. Smith, and Sara Stanley, "The Marcellus Shale Gas Boom in Pennsylvania: Employment and Wage Trends," *U.S. Bureau of Labor Statistics Monthly Labor Review*, February 2014, https://www.bls.gov/opub/mlr/2014/article/the-marcellus-shale-gas-boom-in-pennsylvania.htm.

FIGURE 2-1 Major U.S. shale and other mudstone basins with reservoirs of oil and gas, 2011.
SOURCE: U.S. Energy Information Administration, "Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays," *Analysis & Projections*, July 8, 2011, https://www.eia.gov/analysis/studies/usshalegas.

Nebraska.[20] This rapid growth in jobs and income boosted state and local tax revenues, but also placed new demands on public infrastructure and services.[21] Roads in rural counties that were once remote and lightly traveled were suffering from traffic congestion and damage caused by trucks carrying equipment and materials to and from production sites.[22]

In the same way that these economic, social, and environmental effects had not been anticipated, operators of transportation systems did not foresee how they would be affected by the speed and magnitude of the changes taking place in domestic energy markets. The increasing supplies of

[20] U.S. Department of Agriculture, "U.S. Bioenergy Statistics," *Economic Research Service*, accessed September 15, 2017, https://www.ers.usda.gov/data-products/chart-gallery/detail.aspx?chartId=40078.

[21] Daniel Raimi and Richard G. Newell, "Shale Public Finance Local Revenues and Costs Associated with Oil and Gas Development" (Duke University Energy Initiative), accessed September 15, 2017, https://energy.duke.edu/sites/default/files/attachments/Shale%20Public%20Finance%20Local%20Revenues%20and%20Costs%20Issue%20Brief%20Final.pdf.

[22] Ana Campoy, "Drilling Strains Rural Roads," *The Wall Street Journal*, July 26, 2012, https://www.wsj.com/articles/SB10000872396390444840104577551223860569402.

crude oil, natural gas, and ethanol had an immediate impact on the transportation sector because of the need for more take-away capacity. However, the origins of this supply had limited transportation options because they were located far from traditional production regions. For instance, by 2015, Pennsylvania had become the second largest domestic producer among states of natural gas,[23] North Dakota ranked second in domestic oil production,[24] and top ethanol-producing states, such as Iowa, Nebraska, and South Dakota, had become the main suppliers of nearly 10 percent of the country's finished gasoline.[25,26] A decade earlier, these states had originated a negligible share of the country's liquid and gas energy, and thus had accounted for a commensurately small percentage of the country's energy transportation infrastructure.

The domestic energy revolution not only created new energy transportation routes, but it also disrupted traditional routings. For example, as more natural gas was produced in western Pennsylvania, there was an increase in demand for local and regional pipeline capacity to serve electric utilities and gas distribution systems located in the nearby communities of the Northeast. In turn, demand waned for gas that was once imported to the region in long-haul pipeline systems originating in the Gulf Coast and Rocky Mountain regions.[27,28] Similarly, as new pipeline take-away capacity was added in North Dakota to transport oil from the Bakken fields to refineries in the Midwest, the long-haul pipelines that had been configured to supply these refineries with oil from Gulf Coast terminals were becoming idle.[29,30]

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[23] U.S. Energy Information Administration, "Rankings: Natural Gas Marketed Production, 2015," *Pennsylvania State Profile and Energy Estimates*, accessed September 15, 2017, https://www.eia.gov/state/rankings/?sid=PA#series/47.

[24] U.S. Energy Information Administration, "Rankings: Crude Oil Production, May 2017," *U.S. States Profiles and Energy Estimates*, accessed September 15, 2017, https://www.eia.gov/state/rankings/?sid=US#/series/46.

[25] State of Nebraska, "Ethanol Facilities' Capacity by State," accessed September 15, 2017, http://www.neo.ne.gov/statshtml/121.htm.

[26] U.S. Energy Information Administration, "Energy Use for Transportation," *Use of Energy in the United States Explained*, accessed September 15, 2017, https://www.eia.gov/Energyexplained/?page=us_energy_transportation.

[27] Brendan Gibbons, "In Northeast Pa., Gas and Power March Together," *Marcellus.Com*, August 17, 2015, http://marcellus.com/news/id/127517/in-northeast-pa-gas-and-power-march-together.

[28] Bradley Kramer, "Rockies Express Pipeline Gets a Second Chance," *North American Oil & Gas Pipelines*, February 25, 2014, http://napipelines.com/resurexion.

[29] Kristen Hays, "Marathon CEO: Capline Pipeline Reversal Likely When Oil Prices Recover," *Reuters*, April 28, 2016, https://www.reuters.com/article/us-marathon-pete-capline/marathon-ceo-capline-pipeline-reversal-likely-when-oil-prices-recover-idUSKCN0XP2QS.

[30] Sandy Fielden, "Diamonds Are Forever—but Northbound Capline Crude Flows May Be Living on Borrowed Time," *RBN Energy*, September 1, 2014, https://rbnenergy.com/diamonds-are-forever-but-northbound-capline-crude-flows-may-be-living-on-borrowed-time.

To provide background for the review of the impacts of the domestic energy revolution on the country's long-haul modes of transportation in Chapter 3, additional detail follows on specific developments in the domestic oil, natural gas, and ethanol markets. Developments in oil markets are discussed first and in greater detail because they have had major reverberations across three modes—pipelines, railroads, and barges.

DEVELOPMENTS IN CRUDE OIL MARKETS

The main use of crude oil is to power transportation. When refined into gasoline, diesel, bunker fuel, and jet fuel, crude oil is the source of more than 95 percent of the energy used for transportation. Other uses include home heating fuel, feedstock for petrochemical plants, and the production of waxes, lubricants, and asphalt.

Most of the country's refinery capacity is located near populated areas, which have high demand for gasoline and other refined products, as well as good connections with pipeline and marine transportation systems that can provide access to oil supplies and markets for refined products (see Figure 2-2). About 47 percent of the country's refinery capacity is located on the Gulf Coast, which has a high concentration of petrochemical plants, proximity to onshore and offshore oil fields, and a dense network of pipelines and waterways.[31] Other major refinery centers are located in the Great Lakes region (13 percent of refining capacity); California (11 percent); Kansas, Oklahoma, and inland Texas (9 percent); and the mid-Atlantic Coast (7 percent). The locations of U.S. refinery capacity have been fairly stable for decades, as most new capacity additions since the 1970s have been confined mainly to traditional refinery centers.

Like the geography of oil refineries, the geography of crude oil production had been stable for many years, as production fields were concentrated in a handful of states—mainly Alaska, California, Oklahoma, and Texas—and offshore in the Gulf of Mexico. By the early 2000s, however, production from Alaska's North Slope and California was declining, and increasing volumes of crude oil were being imported from Canada, Mexico, and Venezuela. Much of this imported crude was dense and high in sulfur content—or "heavy" and "sour." Refineries along the Gulf Coast, and some on the Great Lakes, invested in special equipment to process these heavy and sour crude oils, which could be obtained at lower prices than the lower-density, lower-sulfur "light" and "sweet" oils that are generally produced in Alaska and Texas. Lacking the specialized equipment to pro-

[31] U.S. Energy Information Administration, "Louisiana Gulf Coast Refinery Utilization and Capacity," *Petroleum & Other Liquids*, accessed September 15, 2017, https://www.eia.gov/dnav/pet/pet_pnp_unc_dcu_r3c_m.htm.

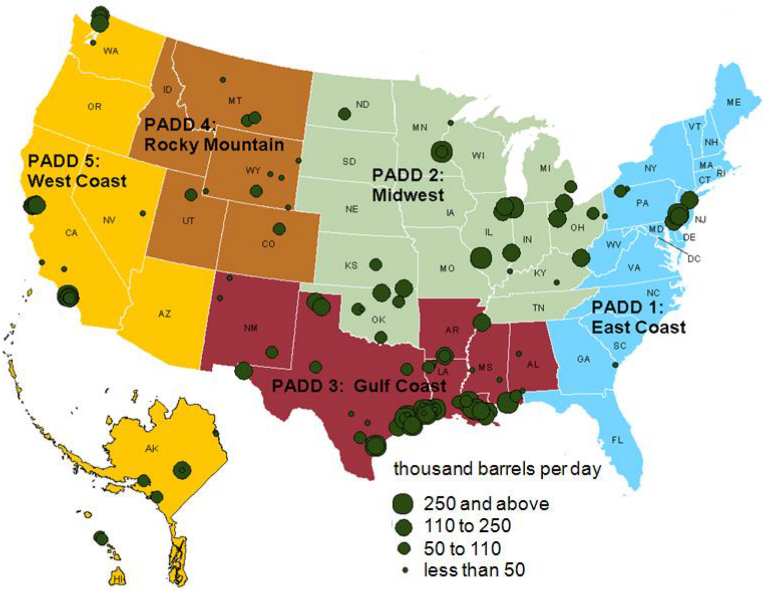

FIGURE 2-2 Location of U.S. oil refinery capacity, 2012.
SOURCE: U.S. Energy Information Administration, "Much of the Country's Refinery Capacity Is Concentrated Along the Gulf Coast," *Today in Energy*, July 19, 2012, https://www.eia.gov/todayinenergy/detail.php?id=7170.

cess heavy and sour crudes, most refineries on the Atlantic Coast and, to a lesser extent, the Pacific Coast, as well as many in the Midwest, obtained increasingly larger amounts of their crude oil from tankers importing lighter grades from overseas.

Before 2010, the location of domestic oil production was even more geographically concentrated than the country's refinery capacity. This is no longer the case. As oil production in California and Alaska has declined, production in the middle of the country has grown (see Table 2-1). Trends in production from basins that use hydraulic fracturing are shown in Figure 2-3. In 2005, these basins produced less than 5 percent of domestic crude oil. In 2015, four of these basins—Eagle Ford and Permian (mostly in Texas), Bakken (mostly in North Dakota), and Niobrara-Codell (mostly in Colorado and Wyoming)—accounted for more than 40 percent of U.S. oil production. During this period, North Dakota went from being a negligible oil producer to the second-highest among states after Texas, while production from Colorado, New Mexico, and Wyoming more than doubled (see Figure 2-4).

TABLE 2-1 Top Crude-Oil-Producing States, 2005 and 2015

2005		2015	
State	Barrels per Day (Thousands)	State	Barrels per Day (Thousands)
Texas	1,076	Texas	3,462
Alaska	864	North Dakota	1,177
California	631	California	551
Louisiana	206	Alaska	483
Oklahoma	168	Oklahoma	432
New Mexico	167	New Mexico	402
Wyoming	142	Colorado	346
North Dakota	98	Wyoming	237
Kansas	92	Louisiana	172
Montana	90	Kansas	125

SOURCE: EIA.

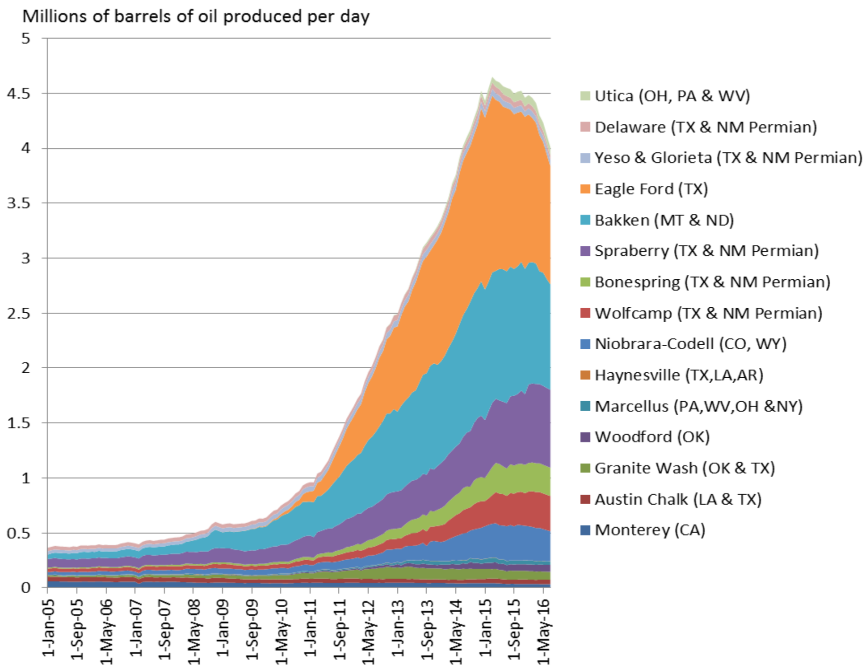

FIGURE 2-3 Trends in oil production from U.S. mudstone basins, 2005–2016.
SOURCE: U.S. Energy Information Administration, "Where Our Natural Gas Comes From," *Natural Gas Explained*, accessed September 15, 2017, https://www.eia.gov/energyexplained/index.cfm?page=natural_gas_where.

Change in barrels per day (thousands), 2005 and 2015

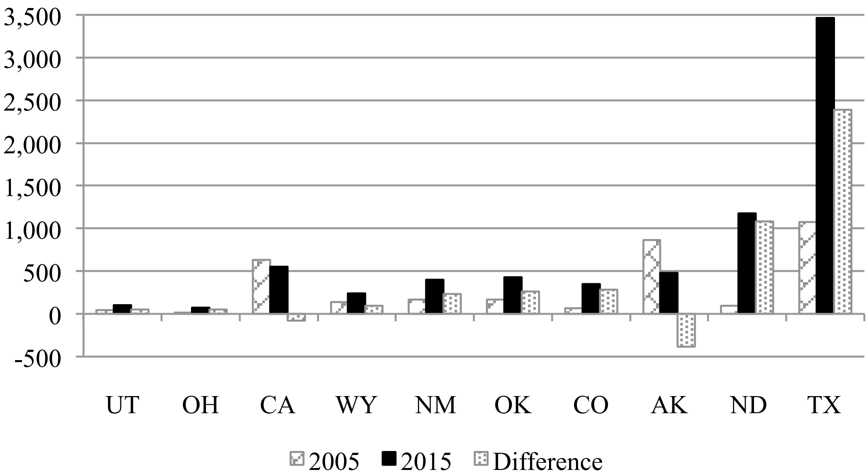

FIGURE 2-4 U.S. states experiencing largest changes in crude oil production, 2005–2015.
SOURCE: EIA, "Crude Oil Production," *Petroleum & Other Liquids*, March 31, 2017, https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm.

Not only did the development of the country's mudstone basins change the oil supply landscape, it also affected the flow of crude oil grades across the continent. Whereas heavy, sour oil imports from Canada had been a main source of growth in North American supplies until the mid-2000s, the oil extracted using hydraulic fracturing consisted of lighter, sweeter grades. As a result, the geographically stable base of refineries, whose oil-processing investments were made on the basis of past trends in crude oil supplies, was facing a dramatic change in both the location of producing regions and the grades and prices of oil available in the market. Although many of the Gulf Coast and Great Lakes refineries that had invested in the equipment needed to process heavy crudes were not natural customers for this lighter, sweeter crude, several refineries on the Atlantic and Pacific coasts were candidates. If properly incentivized by price differentials, they could use this oil instead of more expensive imports from overseas and from the dwindling supply of light oil from Alaska.

Faced with this mixture of refinery interest, many of the new producing regions, such as North Dakota, had limited connectivity to the large pipeline networks that could efficiently move the crude oil to meet demand. Limited pipeline take-away capacity had been stretched thin by growing production volumes spurred by sharply rising world oil prices from 2009 to 2011.[32] As pipeline transportation and storage bottlenecks formed across the Great Plains and Upper Midwest, the oil supply surplus depressed oil prices in the middle of the country. At times during 2012, the surplus led to Bakken crude oil selling for $10 to $25 less per barrel than the West Texas Intermediate (WTI) benchmark rate (see Figure 2-5). Price differentials of this magnitude created powerful incentives for refineries to seek alternative transportation means to obtaining these less expensive, bottlenecked supplies.

During 2010 and 2011, the nation's freight railroads had been experiencing steady increases in crude oil traffic. By 2012, when the pipeline bottlenecks were at their peak, the number of carloads of crude oil was nearly 10 times higher than in 2010.[33] During the same period, barge operators were investing heavily in new tank barges to accommodate the growing volume of domestic crude oil being shipped. Not only did the country's extensive freight rail and barge networks reach deep into the new oil-producing regions, they could move shipments in directions not served by pipelines. For refineries that process light crude oil, the decision to ship by rail or by barge was a simple matter of economics. The decision rested on the lower end price of acquiring the bottlenecked oil when shipped by rail or by barge than that of oil supplies received by other means, such as tanker imports from overseas.

At a time when oil prices were highly volatile and the long-term prospects of profitable production from hydraulic fracturing remained uncertain, an advantage of rail and barge service was flexibility for shippers. However, as a longer-term means of transportation, rail and barge presented some difficult investment choices. The tank car and barge fleet would need to be expanded, and bulk loading and offloading facilities would need to be built. These investments would need to be made with an eye toward the eventual ability of competing pipelines to expand their networks and for the price differentials between domestic and imported crude oil to remain sufficiently attractive to make rail equipment and infrastructure investments pay off. Indeed, from June 2014 to January 2016, U.S. oil prices declined by 69 percent, from $114 to $35 per barrel.[34] In the years since bottleneck conditions emerged in 2012, the oil supply surpluses in the Midwest had been cleared, in part because of the use of rail and barge transportation.

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[32] From January 2009 to April 2011, the benchmark price of West Texas Intermediate (WTI) oil increased from $42 to $113 per barrel.

[33] Association of American Railroads, "U.S. Rail Crude Oil Traffic," accessed September 15, 2017, https://www.aar.org/BackgroundPapers/US%20Rail%20Crude%20Oil%20Traffic.pdf.

[34] U.S. Energy Information Administration, "Europe Brent Spot Price FOB," *Petroleum & Other Liquids*, accessed September 15, 2017, https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=D.

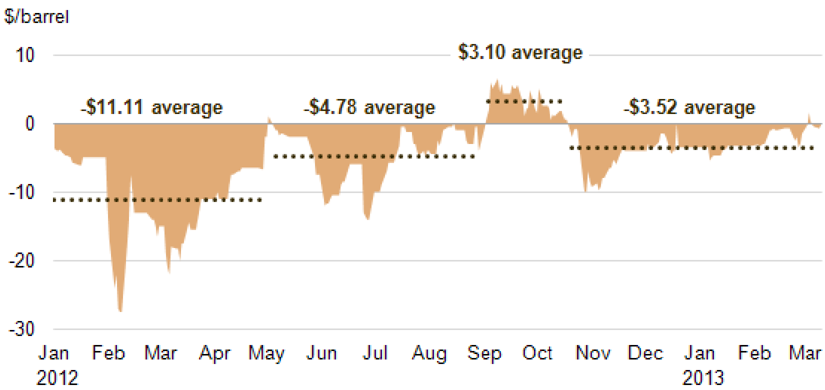

FIGURE 2-5 Average difference in price from WTI benchmark, Bakken crude oil, January 2012–March 2013.
SOURCE: EIA, "Bakken Crude Oil Price Differential to WTI Narrows Over Last 14 Months," *Today in Energy*, March 19, 2013, https://www.eia.gov/todayinenergy/detail.php?id=10431.

Having peaked in 2014, crude-by-rail traffic was down 20 percent in 2015. Figure 2-6 shows graphically how the once-rail-dependent Bakken fields had become pipeline accessible by 2016.

When this report was being prepared in early 2017, the future of crude by rail was dimming as pipeline companies expanded their networks to offer more scale economies in crude oil transportation. Nevertheless, rail and barge transportation were holding onto some of their advantages by offering producers additional routing options, especially for moving short-term supply surpluses and serving newly developed, lower-volume basins. Perhaps the most one can predict at this juncture is that these two modes will continue to account for a meaningful portion of the country's crude oil traffic, but at levels substantially lower than in recent years.

DEVELOPMENTS IN ETHANOL MARKETS

Ethanol has been distilled and denatured for mixing with gasoline for decades. Traditionally, "gasohol" blends were used mainly by motorists in corn-growing states of the Midwest. The oil supply shocks of the 1970s prompted the federal government and several states to introduce policies aimed at increasing fuel ethanol supplies in support of U.S. farmers and to reduce reliance on imported oil. These policies included federal and state exemptions of ethanol from motor fuel excise taxes, blending and production tax credits, producer loan guarantees, and research grants. In the years that

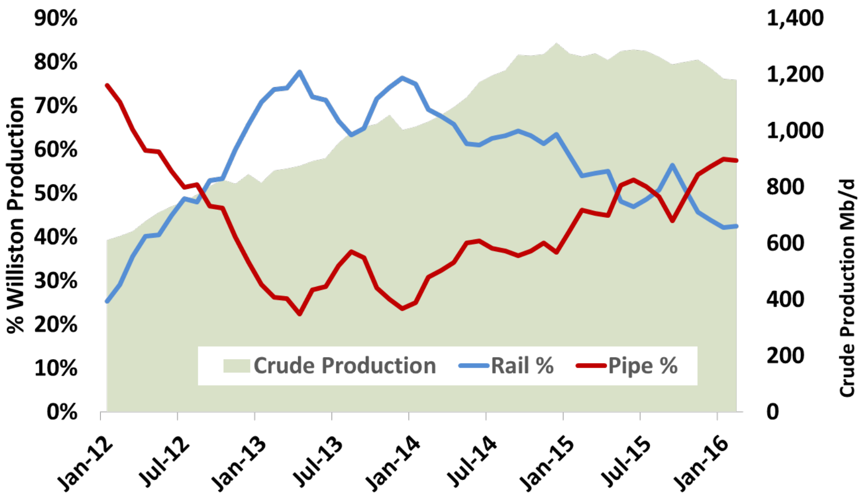

FIGURE 2-6 Crude oil transportation by rail and by pipelines from the Williston Basin's Bakken play.
NOTE: Mb/d = thousands of barrels per day.
SOURCE: E. R. Braziel, presentation to committee.

followed, federal and state mandates for the reformulation of gasoline to improve air quality eventually led to the widespread adoption of ethanol as a fuel oxygenate, which displaced methyl tertiary-butyl ether. Consequently, demand for the biofuel gradually increased during the 1980s, as ethanol was being transported to more markets outside the Midwest. Nevertheless, by the late 1990s, ethanol remained a niche fuel, produced in quantities equivalent to only about 1 or 2 percent of the country's total gasoline supply.

Since the early 2000s, public policy has continued to play an important role in spurring ethanol demand and supply. The most important policy development has been the Renewable Fuel Standard (RFS), established by the U.S. Congress in the Energy Policy Act of 2005. The legislation requires minimum volumes of biofuels to be used each year in the motor vehicle fuel supply. The first RFS called for at least 4 billion gallons of biofuel to be used in 2006, rising to 7.5 billion gallons by 2012. The Energy Independence and Security Act of 2007 greatly increased the mandated volumes and extended the compliance period through 2022. This new standard required the annual use of 9 billion gallons of biofuel in 2008, rising to 36 billion gallons in 2022.[35]

[35] The 36 billion gallons were supposed to consist of at least 16 billion gallons made from cellulosic biofuels, followed by an eventual cap of 15 billion gallons of corn-based ethanol.

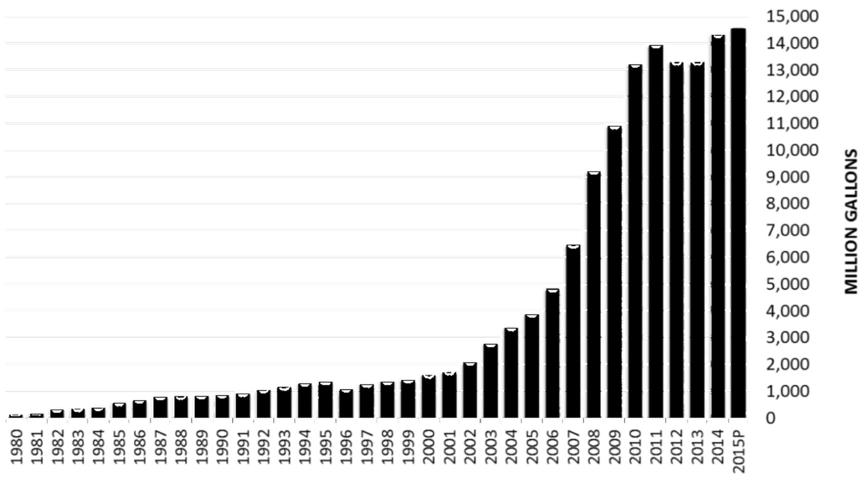

FIGURE 2-7 Annual U.S. ethanol production, 1980–2015.
SOURCE: Renewable Fuels Association.

Figure 2-7 shows how ethanol volumes increased sharply after passage of the first RFS in 2005 and the second RFS in 2007. Fuel ethanol is now consumed in all 50 states, and total ethanol production was nearly 5 times higher in 2015 than in 2005. Ethanol's share of gasoline sales reached 9.8 percent in 2014.[36] The U.S. Environmental Protection Agency (EPA) proposed RFS requirements for 2017 that would increase conventional renewable fuel volumes (mostly corn ethanol) to 14.8 billion gallons.[37] Although this level would represent an increase of 300 million gallons over 2016 volumes, it is 200 million gallons less than required by the 2007 law.

By mandating the use of ethanol in the U.S. gasoline supply, RFS turned fuel ethanol into a widely shipped commodity. Because it takes about 20 pounds of corn to produce 1 gallon of ethanol (weighing about 6.5 pounds), it makes economic sense for distillation plants to be located near cornfields to reduce raw material transportation costs and make economic use of distillation byproducts, such as the distillers' dried grain used

[36] U.S. Energy Information Administration, "Corn Ethanol Yields Continue to Improve," *Today in Energy*, May 13, 2015, https://www.eia.gov/todayinenergy/detail.php?id=21212.

[37] U.S. Environmental Protection Agency, "Proposed Renewable Fuel Standards for 2017, and the Biomass-Based Diesel Volume for 2018," *Renewable Fuel Standard Program*, May 17, 2016, https://www.epa.gov/renewable-fuel-standard-program/proposed-renewable-fuel-standards-2017-and-biomass-based-diesel.

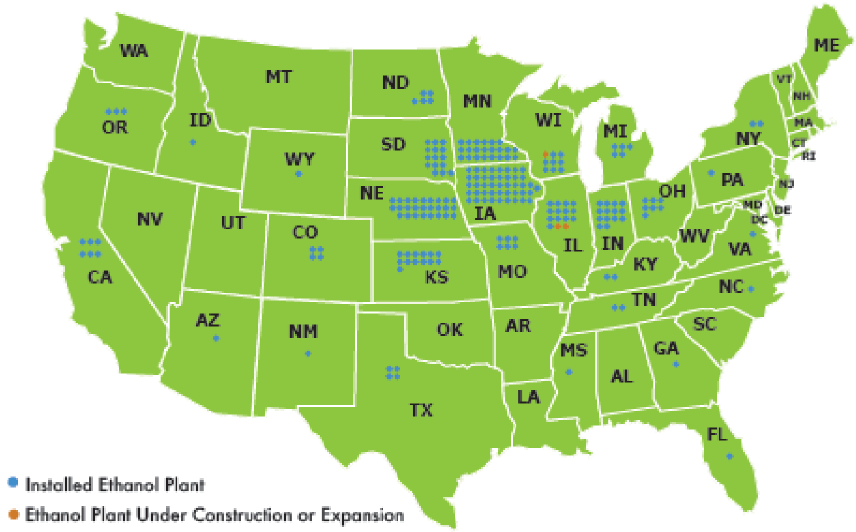

FIGURE 2-8 Fuel ethanol production facilities in 2016, by state.
SOURCE: Renewable Fuels Association.

in livestock feed.[38] Ethanol distilleries have therefore remained centered in a handful of corn-growing Midwestern states, led by Illinois, Indiana, Iowa, Minnesota, and Nebraska (see Figure 2-8). The distilled and denatured product is then transported on long-distance routes—mostly by rail—radiating out from the Midwest to gasoline distribution and blending centers located near motorist demand. In 2015, the top five states in ethanol consumption were California, Texas, Florida, New York, and Ohio.[39]

As discussed more in the next chapter, about 70 percent of the country's ethanol production moves by rail, mostly in trains consisting of 60 to 120 tank cars, each holding about 30,000 gallons (1.8 to 3.6 million gallons per train). Because of the limited number of ethanol plants located near rivers, barges transport only about 10 percent of the volume produced, typically in 2-barge tows that hold 2.5 million gallons. Very little ethanol is shipped by pipeline, in part because of the fuel's propensity to attract water, which can corrode the steel in pipelines. Another reason for the limited movement

[38] Renewable Fuels Association, "2016 Ethanol Industry Outlook: Fueling a High Octane Future" (Washington, D.C., 2016), http://www.ethanolrfa.org/wp-content/uploads/2016/02/RFA_2016_full_final.pdf.

[39] U.S. Energy Information Administration, "Table F4: Fuel Ethanol Consumption Estimates, 2015," *U.S. States Profiles and Energy Estimates*, accessed September 19, 2017, https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_use_en.html.

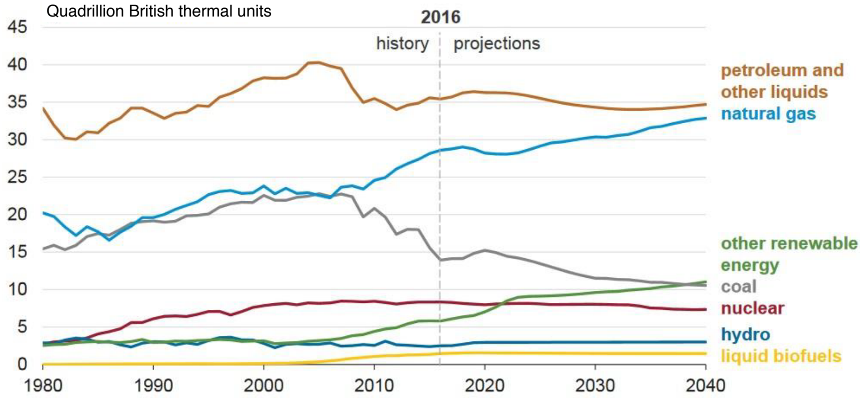

FIGURE 2-9 Historical trends and projections in U.S. energy consumption, by fuel source.
SOURCE: EIA, "Annual Energy Outlook 2017," 9.

by pipeline is that the ethanol industry is fairly dispersed such that significant infrastructure investments would be required to consolidate traffic to achieve the quantities needed for pipeline transportation.

DEVELOPMENTS IN NATURAL GAS MARKETS

Natural gas is a mixture of several hydrocarbon gases. Although its main constituent is methane, it can also contain ethane, propane, and butane, as well as other gases such as carbon dioxide, oxygen, and hydrogen sulfide. Once flared off as an unwanted side-product of oil extraction, natural gas now accounts for about 30 percent of U.S. energy consumption (see Figure 2-9). More than half of U.S. homes use natural gas as their main heating source.[40] Natural gas is also used to produce electricity in about 30 percent of the country's power plants and it is an important heating fuel for numerous manufacturing processes, including steel, glass, and paper production.[41] The hydrocarbons in natural gas are also used as chemical feedstocks in the manufacture of plastics and other organic chemicals.

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[40] U.S. Energy Information Administration, "Everywhere But Northeast, Fewer Homes Choose Natural Gas as Heating Fuel," *Today in Energy*, September 25, 2014, https://www.eia.gov/todayinenergy/detail.php?id=18131.

[41] U.S. Energy Information Administration, "What Is U.S. Electricity Generation by Energy Source?," *Frequently Asked Questions*, accessed September 19, 2017, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

When extracted from the well, raw natural gas is often described as being "dry" or "wet." Dry gas consists almost entirely of the light molecule methane, whereas wet gas contains more of the heavier hydrocarbons, such as ethane, propane, and butane. These heavier hydrocarbons are referred to as natural gas liquids (NGLs; EIA uses the term hydrocarbon gas liquids) and can be separated from the gas stream. Their separation from methane, or dry gas, usually takes place near the production site at gas-processing facilities. The methane is then transported under pressure by transmission pipelines directly to large industrial users, power plants, and gas distribution systems. The NGL stream is usually transported by pipeline to fractionator plants that separate the stream into its constituent compounds, or "purity products." In the case of propane and butane, they are usually compressed into a liquefied form (liquefied petroleum gas, or LPG) and transported by pressure pipeline, barge, and railroad tank car to large industrial users or by tank truck, tank container, and cylinder for use by homeowners and other consumers. Ethane, the lightest and most volatile of the main NGL compounds, is mainly used as a petrochemical feedstock. Because of the need to transport it under pressures too high for safe and economical movement by tank barge, tank car, and tank truck, ethane is domestically transported by pipeline only, usually from fractionators to storage terminals and then to industrial users.

Having been turned into a major energy source and petrochemical feedstock, natural gas supplies in the United States were no longer viewed as being overabundant by the end of the 20th century. In its *Annual Energy Outlook for 2008*, EIA observed that most of the country's major conventional gas reserves had been discovered. Indeed, the combination of increasing demand and limited growth in domestic production had contributed to a fivefold increase in natural gas prices from the late 1990s to 2008.[42] By that time, large investments were being contemplated for LNG import facilities, as most analysts expected natural gas prices to continue to rise because of growing demand and lagging domestic supplies. In its 2008 report, EIA predicted that U.S. production would grow only incremental for the next 20 years, aided only by small additions from offshore fields, Alaska, and unconventional sources such as sandstone and shale.[43]

EIA's 2008 forecast would not stand the test of time. Just 4 years later, in its *Annual Energy Outlook for 2012*, the agency predicted the country

[42] U.S. Energy Information Administration, "Henry Hub Natural Gas Spot Price," *Natural Gas*, accessed September 19, 2017, https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm.

[43] U.S. Energy Information Administration, "Annual Energy Outlook 2008 with Projections to 2030" (Washington, D.C., June 2008), 77, https://www.eia.gov/outlooks/archive/aeo08/pdf/0383(2008).pdf.

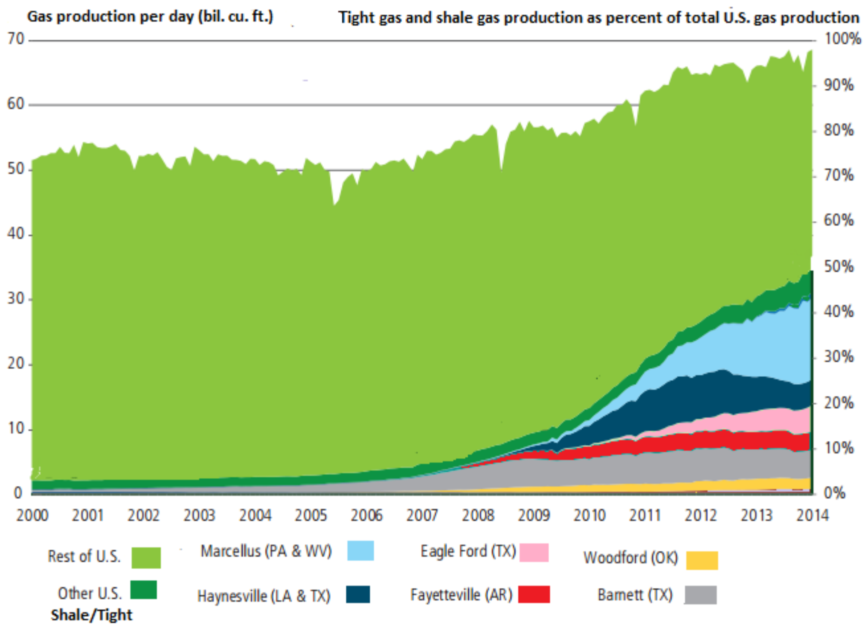

FIGURE 2-10 Trends in U.S. natural gas production volumes by basin, 2000–2014.
SOURCE: EIA.

would be a net exporter of natural gas by 2035.[44] In its *Annual Energy Outlook for 2016*, the agency predicted that the United States would become a net exporter of natural gas by 2018.[45] As was the case with domestic crude oil production, energy analysts did not foresee the dramatic impact that development of the country's shale and other mudstone basins would have on domestic gas production. As shown in Figure 2-10, output from hydraulic fracturing sources grew to make up nearly half of the U.S. dry natural gas production by 2014, driven by especially large volumes recovered from the Marcellus Basin in Pennsylvania and West Virginia. Just a few years earlier, these states had accounted for a negligible share of natural gas production, and the Northeast was generally viewed as "gas

[44] U.S. Energy Information Administration, "Annual Energy Outlook 2012 with Projections to 2035" (Washington, D.C., June 2012), 74, https://www.eia.gov/outlooks/aeo/pdf/0383(2012).pdf.

[45] U.S. Energy Information Administration, "Most Natural Gas Production Growth Is Expected to Come from Shale Gas and Tight Oil Plays," *Today in Energy*, June 7, 2016, https://www.eia.gov/todayinenergy/detail.php?id=26552#.

starved" due to its distance from domestic supplies and limited access to cross-country gas transmission pipelines.

Because they are co-produced with natural gas, NGLs were similarly forecasted to experience declining supplies during the early 2000s. When the hydraulic fracturing boom began around 2008, dry natural gas prices were at an all-time high, creating incentives for the development of fields that produced more dry gas than wet gas. Interest in dry gas was particularly strong in the Marcellus Basin, which had access to natural gas pipelines but not substantial NGL pipeline and processing capacity. Most of the country's NGL pipelines and fractionators are located in Texas and Louisiana, close to conventional gas fields and petrochemical centers that demand ethane and other NGLs. However, by 2009, the large influx of dry natural gas from hydraulic fracturing contributed to sharp decreases in the commodity's price. Under these circumstances, producers began to place greater value on basins that produced wet gas in order to recover the NGL streams that could be sold separately and had not experienced the same precipitous declines in price.

The growth in wet gas production has led to investments in gas-processing capacity in the Northeast, as well as investments in fractionation capacity, so that some of the purity products, especially propane and butanes, can be separated locally and sold in regional markets (see Figure 2-11). Currently, the supply of NGLs from the Marcellus and Utica Basins exceeds demand in the Northeast, particularly for ethane, whose main market continues to be the petrochemical industry centered in the Gulf Coast states. In 2014, the United States switched from being a net importer of ethane to a net exporter after the opening of two new ethane pipelines that transport methane from North Dakota and Pennsylvania to Canada.[46] The future market for the NGLs produced from hydraulic fracturing will therefore depend on many factors, including market prices, export demand, changes in the size and location of the petrochemical industry, and transportation options. In the next chapter, more discussion is given to the development of NGL transportation capacity.

[46] U.S. Energy Information Administration, "Ethane Production Expected to Increase as Petrochemical Consumption and Exports Expand," *Today in Energy*, April 1, 2016, https://www.eia.gov/todayinenergy/detail.php?id=25632.

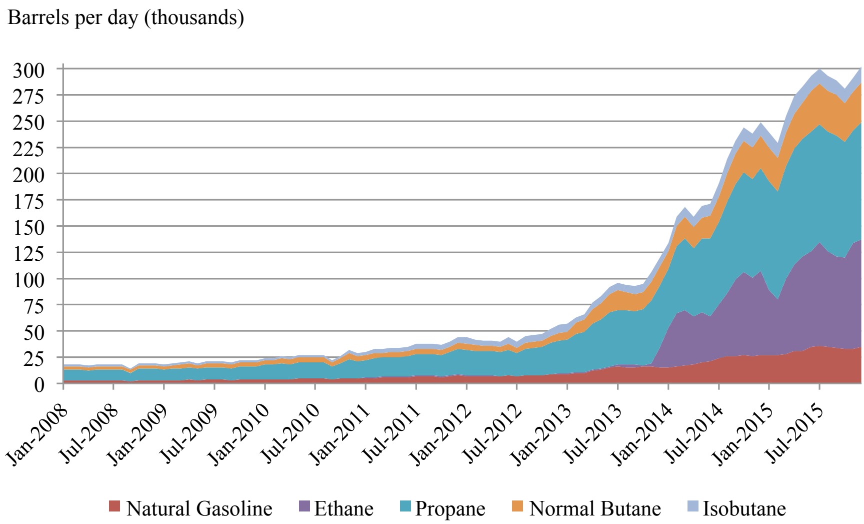

FIGURE 2-11 Natural gas field plant production of NGLs in and near the Marcellus and Utica Basins.
SOURCE: EIA, "Appalachian No. 1 Natural Gas Plant Field Production," *Petroleum & Other Liquids*, April 28, 2017, https://www.eia.gov/dnav/pet/pet_pnp_gp_dc_rap_mbblpd_m.htm.

3

The Role of Freight Transportation in the Domestic Energy Revolution

The U.S. freight transportation sector's response to the rapid and largely unanticipated growth in demand for the movement of crude oil, ethanol, and natural gas during the past decade has been a remarkable, but sometimes overlooked, aspect of the domestic energy revolution. Although by no means flawless, as new safety issues emerged and bottlenecks were created by temporary capacity shortages, the industry showed a high degree of adaptability and innovation. Freight railroads and barge operators were quick to fill gaps in the nation's pipeline coverage, and pipeline operators soon expanded, repurposed, and redirected their networks to reestablish their central role in the long-haul movement of oil and gas.

This chapter describes how these three freight modes—pipeline, railroad, and barge—accommodated the escalating volumes of domestic crude oil, ethanol, and natural gas shipments. Background is provided on the size and scope of each mode's network as well as the specific means of conveyance used for these energy liquids and gases, from tank barge tows and tank car unit trains to buried pipes that span hundreds of miles. Trends in the amount of crude oil, ethanol, and natural gas shipped by the three modes are reviewed, both before and after the start of the domestic energy revolution. Volume trends, however, reveal only part of the story of the sector's impressive response. Not only were the three modes asked to move energy liquids and gases in much larger quantities, but they were also asked to do so over new routes, and in some cases by new methods of conveyance. It is the combination of higher traffic volumes, new routings, and new conveyance methods that make the sector's response so remarkable.

PIPELINE TRANSPORTATION

Transmission pipelines are responsible for most domestic movements of crude oil and natural gas liquids (NGLs) and nearly all long-distance movements of natural gas. They are not used for ethanol, with the exception of a short pipeline in Florida. This section describes the country's network of oil and gas transmission pipelines, beginning with an overview of the geographic scope of the systems before reviewing key features of their design and operation. Recent trends in the amount of crude oil, natural gas, and NGLs transported by pipeline are then reviewed.[1]

Transmission Pipeline Network

Crude oil and natural gas are transported by pipeline in upstream gathering and midstream transmission systems. In the case of natural gas, downstream systems of distribution pipelines are also used to deliver the commodity to local distribution companies that serve residential and commercial users.[2] It is important to distinguish among these pipeline systems because their size, design, operating environments, and uses are quite different.

Gathering systems are used to transport raw crude oil and natural gas short distances from the wellhead to nearby processing plants and storage tanks. These systems usually consist of low-pressure steel lines less than 8 inches in diameter. The raw crude oil that exits gathering lines is usually treated and vented at field plants to remove impurities such as water, sediment, and dissolved gasses (e.g., carbon dioxide and hydrogen sulfide). Likewise, natural gas is transported from the production field in gathering lines to nearby gas-processing plants to extract valuable NGLs and unwanted gases and liquids. There are about 500 natural gas–processing plants nationwide.

The removal of impurities from the crude oil and natural gas streams is necessary to meet the quality specifications of the midstream transmission pipelines, particularly to prevent corrosion. This initial processing is also necessary to meet the commodity specifications of receiving refineries, utilities, and factories. In the case of natural gas, the NGLs removed at gas-processing plants create a third commodity stream that is carried through transmission pipelines to downstream fractionators where NGLs, such as propane, butane, and ethane, are extracted for storage and transportation (often again, by pipeline) to their end-use markets. There are about 100 fractionation facilities in the United States.

[1] There are only 16 miles of transmission pipeline used for ethanol.

[2] Natural gas distribution systems consist of mains, which can exceed 20 inches in diameter, and service laterals, often made of plastic, which are usually less than 2 inches in diameter. Because distribution lines are not part of this study, they are not discussed further.

Gas and oil transmission pipelines are made of steel, normally 8 to 48 inches in diameter, and operated at high pressures ranging from 400 to 1,400 pounds per square inch (psi). Lines typically run several hundred miles, often accompanied by other lines in shared rights of way. More detail on the crude oil, natural gas, and NGL transmission pipeline systems are provided next.

Crude Oil Transmission Pipelines

Crude oil transmission pipelines originate at one or more inlet stations, or storage terminals, where custody of the shipment is transferred from its original owner to the pipeline operator.[3] These stations can be access points for tank trucks, railroad tank cars, and tank barges, as well as upstream gathering pipelines. Different grades of crude oil are often blended at these facilities to meet the specifications of receivers and to create a more transportable product. It is common for crude oil shipment specifications to define the maximum allowable sediment and water content, viscosity, density, vapor pressure, and temperature of the shipment. The specifications are designed to protect the integrity of the pipeline and the ancillary facilities, ensure the shipment meets the needs of the refiner, and prevent valuable throughput capacity from being consumed by unwanted sediment and water. Sampling, metering, and blending facilities are usually located at these stations to ensure the commodity injected into the pipeline meets the quality control requirements of the pipeline operator and intended recipients.

There are more than 70,000 miles of crude oil transmission pipeline in the United States. This transmission system experienced marked growth between 2012 and 2015 (see Figure 3-1). Most of the capacity of these lines is contained in about two dozen long-line systems.[4] As shown in Figure 3-2, the U.S. crude oil pipeline network is centered in the country's interior, fanning out from the Gulf Coast to the Rocky Mountain, Plains, and Great Lakes states. Except for a single crossing from Canada into Maine, there are no crude oil pipelines east of the Appalachian Mountains. Several trunk lines enter from Canada, mainly from the oil-producing regions of Alberta and Saskatchewan. On the West Coast, the Trans-Alaska Pipeline System

[3] National Research Council, ed., *Effects of Diluted Bitumen on Crude Oil Transmission Pipelines*, Special Report/Transportation Research Board 311 (Washington, D.C: Transportation Research Board, 2013). The discussion in this section is informed by this report.

[4] Department of Transportation's Pipeline and Hazardous Materials Safety Administration, "Distribution, Transmission & Gathering, LNG, and Liquid Annual Data," *PHMSA-Data & Statistics*, accessed August 20, 2015, http://phmsa.dot.gov/portal/site/PHMSA/menuitem.6f23687cf7b00b0f22e4c6962d9c8789/?vgnextoid=a872dfa122a1d110VgnVCM1000009ed07898RCRD&vgnextchannel=3430fb649a2dc110VgnVCM1000009ed07898RCRD&vgnextfmt=print.

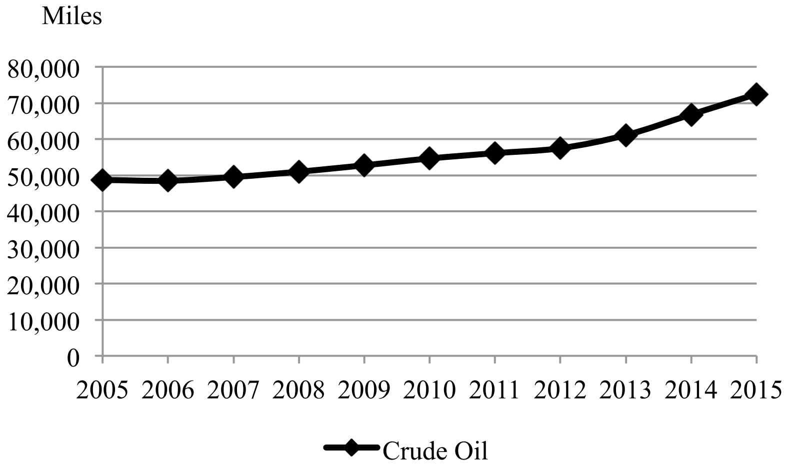

FIGURE 3-1 Miles of U.S. crude oil pipeline, 2005–2015.
SOURCE: PHMSA, "Annual Report Mileage for Hazardous Liquid or Carbon Dioxide Systems," accessed August 1, 2016, http://phmsa.dot.gov/pipeline/library/data-stats/annual-report-mileage-for-hazardous-liquid-or-carbon-dioxide-systems.

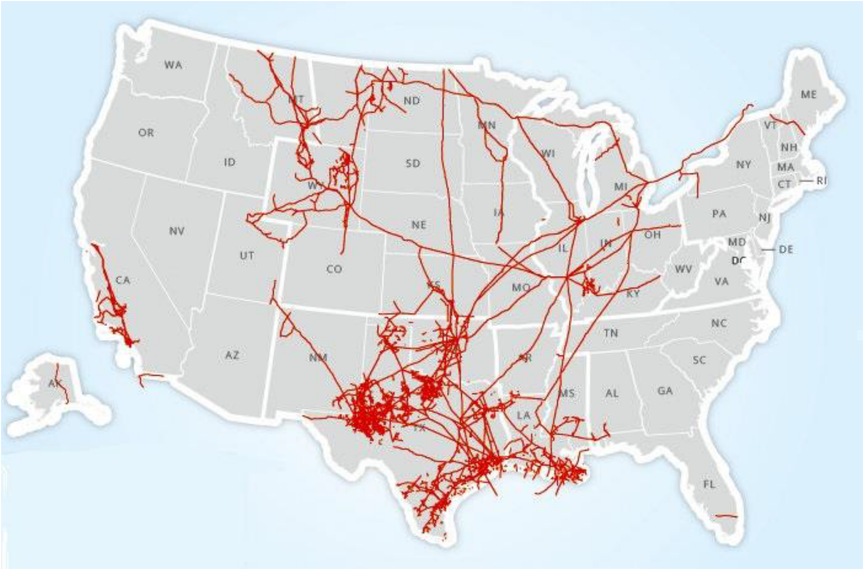

FIGURE 3-2 U.S. crude oil transmission pipeline network.
SOURCE: http://www.pipeline101.com/Where-Are-Pipelines-Located.

transports crude oil from Alaska's North Slope to the port of Valdez, while a pipeline from Canada serves the refineries of Washington State. California has several transmission pipelines that do not have interstate connections but carry heavy crude oil from the state's inland oil fields to refineries on its coast.

The Gulf Coast and the Midwest orientations of the transmission system can be explained by the fact that more than 50 percent of U.S. refining capacity resides in Texas and Louisiana, with the next largest center on the Great Lakes.[5] The combination of production fields, large refineries, oil-import facilities, and tank storage hubs has resulted in an especially dense pipeline network in Louisiana, Oklahoma, and Texas. These three states alone account for about 40 percent of the crude oil transmission pipeline mileage. The country's largest crude oil storage hub is in Cushing, Oklahoma, where eight major transmission pipelines and several smaller ones converge. Cushing is a transshipment point for crude oil moving between the Gulf Coast and the Midwest. Other major pipeline hubs are located in Houston, Texas (i.e., Houston Ship Channel), and St. James, Louisiana; and regional hubs can be found in Patoka, Illinois; Clearbrook, Minnesota; and Guernsey, Wyoming.

Natural Gas Transmission Network

As shown in Figure 3-3, the country's natural gas transmission network is much more expansive than the crude oil transmission network. There are some 300,000 miles of natural gas transmission pipeline in the United States, including about 4,000 offshore miles.[6] About two dozen companies own 80 percent of this mileage—with each company operating systems that contain 1,000 miles or more.[7] The natural gas system dwarfs the crude oil system in large part because the former, a finished fuel, must access thousands of downstream local distribution companies and other large-volume users scattered across the country, as opposed to the fewer than 150 refineries that receive the most crude oil.

Much like the crude oil pipeline network, however, the natural gas network is densest on the Gulf Coast, as the large gas-producing and gas-consuming states of Louisiana and Texas account for nearly 25 percent of

[5] U.S. Energy Information Administration, "Regional Refinery Trends Evolve to Accommodate Increased Domestic Crude Oil Production," *Today in Energy*, January 15, 2015, https://www.eia.gov/todayinenergy/detail.php?id=19591.

[6] Pipeline and Hazardous Materials Safety Administration, "Annual Report Mileage for Natural Gas Transmission and Gathering Systems," *Data and Statistics*, September 1, 2017.

[7] U.S. Energy Information Administration, "Interstate Natural Gas Pipeline Segment," *About U.S. Natural Gas Pipelines—Transporting Natural Gas*, accessed September 19, 2017, https://www.eia.gov/naturalgas/archive/analysis_publications/ngpipeline/interstate.html.

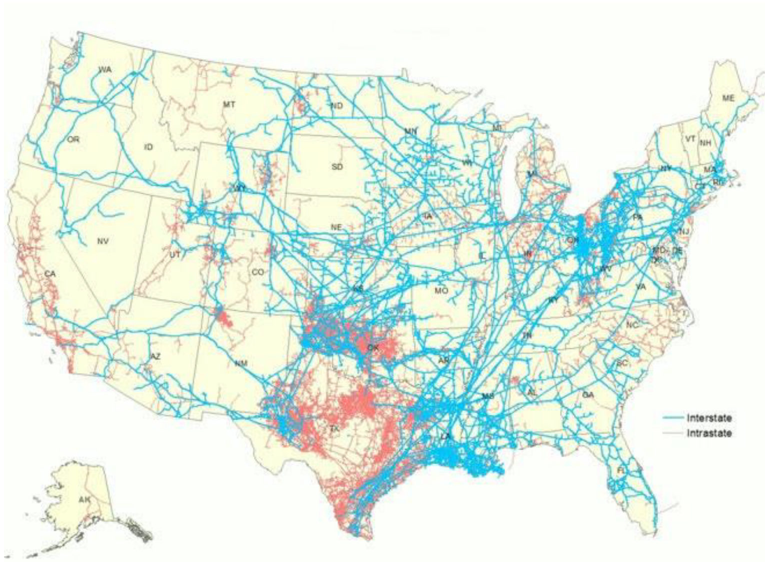

FIGURE 3-3 U.S. natural gas transmission pipeline network, 2013.
SOURCE: http://www.pipeline101.com/Where-Are-Pipelines-Located/Natural-Gas-Pipelines-Map.

the country's transmission pipeline mileage.[8] Because of its central location and large industrial and residential demand, the Midwest also has a dense network of gas transmission pipelines. The Great Lakes states of Illinois, Indiana, Michigan, Ohio, and Pennsylvania account for nearly 25 percent of total line mileage. However, unlike the more geographically limited crude oil network, the natural gas system forms a dense grid that connects all regions of the country. In recent years, transmission pipelines have been built to provide natural gas to regions that were once underserved, especially New York and New England.[9]

At one time, pipeline operators were required by regulation to own the natural gas that moved through their systems. Today the rates charged by

[8] Pipeline and Hazardous Materials Safety Administration, "Pipeline Miles and Facilities 2010+," accessed September 19, 2017, https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?Portalpages&NQUser=PDM_WEB_USER&NQPassword=Public_Web_User1&PortalPath=%2Fshared%2FPDM%20Public%20Website%2F_portal%2FPublic%20Reports&Page=Infrastructure&Action=Navigate&col1=%22PHP%20-%20Geo%20Location%22.%22State%20Name%22&val1=%22%22.

[9] For example, the Rockies Express line was completed in 2009, extending from Colorado to Ohio and bringing more gas to pipeline hubs with connections to the Northeast.

operators are regulated, but the transportation services are sold independently to the owners of the commodity. The pipeline systems have therefore become even more integrated to form a truly national transportation network.

NGL Pipeline Network

As explained in Chapter 2, NGLs are first recovered at natural gas–processing plants located upstream from transmission pipelines, which then transport them to fractionators to create the purity products butane, ethane, isobutane, and propane. The purity products are then carried in other transmission pipelines or by other means, such as tank trucks and railroad tank cars, to storage hubs and end users such as petrochemical plants. Because the purity product ethane must move under high pressure, it can be transported only by pipeline. Some pure NGLs, such as propane, are also produced by oil refineries (as opposed to raw NGL fractionators), and they too are transported by pipeline and other modes to end-use markets.

Because Texas accounts for a large portion of the country's natural gas production and fractionation capacity (i.e., Mont Belvieu), it contains most of the country's transmission pipelines used for NGLs. Kansas is also home to another major NGL storage and fractionation center (i.e., Conway), which is connected to transmission pipelines that originate from natural gas–processing plants in Colorado, New Mexico, Oklahoma, and Wyoming. In response to the increasing supply of NGLs from mudstone basins, new fractionators are being built in North Dakota, Pennsylvania, the Rocky Mountain states, and west Texas. The development of this new processing capacity has led to NGLs and purity products being transported by pipeline from these regions to industrial users and storage terminals on the Great Lakes and in Canada.

The total size of the NGL transmission pipeline network can be difficult to define because publicly available mileage statistics often include lines used for other hazardous materials such as anhydrous ammonia (see Figure 3-4). NGL pipelines are categorized by the Pipeline and Hazardous Materials Safety Administration (PHMSA) as highly volatile liquid (HVL) pipelines because they pose flammable and toxic hazards when released to the atmosphere. There are about 65,000 miles of HVL transmission pipeline, including about 40,000 miles on interstate systems (see Figure 3-5). For reasons explained above, Kansas, Louisiana, Oklahoma, and Texas account for about 70 percent of this pipeline mileage.[10] Nevertheless, because of the demand for propane and ethane in other regions, such as the South-

[10] Pipeline and Hazardous Materials Safety Administration, "Pipeline Miles and Facilities 2010+."

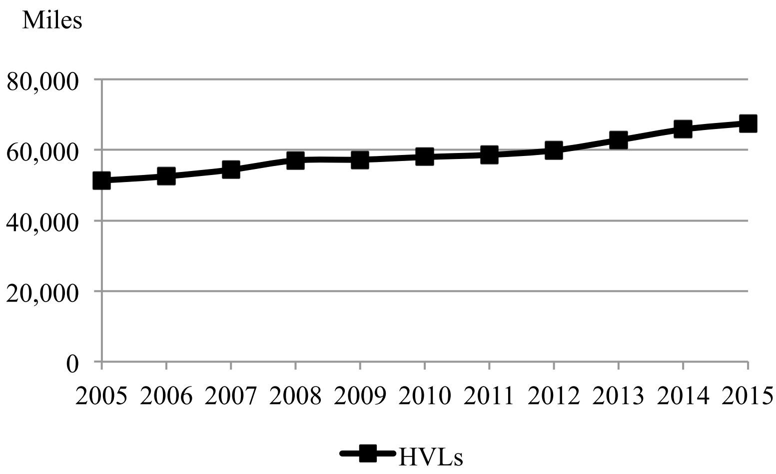

FIGURE 3-4 Miles of U.S. transmission pipeline used to transport HVLs, 2005–2015.
NOTE: These data include mileage for all HVLs, of which NGLs are the predominant shipment.
SOURCE: PHMSA, "Annual Report Mileage for Hazardous Liquid or Carbon Dioxide Systems."

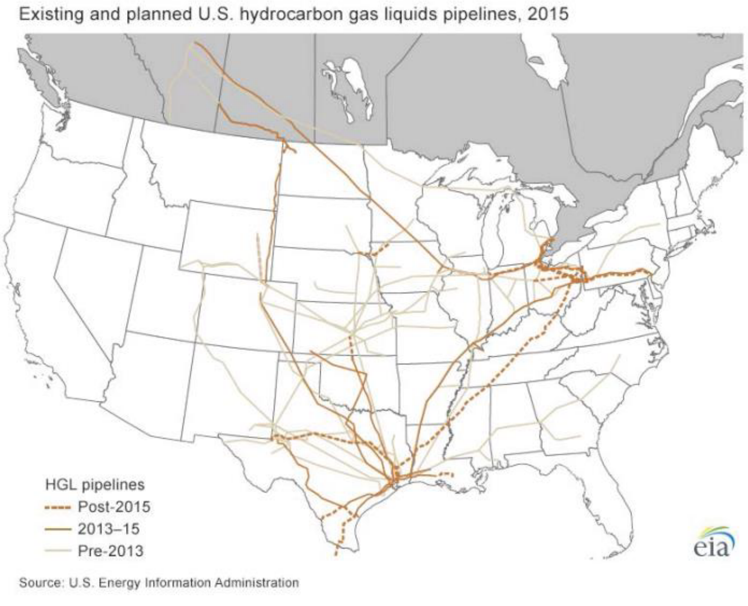

FIGURE 3-5 Network of U.S. transmission pipelines used to transport HVLs (also known as hydrocarbon gas liquids, or HGLs).
SOURCE: U.S. Energy Information Administration [EIA].

east, some of the transmission pipelines can extend for more than 1,500 miles. As demand for propane and ethane change, there may be further buildout of these systems, especially to accommodate exported shipments.

Key Pipeline System Components

Pipe segments in transmission pipelines are usually 40 to 80 feet long with a diameter of 8 to 42 inches. Wall thicknesses vary depending on the pipe's diameter and pressure requirements and may be increased where the line crosses a body of water or in areas that are densely populated, environmentally sensitive, or prone to additional external forces such as seismic activity. It is standard practice for transmission pipelines to be coated externally to provide a physical barrier between the steel and the corrosive environment. The inside of the pipe is usually uncoated and unlined bare steel.

To maintain desired pressure levels and flow rates, gas compressors or liquid-pumping stations are positioned along the pipeline at intervals of 20 to 100 miles depending on factors such as topography, pipe diameter, operating pressure, and the properties of the product being transported. Because natural gas creates less friction than liquids, it tends to require fewer compressor stations. These stations are often automated and equipped with sensors, programmable logic controllers, switches, alarms, and other instrumentation allowing the continuous monitoring and control of the pipeline as well as its orderly shutdown if an alarm condition occurs or an operating parameter is violated.

Pipelines are equipped with shutoff valves that are strategically located at compressor and pump stations, certain road and water crossings, and other points to facilitate the starting and the stopping of flow and to minimize the impact of leaks. These valves, many of which can be controlled remotely, ensure that portions of the line can be isolated in the event of a leak or the need for repair or maintenance. In addition, check valves that prevent backflows may be located at elevation changes and other intermediate points in hazardous liquids pipelines. The opening and the closing of valves are sequenced to prevent problems associated with over- and underpressurization. Bypass lines, relief valves (e.g., pressure and thermal relief), and surge tanks may be sited at stations to relieve pressure.

Operations and Control

Pipelines carrying gases and liquids are operated differently because of the nature of the products they carry. For instance, unlike homogenous natural gas, crude oils and NGLs vary in grade and type. This variation in the characteristics of hazardous liquids presents an opportunity for pipeline operators to batch more than one commodity in a single pipeline.

Thus, a long-distance hazardous liquids pipeline can transport dozens of commodity types at one time, typically in batches of at least 50,000 barrels. To reduce undesirable mixing at interfaces, the batches are sequenced according to characteristics such as density, viscosity, and sulfur content in the case of crude oil. Maintaining batch separation requires that operators closely monitor the flow characteristics of the pipeline, since reductions in flow velocity and loss of flow turbulence can lead to undesirable intermixing. Hazardous liquids pipeline operators strive to maintain turbulent flow, characterized by chaotic motion, to reduce intermixing of batches, and to keep impurities, such as water and sediment, suspended to prevent settling that can cause internal corrosion.

Choosing a desired gas pressure and liquids flow regime requires the balancing of many technical and economic factors. Increasing operating pressure will increase pipeline throughput, which is generally desired by an operator to increase revenue capacity. Higher operating pressures, however, require a larger investment in pipe materials and compressor and pumping capacity, and will increase energy use and operating costs.

In the case of crude oil pipelines, the characteristics of the crude oil are important considerations in establishing a flow regime. For instance, more energy is needed to pump dense, viscous crude oils than light crude oils with lower viscosity. Some crude oils are too viscous naturally to be pumped. The normal response when a highly viscous crude oil is transported entails diluting it with lighter oil, referred to as diluent. When a diluent is too costly or unavailable, an alternative approach is to transport the crude oil in a heated pipeline. Heated oil transmission pipelines are rare, except in California, which produces very viscous crude.

Pipeline throughput and flows are usually monitored and controlled by operators from one or more central control centers, where supervisory control and data acquisition (SCADA) systems collect and analyze data signals from sensors and transmitters positioned at compressors and pumps, valves, tanks, and other points en route. Parameters other than flow rate, such as line pressure, pump and compressor discharge pressures, and temperatures, are also monitored for routine operational and maintenance decisions and for leak detection. In the next chapter, further consideration is given to the safety features and maintenance of transmission pipelines.

Trends in Pipeline Transportation of Crude Oil, Natural Gas, and NGLs

Recent Trends in Traffic

Pipelines have long accounted for the dominant share of long-haul crude oil movements in the United States. Since the late 1990s, pipelines have carried more than 70 percent of crude oil shipped as measured in ton-miles.[11] By 2010, this share had reached 80 percent of ton-miles[12] and 85 percent of refinery receipts.[13] However, as demand for oil takeaway capacity grew, the less capital-intensive rail and water modes began to account for increasing shares of crude oil traffic. The two modes, particularly rail, offer more flexible routing options, allowing for en-route changes in shipment destination in response to changing market demand and price differentials. In 2012, the pipeline share of crude oil ton-miles was at about 75 percent.[14] However, since 2012, as more miles have been added to the network, pipelines have hauled increasingly larger crude oil traffic volumes. As shown in Figure 3-6, trunk pipelines carried about 54 percent more barrels in 2015 than in 2011.

Unlike crude oil, all long-distance natural gas shipments move by pipeline. As a precursor to the domestic energy revolution, natural gas traffic by transmission pipeline increased nearly 20 percent between 2005 and 2010. Growth leveled off after 2010, and by 2015 volumes were comparable to those in 2005 (see Figure 3-7). In the case of NGLs, this traffic is also moved predominantly by pipeline. Like natural gas, NGL shipments grew rapidly from 2005 through 2009, but it has also experienced periods of additional marked growth over the past 5 years (see Figure 3-8).

Geography of the Traffic

The geographic change in oil pipeline movements has been dramatic over the past decade. Between 2005 and 2015, crude oil shipments from the Midwest increased by an order of magnitude as production in the Williston Basin ramped up (see Figure 3-9). At the same time, movements from the Gulf Coast to the Midwest have been falling as imports are down. The trend reached a milestone in 2015 when Midwest shipments to the Gulf Coast surpassed Gulf Coast shipments to the Midwest by nearly 29 million barrels.

In the case of natural gas, it is difficult to track shipments because its fungible quality means that pipelines are in some sense a storage vehicle. However, the routing of individual pipelines has shifted in response to the new supply origins. These changes are the result of new pipelines, conversions of existing pipelines to or from natural gas service, and directional

[11] Bureau of Transportation Statistics, "Table 1-55: Crude Oil and Petroleum Products Transported in the United States by Mode," July 2010, http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/2010/index.html.

[12] Ibid.

[13] U.S. Energy Information Administration, "U.S. Refinery Receipts of Crude Oil by Method of Transportation," November 10, 2016, http://www.eia.gov/dnav/pet/pet_pnp_caprec_dcu_nus_a.htm.

[14] Ibid.

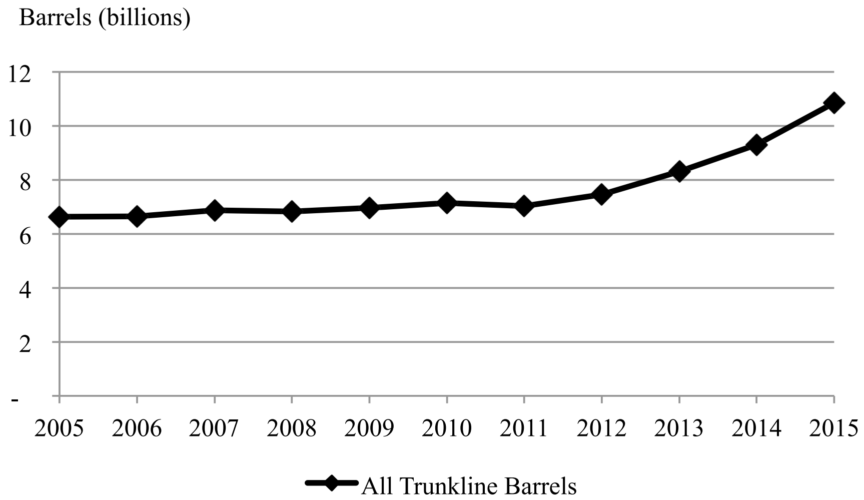

FIGURE 3-6 U.S. pipeline crude oil traffic volume, 2005–2015.
SOURCE: Federal Energy Regulation Commission, https://www.ferc.gov/docs-filing/forms/form-6/data.asp.

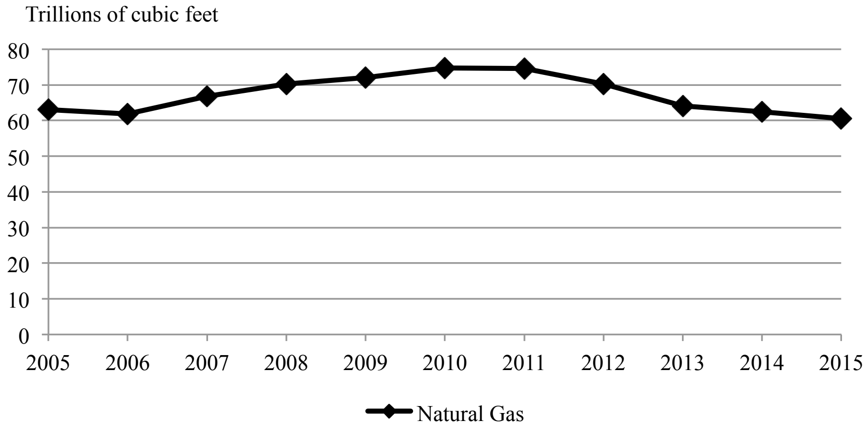

FIGURE 3-7 U.S. interstate pipeline deliveries of dry natural gas, 2005–2015.
SOURCE: EIA.

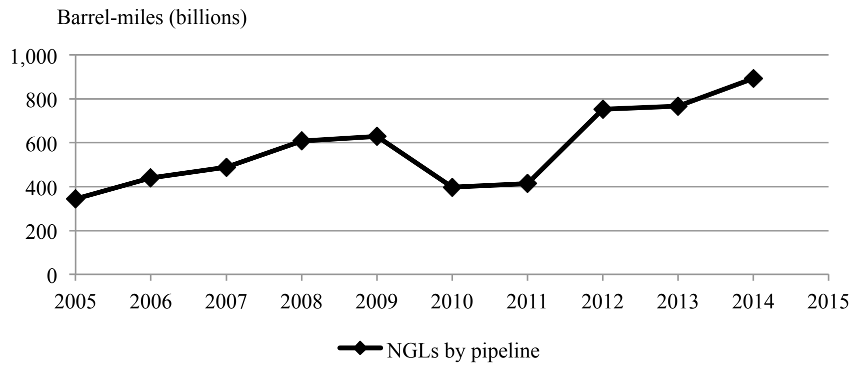

FIGURE 3-8 U.S. pipeline shipments of NGLs.
SOURCE: PHMSA, "Data and Statistics," accessed September 21, 2016, http://www.phmsa.dot.gov/pipeline/library/data-stats.

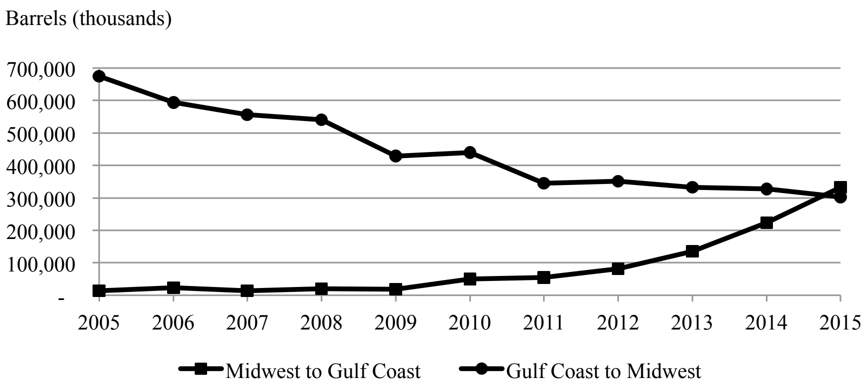

FIGURE 3-9 U.S. pipeline shipments of crude oil between the Midwest and the Gulf Coast, 2005–2015.
SOURCE: EIA, "Crude Oil and Petroleum Products Movements by Pipeline between PAD Districts," accessed November 8, 2016, http://www.eia.gov/dnav/pet/pet_move_pipe_a_EP00_LMV_mbbl_m.htm.

reversals.[15] The U.S. Energy Information Administration (EIA) reports there were 38 line reversals and conversions from 1996 through 2015.[16] Since 2013, most reversals have been made to accommodate the growth in natural gas traffic originating in the Marcellus and Utica regions. By comparison, most NGL traffic continues to move along the well-established NGL pipeline network in the Gulf Coast region. However, the supply from hydraulic fracturing has prompted new pipeline traffic on the East Coast; for instance, through Philadelphia where NGL shipments are being exported to European petrochemical plants.

RAIL TRANSPORTATION

This section describes how freight railroads transport domestic supplies of crude oil, ethanol, and NGLs, including the types of trains and rail cars used. In the decade since the start of the domestic energy revolution, there has been tremendous growth in the amount of ethanol and crude oil moved by rail, with volumes escalating each year from 2008 to 2014. However, traffic levels have varied from stable to declining rates over the past 2 to 3 years. These changing trends, and their causes, are discussed after providing an overview of the nation's freight rail network, which is best viewed as a continental system because of its integration with Canadian railroads and crossings into Mexico.

North American Freight Rail Network

Most of the U.S. freight rail system is owned and operated by four major railroads. Union Pacific Railroad and BNSF Railway own most of the mainline track west of the Mississippi River, and CSX Transportation and Norfolk Southern Railway own most of the track to the east (see Figure 3-10). The Canadian Pacific Railway and the Canadian National Railway operate several thousand miles of mainline track in the upper Midwest, the mid-Atlantic, and the Great Lakes region, as well as southward to the Gulf Coast. The Kansas City Southern Railway Company operates in the Mississippi Valley on mostly north–south routes, including extensions into Mexico as Kansas City Southern de Mexico. Collectively, these seven

[15] U.S. Energy Information Administration, "Oklahoma State Profile and Energy Estimates," January 21, 2016, https://www.eia.gov/state/analysis.cfm?sid=OK.

[16] U.S. Energy Information Administration, "Natural Gas," accessed November 8, 2016, http://www.eia.gov/naturalgas/data.cfm#pipelines. EIA issues a disclaimer about these data noting that they are not part of a survey and rely on several sources. PHMSA reports having begun to collect data on conversions and reversals around 2013, but data are not yet publicly available.

Class I railroads own, operate, and maintain about 162,000 miles of track in the United States.

The Class I railroads provide long-distance freight transportation. During the past 30 years, they have fundamentally restructured their networks and operations to concentrate traffic on high-capacity trunk lines by using increasingly longer and heavier trains. They now specialize in the transcontinental movement of intermodal containers, as well as the long-haul movement of bulk and carload commodities such as grain, coal, and chemicals.

As shown in Figure 3-10, the 162,000-mile Class I freight rail network is dense and highly integrated, allowing service to thousands of origin–destination pairs. Not shown in Figure 3-10 are the more than 40,000 miles of branch-line track operated by several hundred regional and short-line railroads (Classes II and III) that provide feeder service. Because no single U.S. railroad spans the entire country from the East Coast to the West Coast, the major railroads also exchange traffic with one another. Shipments of wheat or crude oil going from North Dakota to the East Coast, for instance, require at least two railroads to complete the trip. The railroads,

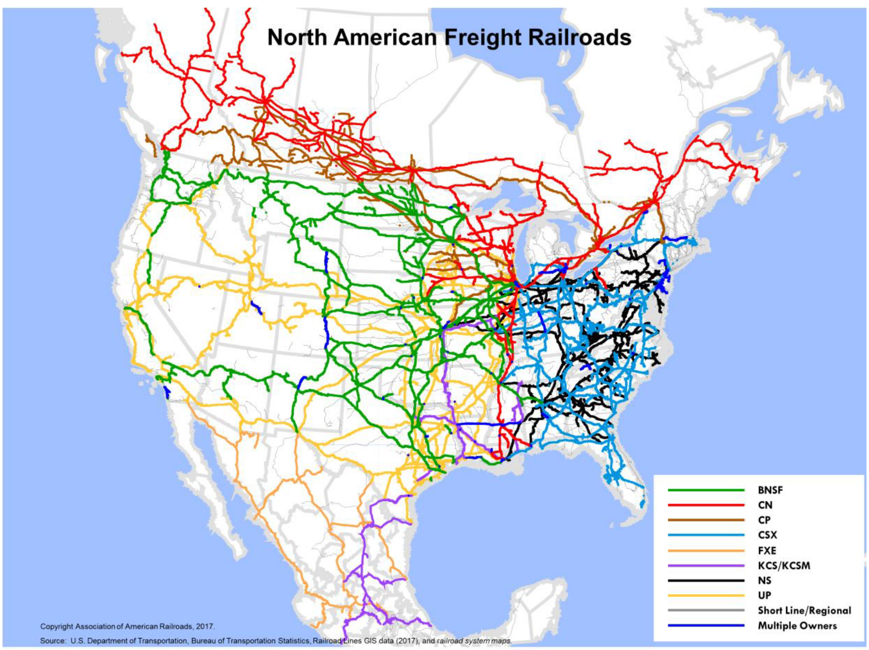

FIGURE 3-10 North American Class I freight railroad network.
SOURCE: U.S. Department of Transportation.

therefore, have long-established standards for the interchange of rail cars over their networks and for the setting of joint rates.

Trains Used for Crude Oil, Ethanol, and NGLs

The Class I railroads operate line-haul trains that typically contain at least 70 cars, and often 100 or more. Trains operating west of the Mississippi River tend to be even longer, sometimes exceeding 120 cars.

These line-haul trains may be constructed to provide either "manifest" or "unit" service. Manifest trains have a mixed consist, meaning they move a variety of cargoes in several different car types and for multiple shippers. The carload shipments are usually traveling between different origin and destination points, and therefore trains are assembled, disassembled, and reassembled in classification yards where car sorting takes place. The sorting schedule, labor, and added circuity that is entailed means that manifest service can be slow and costly, which has led to a steady decline in its use over the past three decades.

The railroads can operate far more efficiently when providing trainload, or unit, service from a single origin to a single destination. Typically formed from more than 100 cars, unit trains carry one type of commodity from a single origin to a single destination, often on a set schedule. Unit trains have long been used to provide fast, cross-country transportation of intermodal containers, as well as coal movements from mines to electric utilities. These train configurations have been used increasingly to transport grain and other bulk commodities. To benefit from the faster transit times and lower rates, shippers and receivers of commodities moved in unit trains may be required to make substantial investments in track and other facilities that can handle the longer trains and faster loading and unloading.

Ethanol began moving in unit trains a few years before a rail market developed for crude oil. As discussed in Chapter 2, low ethanol production volumes and limited national demand had made unit trains uneconomical until the federal Renewable Fuel Standard (RFS) mandate led to increased demand after 2005. Faced with growing demand, ethanol plants began pooling their shipments by using "sweep" trains that pick up cars from the sidings of several plants, usually in blocks of at least two dozen cars.[17] These operational changes, as well as the advent of third-party ethanol consolidators and the acquisition of smaller ethanol plants by larger-volume producers, led to an increasing share of ethanol traffic being moved by unit trains as production volumes grew in response to RFS.

[17] Union Pacific, "Ethanol Sweep Train Tariff Condition Change," March 8, 2013, http://www.up.com/up/customers/announcements/agriculturalproducts/ethanolandbiodiesel/AG2013-19.html.

When the rail market for crude oil began to develop as the use of hydraulic fracturing technology grew, the service was often provided in manifest trains because of a lack of volume. Many of the new oil-producing fields lacked high-capacity gathering and storage systems, as well as car-loading infrastructure. Blocks of railroad tank cars were thus filled on sidings by tank trucks and then scheduled for rail pickup two or three times per week. The transfer from truck to tank car was often made using portable transloader platforms, as shown in Figure 3-11. As production volumes increased and pipeline gathering and tankage systems were installed, shipper investments in the added trackage, loading, and storage facilities required for unit train service became more attractive. These investments allowed faster and less expensive trainload movements of up 80,000 barrels (i.e., more than 3 million gallons) at a time. The largest terminals were built with loop track designs and loading racks with enough positions to simultaneously fill several dozen tank cars (see Figure 3-12).

Like the crude oil from hydraulic fracturing sites, NGLs being recovered from wet gas drilling often lacked pipeline take-away capacity. These liquids too could be transported by rail using the pressure tank cars traditionally used for hauling propane and butane, as long as the ethane content in NGL was minimal. Indeed, some unit trains were created to bring NGL shipments from the Bakken fields in North Dakota to fractionators in

FIGURE 3-11 Direct truck-to-rail transloading.

(*a*)

(*b*)

FIGURE 3-12 Siding loop (*a*) and crude oil–loading rack (*b*) for unit train service.

Kansas and Texas.[18] When compared with their use for crude oil, however, unit trains have had less applicability for NGLs, in part because of the added cost and complexity of preparing shipments and the relative scarcity of pressure tank cars.

Tank Cars Used for Crude Oil, Ethanol, and NGLs

There are about 350,000 tank cars in the North American rail car fleet. Nearly all are owned by shippers or car-leasing companies. About two-thirds of the fleet is used to carry materials regulated by the U.S. Department of Transportation (U.S. DOT) and Transport Canada because they are flammable, corrosive, poisonous, or pose other hazards. Through the Federal Railroad Administration (FRA) and PHMSA, U.S. DOT sets the minimum design standards for the cars. Various design features are required to accommodate differences in the physical, chemical, and hazard characteristics of the materials shipped. The Association of American Railroads (AAR) Tank Car Committee assists in the development of detailed tank car design specifications that comply with U.S. DOT standards. AAR performs this supportive function in accordance with its traditional role in setting industry rules and standards for the interchange of equipment.

There are two basic types of tank cars: pressure and nonpressure. The former are used to transport gases compressed to a liquefied state.[19] The pressure designs that can be used for hauling unfractionated NGLs are the DOT-105 and the DOT-112 specifications; the latter is often referred to as a propane car.[20] The tanks in these pressure cars can hold about 34,000 gallons. Their safety features include a thermal insulation system, consisting of a fiber blanket wrapped around the tank held in place by a metal jacket; pressure-relief devices; steel head shields covering the tank ends to make them more resistant to punctures; and protective housings for valves and other fittings. There are about 50,000 DOT-105s and DOT-112s in the North American tank car fleet.

The most common nonpressure tank car is the DOT-111. It is used to carry many kinds of hazardous and nonhazardous liquids, including gasoline, diesel, caustic soda, molten sulfur, and sulfuric acid. It can hold about 30,000 gallons of flammable liquid. While the safety performance of

[18] Kelly Van Hull, "The Race Is On and It Looks Like ONEOK—Bakken NGLs Production Growth," *RBN Energy*, April 28, 2013, https://rbnenergy.com/the-race-is-on-and-it-looks-like-oneok-bakken-ngls-production-growth.

[19] National Research Council (U.S.), *Ensuring Railroad Tank Car Safety*, Special Report 243 (Washington, D.C.: National Academy Press, 1994). For more details on U.S. DOT tank car specifications, see *Ensuring Railroad Tank Car Safety*, which describes the varying design standards appropriate for cargo characteristics.

[20] The DOT-114 tank car design is also used for propane service.

these general-service tank cars when used in hazardous materials service has been questioned for years, their increased use in crude oil and ethanol unit trains has prompted new concerns and several modifications to the design standard, as discussed next. Not satisfied with these modifications, U.S. DOT created an entirely new design specification for tank cars transporting these flammable liquids in 2015.

The transition to a new tank car for transporting ethanol and crude oil began shortly after passage of RFS and as oil production from hydraulic fracturing began to grow. The first major modification was the introduction of the AAR Casualty Prevention Circular (CPC) 1232 upgrade to the DOT-111 design. In 2011, the AAR Tank Car Committee required that all new tank cars used for ethanol and crude oil meet the CPC-1232 standard, which added half-height head shields, top rollover protection, thicker tank steel, and bottom skid protection to the DOT-111. However, even as CPC-1232 tank cars began entering the fleet in larger numbers during 2012, ethanol and crude oil volumes had been escalating, creating more demand for the large fleet of older DOT-111s. Additionally, in March 2012, the National Transportation Safety Board (NTSB) recommended that all tank cars authorized for fuel ethanol and crude oil, not just new ones, be required to have enhanced puncture resistance and top fittings protection.

Yet, as accident experience with the new CPC-1232s grew, questions were raised about the adequacy of its protections, particularly its lack of a thermal protection system to withstand heat-induced tears when exposed to a liquid pool fire and its use of half-height head shields instead of full-height head shields. In response to these concerns, U.S. DOT introduced a new DOT-117 specification for tank cars carrying these flammable liquids. The design has a jacketed and thermally protected shell made of thicker steel, 0.5-inch-thick full-height head shields, larger-flow pressure relief devices, bottom outlet valve protection, and rollover protection for top fittings. All new tank cars constructed after October 1, 2015, are required to meet the new design standard (or an equivalent performance-based standard) to qualify for flammable liquids service. If they are to remain in crude oil and ethanol service, DOT-111s and CPC-1232s must be made compliant with a retrofit (DOT-117R) standard according to a phase-in schedule ending in 2025.

Trends in Rail Transportation of Crude Oil, Ethanol, and NGLs

Recent Trends in Rail Traffic

Figure 3-13 shows the number of carloads of crude oil and ethanol moved by rail from 2005 to 2015. The data show that crude oil was a minor component of railroad traffic before 2011. Indeed, from the 1980s to the mid-2000s, railroads carried only about 0.1 percent of all crude oil barrels

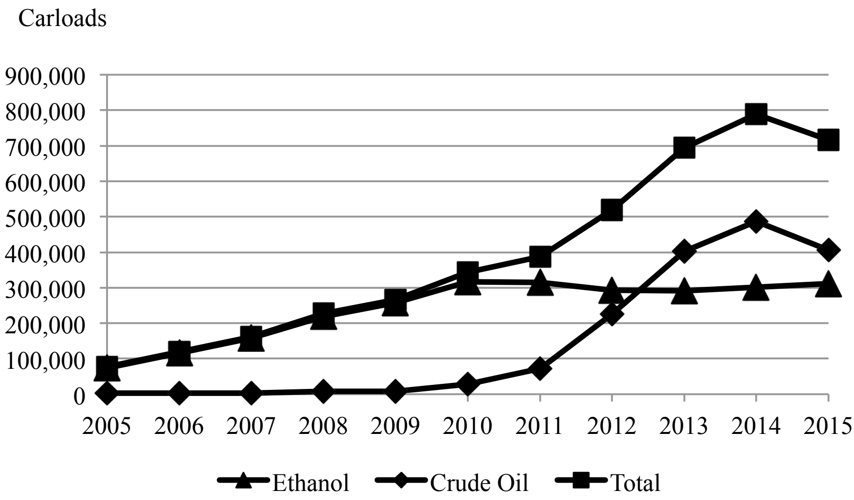

FIGURE 3-13 U.S. crude oil and ethanol rail carloads, 2005–2015.
NOTE: One carload equals approximately 700 barrels.
SOURCE: Association of American Railroads (AAR).

shipped each year within the United States.[21] Even in 2011, railroads accounted for less than 1 percent of domestic receipts of crude oil by U.S. refineries; it was not until 2014 that this share had increased to more than 4 percent.[22]

In the case of ethanol, rail traffic growth peaked in 2010 and has been flat since. As discussed in the previous chapter, the sharpest increase in ethanol production volumes occurred in response to changes in the federal RFS from 2005 to 2010. The amount of ethanol shipped by rail since 2010 has remained largely stable after the earlier years of rapid growth.[23]

Geography of the Traffic

The spread of crude oil and ethanol shipments through new regions of the country began shortly after 2005, when ethanol production began ramping

[21] Bureau of Transportation Statistics, "Table 1-55: Crude Oil and Petroleum Products Transported in the United States by Mode."

[22] U.S. Energy Information Administration, "U.S. Refinery Receipts of Crude Oil by Method of Transportation."

[23] Ethanol volumes are affected by gasoline demand. The amount of driving as measured in vehicle miles traveled (VMT) did not return to early 2008 levels until late 2014; http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/Performance-summary-report-12152014-v2.pdf, p. 4.

up to meet national demand spurred by RFS. Whereas ethanol had previously been produced in the Midwest for consumers in that region, by 2010 it was being transported throughout the country. Figure 3-14 shows how a substantial portion of the demand for ethanol is in the country's population centers, as nearly half of the ethanol produced in 2015 was transported from the Midwest to the East Coast. By and large, all of this traffic has moved in railroad tank cars over routes that accommodated much less flammable liquids traffic before 2005.

Likewise, in the case of crude oil, the volumes being produced from basins in Colorado, North Dakota, and Wyoming were being transported on rail routes originating in these states and headed to refineries and storage terminals in distant states that had previously received most of their crude oil by pipeline or tanker ship. Figure 3-15 shows the weekly number of crude oil trains originating from North Dakota in 2014, and how the predominant routes were oriented East to West, serving refineries on the Atlantic and Pacific Coasts.

The emergence of these new energy routes is evident by a review of the average length of haul of crude oil and ethanol rail traffic. As shown in Figure 3-16, the average distance traveled by crude oil shipments increased dramatically between 2007 and 2010, when North Dakota crude oil started to be transported in large volumes to coastal refineries. By comparison, the average length of haul of ethanol fuel remained relatively stable over the

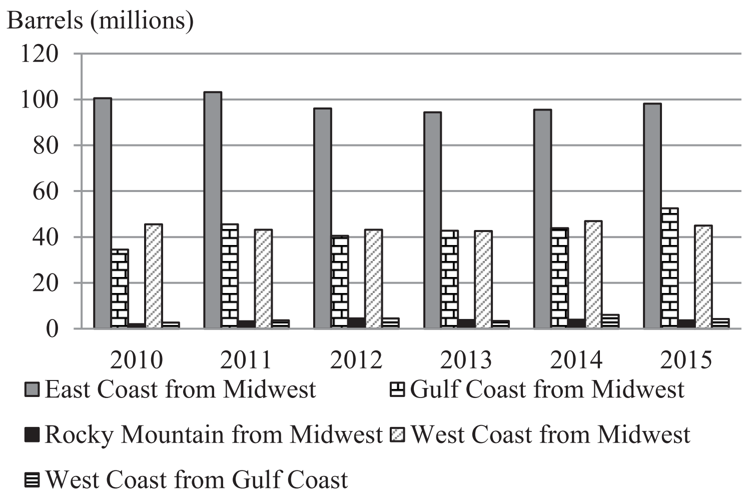

FIGURE 3-14 Volume of ethanol fuel transported by rail interregionally in the United States, 2010–2015.
SOURCE: EIA.

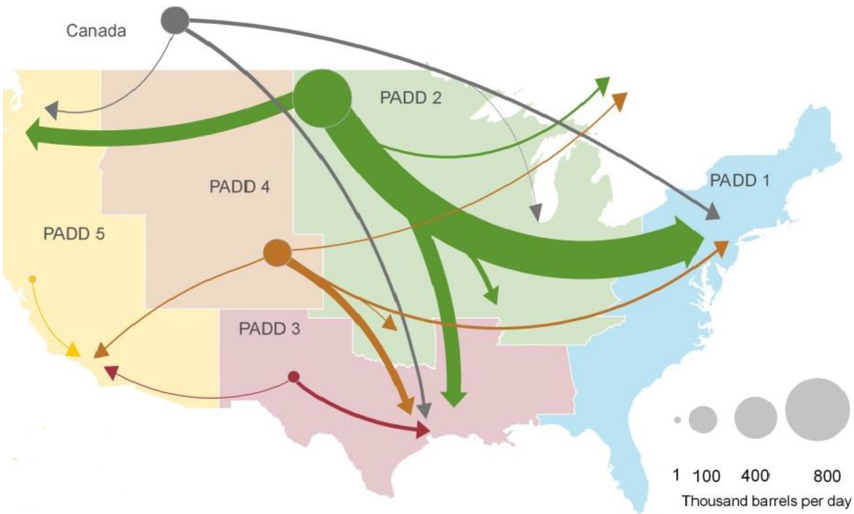

FIGURE 3-15 Location and volume of rail traffic of North Dakota Bakken crude oil (in green), 2014.
NOTE: PADD = Petroleum Administration for Defense District, the EIA term used in delineating U.S. regions.
SOURCE: EIA.

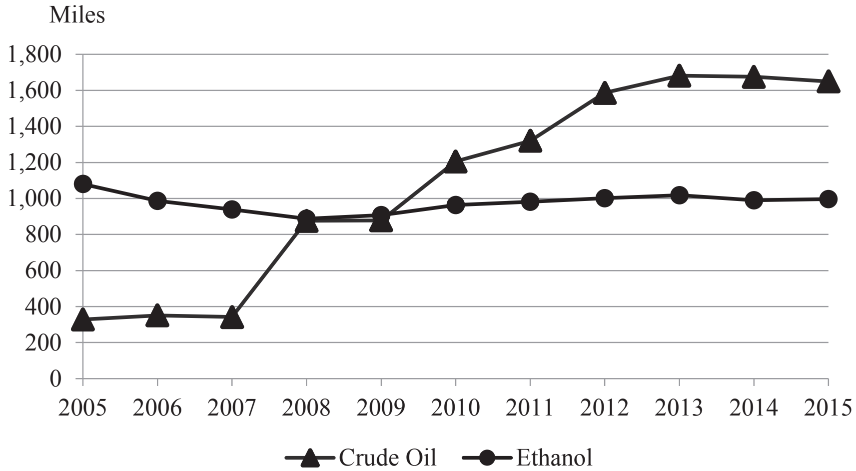

FIGURE 3-16 Average length of haul of crude oil and ethanol rail shipments in the United States, 2005–2015.
SOURCE: Federal Railroad Administration (FRA) review of Surface Transportation Board (STB) Waybill Sample.

period, reflecting the more geographically diverse destinations; that is, storage terminals and gasoline distribution centers located in all regions, many of which being equidistant from the Midwest.

As rail crude oil and ethanol volumes increased over the new routes, many more jurisdictions started experiencing new traffic flows. There are 3,108 counties in the contiguous United States. Figure 3-17 shows the number of counties that experienced crude oil and ethanol rail traffic each year from 2005 to 2015. In 2005, slightly fewer than 1,100 counties were exposed to this rail traffic, but by 2008 the number had increased to more than 1,800, largely because of increases in ethanol movements. This sharp increase can be explained by the growth in production in response to RFS and by the fact that ethanol moves to so many destinations (e.g., gasoline distribution centers nationwide), and mostly by rail when shipped long distances. The effect of increased crude oil traffic can also be seen in Figure 3-17. The largest growth in counties experiencing crude oil traffic occurred after 2010, when production from the Bakken fields and the counties of mudstone basins started to ramp up. In 2005, less than 3 percent of U.S. counties had experienced crude-by-rail traffic, but by 2013 this figure had grown to nearly 40 percent (see Figure 3-18).

Railroads carry a small fraction of the country's NGL traffic, most of which is moved by pipeline. There has been an increase in this traffic,

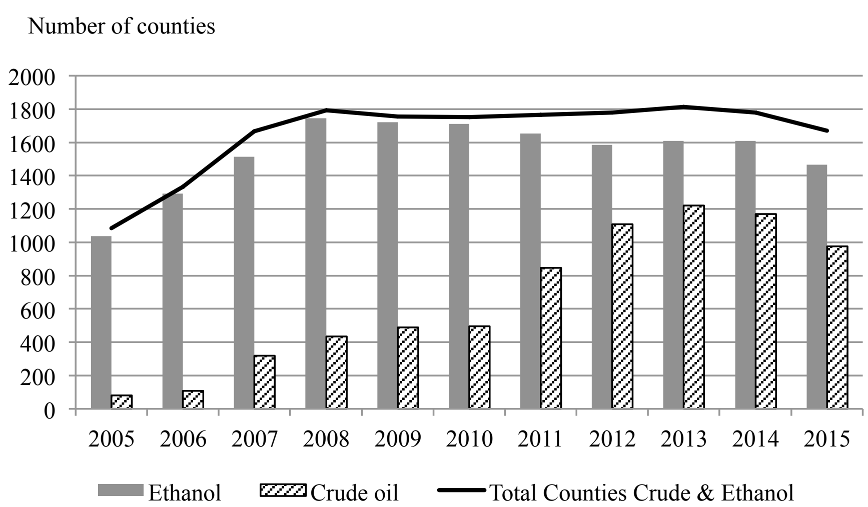

FIGURE 3-17 Total number of counties transited by crude oil and ethanol rail shipments in the United States, 2005–2015.
NOTE: There are 3,108 counties in the contiguous United States.
SOURCE: FRA analysis of STB Waybill Sample.

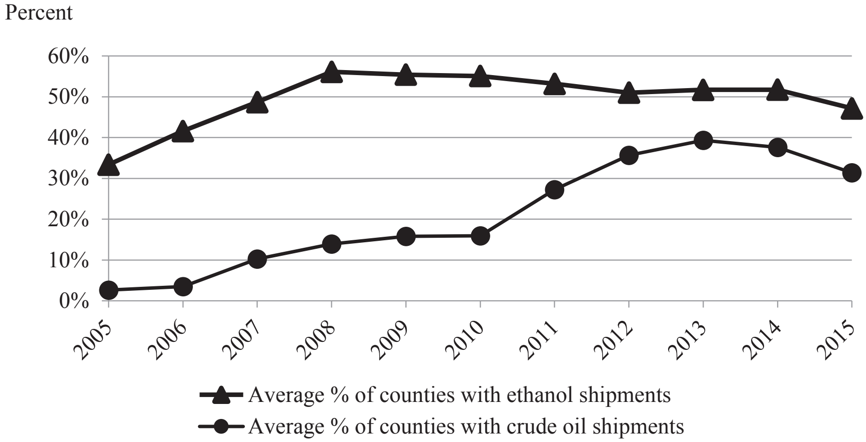

FIGURE 3-18 Average percentage of counties in each state with crude oil and ethanol shipments passing through by rail, 2005–2015.
SOURCE: FRA analysis of STB Waybill Sample data.

however, as shown in Figure 3-19.[24] It is difficult to know how much of this increase is a result of the movement of raw (unfractionated) NGLs because crude oil–derived liquefied petroleum gas (LPG) and propane have been carried by railroads in manifest service for decades.[25]

WATER TRANSPORTATION

Much of the bulk freight moved within the United States, and the vast majority moved in international commerce, uses the nation's marine transportation system.[26] The system is varied and immense. It consists of thousands of miles of navigable channels and hundreds of port complexes. Thousands of individual terminals are located along the nation's rivers, lakes, and coastal waterfronts, served by carriers operating a varied mix of vessels.

Background on the country's navigable waterways is provided next, followed by a closer look at how this transportation system is used to transport crude oil, ethanol, and NGLs. As with rail, waterborne movements of crude oil grew sharply as a result of the domestic energy revolution. This

[24] E. Russell Braziel, *The Domino Effect*, 2016, 176.

[25] Ibid., 95.

[26] National Research Council, *Funding and Managing the U.S. Inland Waterways System: What Policy Makers Need to Know*, Transportation Research Board Special Report 315 (Washington, D.C.: Transportation Research Board, 2015). The discussion in this section is informed by this report.

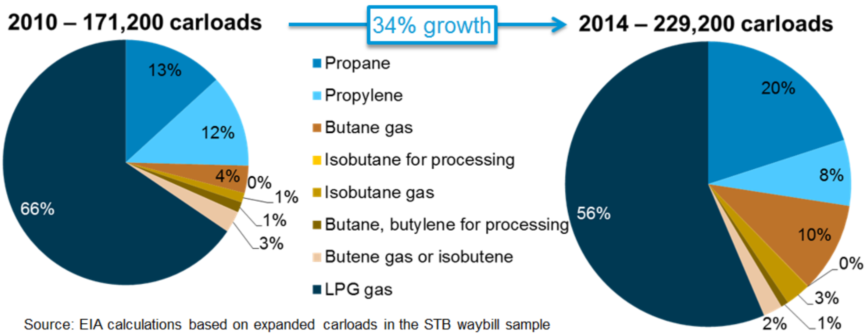

FIGURE 3-19 NGL rail carload traffic in the United States, 2010 and 2014.
SOURCE: Warren Wilczewski, "EIA's Forthcoming HGL-by-Rail Data: Approaches and Initial Findings," IHS 2016 International LPG Seminar, Houston, Texas, April 6, 2016.

traffic has declined in recent years for the many of same reasons it declined for rail.

Waterway System

Since the country's founding, the federal government has taken the lead in developing and maintaining the nation's navigable waterways. The U.S. Army Corps of Engineers (USACE) is the chief federal agency responsible for channel dredging and for building, maintaining, and operating the system of locks, dams, and other infrastructure to control water flows and channel depths. The inland and intracoastal waterways consist of some 36,000 miles of navigable river, lake, canal, and coastal channels, of which nearly 12,000 miles are active commercial routes (see Figure 3-20). Most of the system consists of shallow-draft river and canal channels with controlling depths of 7 to 12 feet. The coastal channels contain a combination of shallow- and deep-draft channels.

River Systems

By far the largest network of waterways in the United States is the Mississippi River System, which fans out across the interior of the country for more than 6,000 miles. The system encompasses navigable channels in more than one dozen tributaries—including the Arkansas, Illinois, Missouri, and Ohio Rivers—that pass through 17 states. Navigable from the Gulf Coast to as far north as Chicago, Minneapolis, and Pittsburgh, the Mississippi River System

FIGURE 3-20 U.S. inland and intracoastal waterways.
SOURCE: USACE Navigation Data Center GIS Viewer.

accounts for more than 80 percent of the length of the country's navigable river channels. Much of the system is made navigable by locks and dams. North of its confluence with the Ohio River, the 858-mile Upper Mississippi River contains 29 lock sites, while the 981-mile Ohio River contains 20, plus an additional 40 on its many tributaries and canals. While the 956-mile Lower Mississippi River does not have any locks, it requires USACE maintenance dredging and training.

The country's second longest river system is the 596-mile Columbia–Snake Rivers System, which originates in the Rocky Mountains and passes through the states of Idaho, Oregon, and Washington to the Pacific Ocean. The 10 locks on the Columbia River can lift barge tows as much as 110 feet.

Although this system and the Mississippi River System account for most of the country's "brown water" barge traffic, small amounts of freight are shipped on a number of other regional rivers, including the Delaware, Hudson, James, and Sacramento Rivers. While traditionally used for local movements of bulk materials, such as stone, cement, sand, and lumber, some of the ports on these smaller rivers have connections to railroads, which can expand their reach and the types of commodities shipped.

Coastal and Intracoastal Systems

Large oceangoing vessels operate regularly over what are technically domestic routes between the West Coast ports and Alaska and Hawaii.

When considering domestic coastwise shipping, however, the country's main "blue water" routes are located along the Gulf Coast. The Gulf Intracoastal Waterway is an interlinked network of canals, bayous, and river channels that runs about 1,100 miles from Texas to Florida, connecting with the Mississippi River north and south of New Orleans. By comparison, the 700-mile Atlantic Intracoastal Waterway, which consists of a series of channels on canals, bays, and sounds extending from Florida to Virginia, is used mainly for short-haul barge movements and by recreational boaters.

Great Lakes System

Consisting of seven waterways linked by a dozen lock sites, the Great Lakes channels accommodate freight moved lakewise within the region and seawise via connections with the St. Lawrence Seaway. The distance from Montreal, the head of deep-draft ocean navigation on the St. Lawrence River, to Duluth, at the western end of Lake Superior, is about 2,300 miles. The distance to Chicago, near the southern end of Lake Michigan, is about 2,250 miles. The system also accommodates some lake-to-river trade as small vessels and barges can travel from Lake Michigan to the Illinois River via the Chicago Sanitary and Ship Canal. While vessels can also access the Hudson River system from Lake Erie via the New York State Barge Canal (Erie Canal), vessel size restrictions preclude most commercial traffic.

Vessels Used for Crude Oil, Ethanol, and NGLs

Barges are the cargo-carrying vessels on the inland system. The U.S. inland waterways fleet comprises nearly 30,000 barges, including about 3,800 shallow-draft tank barges that carry liquids such as crude oil, refined products, and chemicals. These barges are usually flat bottomed and rectangular with cargo space below the deck. The tanks may be integrated into the hull or carried independently. Each barge can usually carry 10,000 to 30,000 barrels of liquid. Two or three of the larger barges (i.e., 20,000 to 30,000 barrel capacity) are often assembled together in a single "unit" tow, thus moving 20,000 to 90,000 barrels. In addition, smaller barges (i.e., 10,000 barrel capacity) are often integrated into larger barge flotillas (i.e., 15 to 40 barges) that carry both liquid and dry cargoes.

Because most refineries have waterside access, barges can bring crude oil supplies with existing water infrastructure, thereby precluding the need for investments in railroad offloading facilities and spur lines. In these cases, crude oil shipments originating on tank cars can be transloaded onto barges for the final leg of the journey to the refinery. As oil volumes from hydraulic fracturing started rising in 2011, the inland tank barge fleet grew by about 25 percent (see Figure 3-21). Because many of these new vessels had tanks

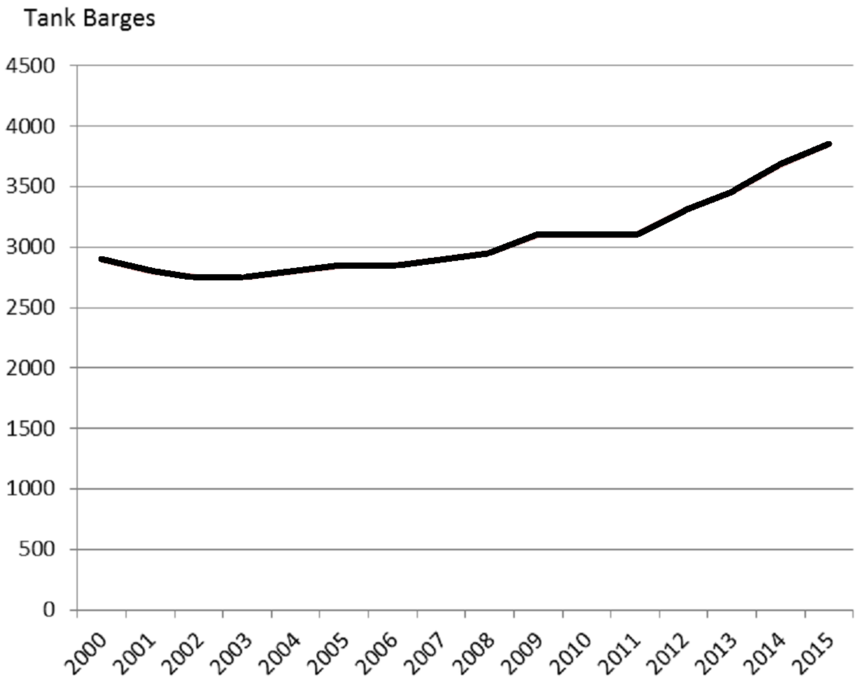

FIGURE 3-21 Tank barges in U.S. inland waterways fleet, 2000–2015.
SOURCE: Kirby Corporation, "Putting America's Waterways to Work," February 2017, 16, http://kirbycorp.com/wp-content/uploads/2017/02/Kirby-Corporation-Feb-2017-Roadshow-1.pdf.

capable of carrying 30,000 barrels, as opposed to the traditional 10,000 barrel tanks, total hauling capacity grew even more. Contrary to the situation with railroads, most of these tank barges are owned by the operators, as opposed to the shippers. There are more than 40 inland barge operators in the United States, but tank carriage is specialized. About 10 of the largest barge operators account for three-quarters of all inland tank barges.[27]

In the case of the coastwise barges, they are designed specifically for deeper-draft waters. The U.S. fleet comprises about 270 coastwise barges, each having a loading capacity of between 30,000 and 195,000 barrels. In addition, some tank barges can travel on open seas. About 100 articulated tank barges operate off U.S. coastal waters. They can hold as much as 340,000 barrels of oil. On some longer-distance intracoastal routes—such

[27] Kirby Corporation, "Putting America's Waterways to Work," February 2017, 20, http://kirbycorp.com/wp-content/uploads/2017/02/Kirby-Corporation-Feb-2017-Roadshow-1.pdf.

as between Baton Rouge and Tampa—self-propelled tank ships are used. There are about 30 of these vessels in the domestic fleet, each capable of carrying between 300,000 and 600,000 barrels.

The use of barges to transport ethanol is limited in part because of the small number of ethanol plants that have waterside access. Most of the ethanol movements made by water originate on the Upper Mississippi River system, typically transported in 10,000-barrel tank barges. In the case of raw NGLs, they can be transported in pressure tank barges used for LPG. These tank barges typically have a capacity of about 16,000 to 17,000 barrels.

Trends in Waterborne Transportation of Domestic Crude Oil, Ethanol, and NGLs

Recent Trends in Waterborne Traffic

Because they had long been used to transport crude oil, NGLs, and ethanol, the waterborne modes were accustomed to hauling flammable liquids when the domestic energy revolution commenced a decade ago. Data for 2005 to 2014 show that even before the growth in crude oil production from hydraulic fracturing, the waterways were handling large volumes of these commodities (see Figure 3-22). Those volumes began to increase sharply, however, after 2010 when crude production from hydraulic fracturing grew dramatically. Crude oil shipments increased by 84 percent from 2010 to 2014. By contrast, shipments of alcohols grew by 27 percent, as ethanol

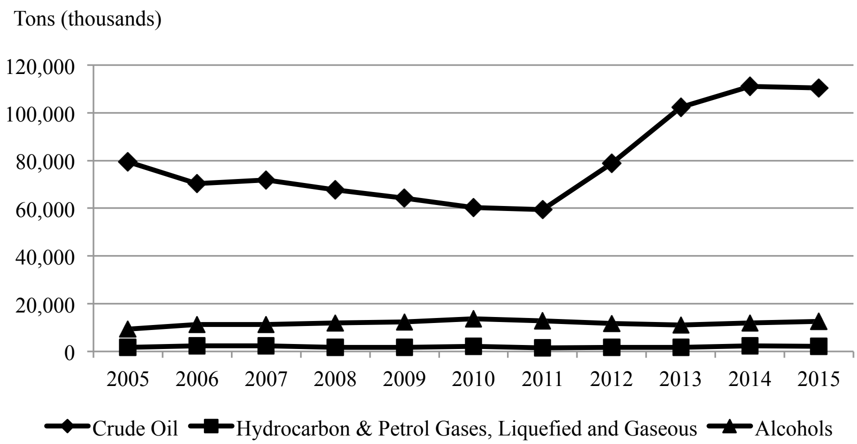

FIGURE 3-22 U.S. waterborne tonnage of crude oil, alcohols (including ethanol), NGLs, and other related commodities, 2005–2014.
SOURCE: U.S. Army Corps of Engineers (USACE).

shipments accounted for a much lower share of the mode's flammable liquids traffic for reasons given in Chapter 2.

Geography of the Traffic

From 2005 to 2011, coastal crude oil traffic was steadily declining. Demand for oil produced by hydraulic fracturing spurred new waterborne traffic, especially on inland waterways. The new crude oil fields generated new opportunities for inland barge movement because of their location in the country's interior. Barge shipments on the Mississippi River System increased because of the development of the Bakken fields in North Dakota. The main period of growth in inland waterways traffic occurred from 2010 to 2014. It was accompanied by a notable increase in oil tank barge traffic on the coastal waterways, reflecting the development of hydraulic fracturing fields in Texas and movements from the Gulf Coast to refineries in the Northeast (see Figure 3-23). As evidence of the growing use of tank barges, the share of U.S. refinery receipts of crude oil by barge increased from 2 to 7.5 percent from 2010 to 2013 (see Figure 3-24).

Although the petroleum traffic data for inland waterways do not distinguish crude oil shipments, between 2006 and 2015, southbound ton-miles of petroleum oil and products on the Mississippi River System increased by nearly 57 percent.[28] The same commodities shipped northbound on the system experienced a traffic drop of nearly 6 percent.

Between 2010 and 2014, domestic crude oil tons moved by water increased nearly fivefold (see Table 3-1). Most of the increase occurred on the Gulf Coast. Trends in waterborne crude oil traffic mirror those of railroads; however, as shown in Table 3-1, the percentage increase in rail traffic was much higher, in large part because rail carried very little crude oil before 2010.

In the case of NGLs, waterborne carriers have historically hauled these commodities from the Gulf Coast to the lower Atlantic Coast. Most of the traffic consists of purity products such as propane and butane. As shown in Figure 3-25, NGL shipments increased on the coastal waterways for a brief period in 2013, but declined in 2014, the last year of available data.

Ethanol waterborne shipments by waterway did not change dramatically during the past decade, as volumes are small (see Figure 3-26). As explained in Chapter 2, rail has been, and remains, the dominant mode for this traffic.

[28] U.S. Army Corps of Engineers, "Final Waterborne Commerce Statistics for Calendar Year 2015: Waterborne Commerce National Totals and Selected Inland Waterways for Multiple Years" (New Orleans, LA: Institute for Water Resources, U.S. Army Corps of Engineers, 2016), http://www.navigationdatacenter.us/wcsc/pdf/Final-wcsc.pdf.

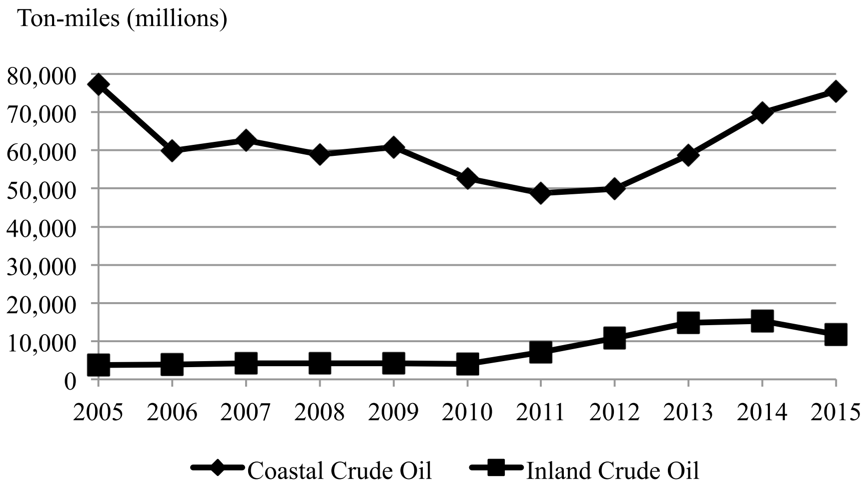

FIGURE 3-23 U.S. waterborne domestic ton-miles of crude oil by waterways type, 2005–2014.
SOURCE: USACE.

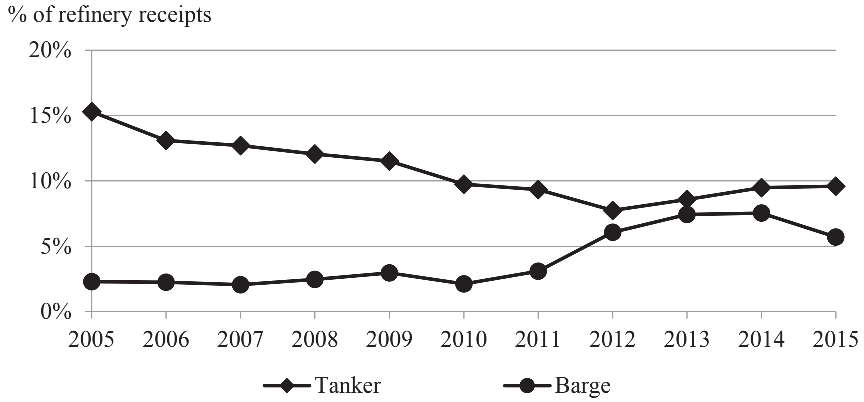

FIGURE 3-24 Percentage of U.S. refinery receipts of crude oil by waterborne vessel type, 2005–2015.
SOURCE: EIA.

TABLE 3-1 U.S. Domestic Waterborne Crude Oil Tonnage, Compared with Rail Tonnage, 2010–2014

Originating Area	2010	2011	2012	2013	2014
Gulf Coast	10.8	14.9	26.6	38.8	50.5
Mississippi River	0.9	3.4	5.7	10.1	7.3
East Coast	1.4	0.5	2.0	5.8	6.4
Total Maritime	13.1	18.8	34.3	54.7	64.2
Total Rail	2.8	6.2	21.8	39.2	48.1

SOURCE: AAR; USACE Waterborne Commerce Statistics Center data, processed via Channel Portfolio Tool.

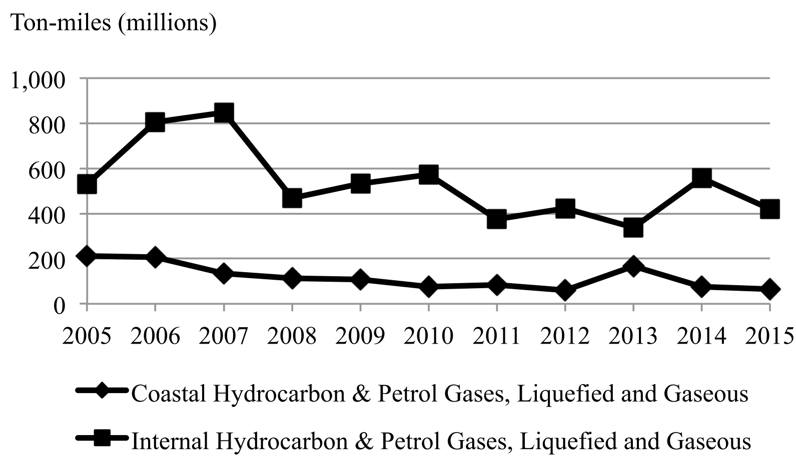

FIGURE 3-25 U.S. waterborne ton-miles of NGL and related traffic by waterway type, 2005–2014.
SOURCE: USACE.

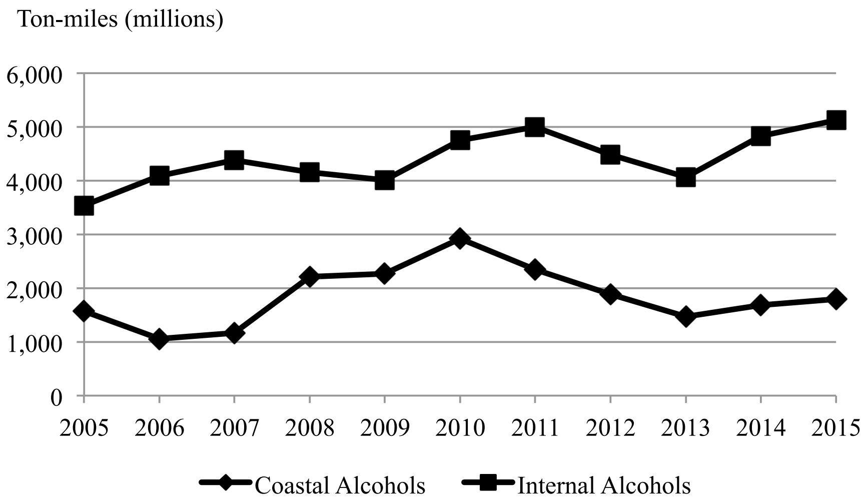

FIGURE 3-26 Ton-miles of alcohol, including ethanol, transported domestically by water by waterway type, 2005–2014.
SOURCE: USACE.

4

Safety Performance of Long-Distance Crude Oil, Natural Gas, and Ethanol Transportation

The transportation of energy liquids and gases is often described as a high-hazard activity, characterized by low-frequency, high-consequence events. An especially tragic example is the July 2013 Lac-Mégantic disaster, in which an unattended, runaway freight train crashed in the center of this rural town in eastern Quebec. Forty-seven people were killed, and 30 buildings were destroyed by explosions and fires fed by more than 1.5 million gallons (~36,000 barrels) of Bakken crude oil carried in the unit train's 63 derailed tank cars.[1] Pipeline and barge incidents have also had severe consequences. A July 2010 rupture of a corroded segment of transmission pipeline caused the release of nearly 850,000 gallons (~20,000 barrels) of viscous Canadian crude oil into a tributary of the Kalamazoo River in Marshall, Michigan, culminating in one of the largest and costliest inland oil spills in U.S. history.[2] In March 2014, a bulk vessel collided with a 300-foot tank barge in the Houston Ship Channel causing a discharge of some 170,000 gallons (4,250 barrels) of fuel oil that sullied about 13 miles

[1] Transportation Safety Board of Canada, "Lac-Mégantic Runaway Train and Derailment Investigation Summary," 2014, http://www.tsb.gc.ca/eng/rapports-reports/rail/2013/r13d0054/r13d0054-r-es.pdf.

[2] National Transportation Safety Board, "Enbridge Incorporated Hazardous Liquid Pipeline Rupture and Release, Marshall, Michigan, July 25, 2010." Accident Report NTSB/PAR-12/01 (Washington, D.C., July 10, 2012), https://ntsb.gov/investigations/AccidentReports/Pages/PAR1201.aspx.

of shoreline, endangered wildlife in several environmentally sensitive areas, and closed one of the country's busiest channels for several days.[3]

Preventing such tragedies is a major concern of industry, government regulators, and public safety officials; but so too is the prevention of smaller, less severe incidents because they can also be disruptive and costly to carriers, shippers, and communities. Smaller hazardous materials incidents may trigger a costly emergency response and be an indicator of safety risks not being properly managed. The long-haul bulk modes of freight transportation—rail, pipeline, and water—move large amounts of hazardous materials on a daily basis, mostly without incident. All have done so for decades, long before the post-2005 growth in domestic crude oil, ethanol, and natural gas production. Accordingly, industry and government have a history of cooperation in developing and improving systems intended to prevent hazardous materials incidents and to mitigate their consequences when they do occur. These systems consist of standards and procedures for the handling, labeling, and packaging of shipments; the design, fabrication, repair, and testing of containers; the operations and maintenance of equipment and infrastructure; and the identification and communication of shipment hazards and emergency response procedures. In addition, both industry and regulators monitor and investigate incidents, sponsor research and testing, and have outreach initiatives to inform carriers, shippers, and local authorities about safety standards and what to do in the event of a hazardous materials incident. Many large shippers and carriers maintain or hire specially trained emergency response teams and support industry-based mutual-aid networks that can assist in the response to hazardous materials incidents.

It is against this backdrop of a broad-based system for assuring the safety of hazardous cargoes that the safety implications and risks of transporting larger volumes of domestic crude, ethanol, and natural gas movements must be considered. In the case of rail, the robustness of the safety assurance system has been tested by the rapid growth in crude oil and ethanol shipments, which until 10 years ago had a negligible rail traffic footprint. By comparison, crude oil has long been transported in bulk on the waterways, and thus the nation's inland and coastal barge operators have considerable familiarity with the commodity's hazards, transportation risks, and potential emergency scenarios. Their safety assurance system was tested less by the introduction of an unfamiliar commodity and more by the large increase in oil volumes moving on waterways that are inherently sensitive to spills.

[3] National Transportation Safety Board, "Collision between Bulk Carrier Summer Wind and the Miss Susan Tow, Houston Ship Channel, Lower Galveston Bay, Texas," Accident Report NTSB/MAR-15/01 (Washington, D.C., March 22, 2014), https://www.ntsb.gov/investigations/AccidentReports/Pages/MAR1501.aspx.

The same commodity familiarity existed in the pipeline industry, in which carriers operate systems that are purpose-built to move hazardous liquids and gases over long distances, under high pressure and in high volumes. While the growth in production of domestic crude oil and natural gas has led to the construction of more pipeline capacity and to changes in the direction, commodity mix, and volumes of some transmission lines, the safety challenges arising from this energy liquids and gas traffic were by no means new to the industry. What has been new, however, is the expansion of oil and gas production to regions of the country that had limited pipeline capacity because they did not have a large production role historically.

This chapter reviews the safety records of each of the three long-distance modes when transporting crude oil, ethanol, and natural gas. Consideration is given to the number, severity, and causes of incidents reported to regulators over the past decade and to safety issues that have been identified during investigations of severe incidents. In the case of pipelines, incidents are reported to and investigated by the Pipeline and Hazardous Materials Safety Administration (PHMSA). PHMSA is the main federal agency responsible for overseeing the safe transportation of hazardous materials in all modes, not only pipelines. However, in the case of rail and water transportation, PHMSA shares hazardous materials safety oversight responsibility with the Federal Railroad Administration (FRA) and the U.S. Coast Guard (USCG), respectively. Incident data and incident investigation results from the three agencies are reviewed, along with relevant findings and recommendations from the National Transportation Safety Board (NTSB), which conducts detailed investigations of major hazardous materials incidents in all modes.

The chapter concludes with a review of major safety-related policies that have been put in place since the domestic energy revolution, particularly for rail transportation, which had not previously carried large quantities of oil or ethanol. The rapid and unanticipated increase in flammable liquids traffic moving over the nation's rail network caught some traversed communities, especially in rural areas, off guard and increased concern about their capacity to respond to a large-scale incident. Policy responses to these concerns, including changes in regulations and initiatives to strengthen state and local emergency response preparations, are discussed.

PIPELINE SAFETY TRENDS

Crude Oil Pipelines

PHMSA requires hazardous liquid pipeline operators to report unintended releases that meet certain significance thresholds based on release quantity and impact severity. Specifically, operators must report any unintended release that involves 5 gallons or more and/or an explosion, fire, serious injury, or significant (i.e., $50,000 or more) property loss and cleanup costs.[4] Releases from any component of the pipeline facility, including line pipe, tanks, valves, manifolds, and pumps, must be reported. The operator must report the proximate cause and the consequences of the incident.[5]

Figure 4-1 shows the number of incidents of reported crude oil releases from 2005 to 2015. From 2005 until 2011, the number was consistently between 143 and 166 per year. After 2011, incidents increased steadily, up by nearly 50 percent when comparing 2015 to 2005. However, aggregate release volumes have fluctuated widely from year to year, with a downward secular trend. Because of Hurricane Katrina, release volumes in 2005 reached a record 100,000 barrels, including nearly 50,000 barrels spilled in the aftermath of the storm. The 2011–2015 period coincided with the build out of the pipeline network to accommodate the increasing volumes of crude oil produced by hydraulic fracturing as well as Canadian imports. As discussed in the previous chapter, the crude oil pipeline network grew by 54 percent from 2005 to 2015. Accordingly, when controlling for the increase in total system miles, the incident rate normalized by pipeline miles (i.e., releases per pipeline mile) remained steady over the decade.

Because major releases are a primary concern, and small releases can distort the safety picture, PHMSA distinguishes "significant" releases as those that involve an explosion, fire, serious injury, or significant property damage and/or when 50 gallons or more of crude oil is released or 5 gallons or more is released into water. If one focuses on these incidents—that is, those that have accounted for more than 98 percent of released quantities—the upward trend in reported incidents persists (see Figure 4-2). However, when normalizing for traffic volume (i.e., barrel-miles), the increase in significant incidents after 2010 appears to be less pronounced and the volume of transported crude oil released has declined, as shown in Figure 4-3.

PHMSA data on the proximate cause of incidents suggest that a reason for the recent annual increase in incidents is more operator reports of equipment failures. Until 2009, corrosion had been the main cause of releases. However, during 2010 to 2015, corrosion-related releases remained fairly steady, as did most other causes (see Figure 4-4). A notable exception was equipment-related releases, which overtook corrosion as the main cause of incidents after 2012. According to PHMSA, equipment failures usually result in a release that is contained on company property, rarely causing

[4] 49 CFR 195.50.

[5] The PHMSA incident database is publicly accessible online at https://www.phmsa.dot.gov/pipeline/library/data-stats/pipelineincidenttrends.

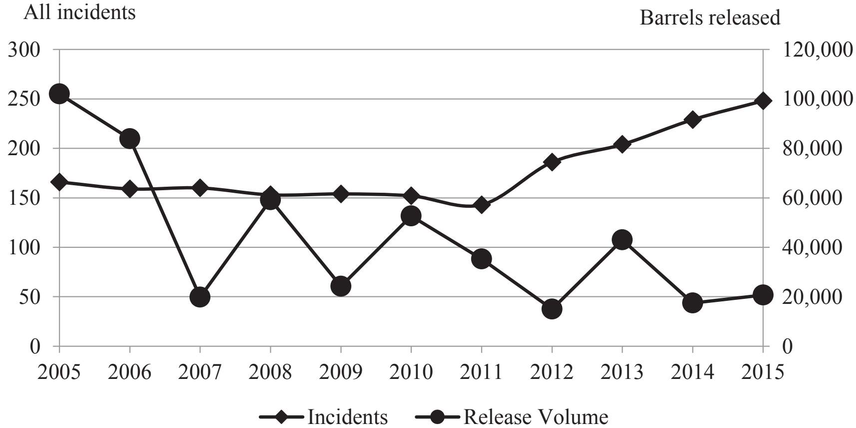

FIGURE 4-1 Crude oil pipeline releases reported to PHMSA in the United States, 2005–2015.
SOURCE: PHMSA, "Pipeline Incident Flagged Files," accessed November 23, 2016, http://www.phmsa.dot.gov/pipeline/library/data-stats/flagged-data-files.

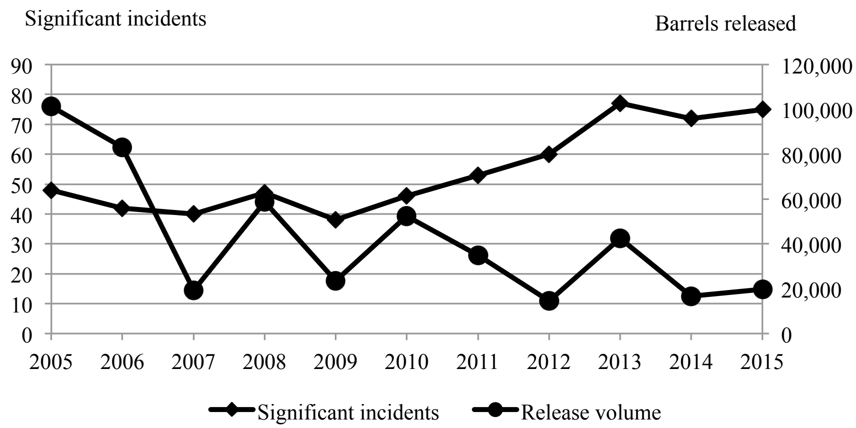

FIGURE 4-2 Significant crude oil pipeline releases reported to PHMSA in the United States, 2005–2015.
SOURCE: PHMSA, "Pipeline Incident Flagged Files," accessed November 23, 2016, http://www.phmsa.dot.gov/pipeline/library/data-stats/flagged-data-files.

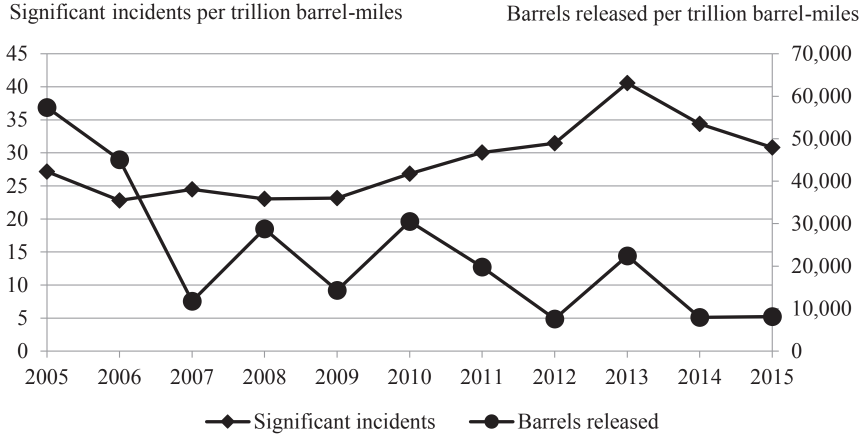

FIGURE 4-3 Significant incidents and release volumes per trillion barrel-miles of crude oil transported in the United States, 2005–2015.
SOURCE: PHMSA, "Pipeline Incident Flagged Files," accessed November 23, 2016, http://www.phmsa.dot.gov/pipeline/library/data-stats/flagged-data-files.

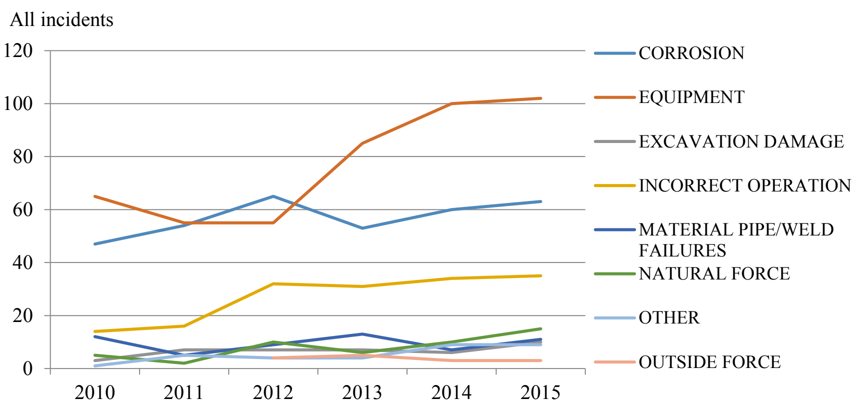

FIGURE 4-4 Crude oil pipeline incidents by reported cause in the United States, 2010–2015.
NOTE: For causes that rely on specialized terminology, the following definitions apply: "equipment" indicates a failure of control systems or relief equipment; "incorrect operation" means operator error; "natural force" refers to damage stemming from naturally occurring phenomena, for instance, earthquakes and floods; and "outside force" indicates damage from human actions other than excavation, such as accidental vehicle collision and earth-moving activity.
SOURCE: PHMSA.

injury or significant damage.[6] Common equipment-related incidents are small releases from faulty seals and gaskets or storage tanks overfilling as a result of meters malfunctioning. The increase in reports of equipment failures explains the seemingly contrary trends of more total incidents but lower total release volumes.

Another important reason for inconsistencies in annual release numbers and total release quantities is that one or two very large incidents can have a disproportionate influence on release totals. This influence is evident in 2010, when more than half of the 52,000 barrels of crude oil was released from two incidents: a 20,000-barrel release in Marshall, Michigan, and 7,500-barrel release in Romeoville, Illinois. Likewise, in 2008, 31,000 of the more than 59,000 barrels of crude oil spilled that year were from a single pipeline release in Denver City, Texas. More discussion is given to such severe incidents later in the section on pipelines.

As might be expected, states with the most pipeline mileage are most likely to experience a release; indeed, California, Oklahoma, and Texas are the most frequent locations for significant incidents, as shown in Figure 4-5. It is notable that several states that have experienced some of the largest gains in crude oil pipeline mileage since the start of the domestic energy revolution are now among states experiencing the most incidents. Three of the top five states in added crude oil pipeline mileage are New Mexico, North Dakota, and Wyoming (see Table 4-1). They are now among the top 10 states in significant releases reported since 2010 (see Figure 4-5).

As industry met the growing demand for additional transmission pipeline infrastructure, for crude oil and the other petroleum liquid and gas commodities, PHMSA inspections began registering critical problems with pipeline quality. During the 2008 and 2009 construction seasons, its inspectors observed new pipelines failing in field pressure tests and from welds,[7] as well as substandard metallurgical properties in pipe materials that exhibited significant weakness.[8] The regulator issued advisory bulletins on these findings and held workshops in which the public, industry, and other

[6] Pipeline and Hazardous Materials Safety Administration, "Fact Sheet: Stakeholder Communications—Equipment Failure," accessed September 19, 2017, https://primis.phmsa.dot.gov/comm/FactSheets/FSEquipmentFailure.htm.

[7] Pipeline and Hazardous Materials Safety Administration, "Pipeline Safety: Girth Weld Quality Issues Due to Improper Transitioning, Misalignment, and Welding Practices of Large Diameter Line Pipe (ABD-10-03)," *PHMSA-Advisory Bulletins*, March 24, 2010, https://www.gpo.gov/fdsys/pkg/FR-2010-03-24/html/2010-6528.htm.

[8] Pipeline and Hazardous Materials Safety Administration, "Pipeline Safety: Potential Low and Variable Yield and Tensile Strength and Chemical Composition Properties in High Strength Line Pipe (ABD-09-01)," *PHMSA-Advisory Bulletins*, May 21, 2009, https://www.gpo.gov/fdsys/pkg/FR-2009-05-21/html/E9-11815.htm.

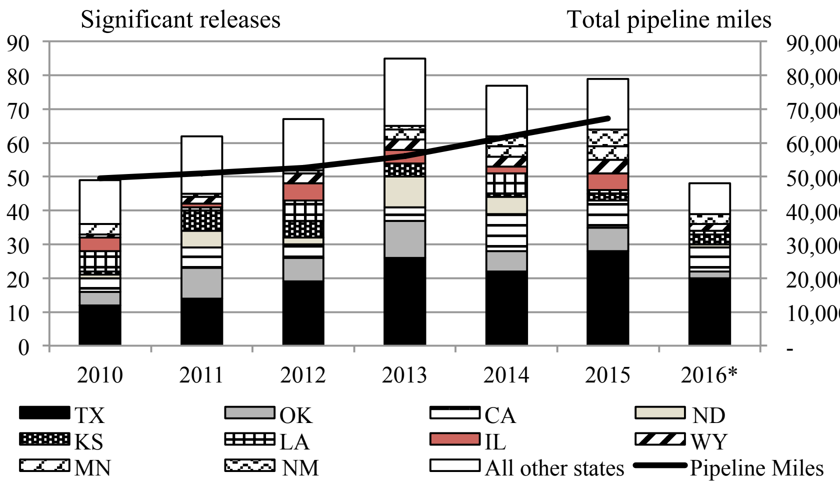

FIGURE 4-5 Reports of significant releases of crude oil from pipelines by state, 2010–2016.

* Incident reports filed as of September 14, 2016. Mileage data were not available for 2016.

SOURCES: PHMSA, "Pipeline Incident Flagged Files." PHMSA, "Pipeline Miles and Facilities 2010+."

TABLE 4-1 Top Five States with Most New Miles of Crude Oil Pipelines, 2010–2015

State	Pipeline Miles Added, 2010–2015	Percentage Increase in Mileage in Each State	Percentage Share of All New Pipeline Miles Added in United States
Texas	8,138	64%	44%
Oklahoma	2,801	78%	15%
North Dakota	1,535	101%	8%
Wyoming	842	25%	5%
New Mexico	591	52%	3%
Subtotal	13,906	NA	75%
U.S. Total	18,451	NA	100%

SOURCE: PHMSA, "Pipeline Miles and Facilities 2010+."

regulatory partners could learn about the issues and find solutions.[9] Efforts jointly made by the regulator and the industry to assure safety early in the pipeline lifecycle are intended to mitigate the risk of threats to integrity management that can worsen over time.

It is important to emphasize, however, that severe pipeline incidents are low-frequency events that occur most often because of time-dependent mechanisms such as corrosion and stress cracking. It is questionable, therefore, that the pipeline system would experience an increase in the occurrence of time-dependent failures because of new pipeline capacity added during the past decade. New crude oil pipelines will undoubtedly suffer eventually from some of the same failure mechanisms observed in the mature system. More pipeline miles—and thus more exposure—can be expected to increase the number of pipeline failures, all else being equal. At the same time, however, the mature, national system contains tens of thousands of miles of pre-1970 pipelines.[10] The newer pipelines built to accommodate oil produced by hydraulic fracturing will have the benefit of more advanced materials and construction techniques, state-of-the-art corrosion protections such as fusion-bonded epoxy coatings, and components and designs that enable faster leak detection and easier cleaning, nonintrusive monitoring, and internal inspections.

Given the superior technology, the safety performance of the new pipelines may be substantially better than that of the existing system. Of course, these pipelines connect with legacy trunklines, some of which had previously carried crude oil from the Gulf Coast to the Midwest but have since had their flow directions reversed. In some cases, the pipelines may have been repurposed to carry crude oil after carrying other products, including gas. Accordingly, the challenge that persists is ensuring that the mature pipeline network, much of it decades old, continues to perform safely, irrespective of whether it is used to carry product originating in the new oil- and gas-producing regions or elsewhere. Inasmuch as changes in the amount of product carried or in the flow direction of a pipeline can require modifications to components such as valves and pumps and create new pressure profiles and stress demands, there remains the possibility of risks being introduced into the legacy network because of the increase in oil production from hydraulic fracturing. PHMSA has issued guidance to op-

[9] Pipeline and Hazardous Materials Safety Administration, "Pipeline Construction," *Pipeline Technical Resources*, https://primis.phmsa.dot.gov/construction.

[10] Pipeline and Hazardous Materials Safety Administration, "The State of the National Pipeline Infrastructure," 7, accessed September 19, 2017, https://opsweb.phmsa.dot.gov/pipelineforum docs/Secretarys%20Infrastructure%20Report_Revised%20per%20PHC_103111.pdf. According to PHMSA data from 2010, more than half of the mileage on the hazardous liquids pipeline network was built before 1970; https://opsweb.phmsa.dot.gov/pipelineforum/docs/Secretarys%20Infrastructure%20Report_Revised%20per%20PHC_103111.pdf.

erators for avoiding and controlling such risks, which may not be detected in incident data for many years.[11] While PHMSA has begun to track these reversals and conversions, its pipeline incident database omits information on whether incidents involved pipelines that had been converted from carrying other products or had their flow reversed.

NGL Pipelines

Inasmuch as the hydraulic fracturing revolution has led to more natural gas liquid (NGL) shipments, the challenge for industry and regulators is to ensure that the new and existing pipelines operate safely. There is no practical and economic alternative to moving highly volatile NGLs in bulk quantities by means other than pipeline. Notably, unlike crude oil, ethane must be moved by pipeline because of its high-pressure requirements. Accordingly, the barrel volumes in an unintentional release can be quite large because the escaping liquids are quickly volatilized. NGL products can pose a risk of flammability and asphyxiation, and a large pressurized release may ignite and result in a highly energetic explosion and fireball.

Figure 4-6 shows the trend in significant NGL pipeline releases reported to PHMSA from 2005 to 2015. As with crude oil, there has been a slight upward trend in incidents since 2005, but with substantial year-to-year variability both in incidents and in total release volumes. This same pattern of year-to-year variability is evident when controlling for traffic volumes (see Figure 4-7). Based on these early incident data at least, there is no indication that the growing volumes of NGLs moved by pipeline have created a new safety risk. As noted above, however, the factors that can cause incidents, including corrosion, can be time-dependent, complicating efforts to assess safety performance over a relatively short period.

Natural Gas Pipelines

As discussed in Chapter 3, natural gas is a much more homogeneous and fungible commodity than crude oil and NGLs. In this sense, once natural gas enters the transmission system it integrates with other natural gas produced domestically, making it impractical to distinguish between gas shipments originating in the new producing regions versus other production areas.

The annual number of significant natural gas releases fluctuated between 40 and 60 per year from 2005 to 2015 (see Figure 4-8). After 2010, PHMSA began to track release volumes. From 2010 to 2015, there was a

[11] Pipeline and Hazardous Materials Safety Administration, "Guidance for Pipeline Flow Reversals, Product Changes, and Conversion to Service," September 2014, http://www.occeweb.com/PLS/2014Gas/Guide-Flo%20Rev-Prod%20Ch-Conver.pdf.

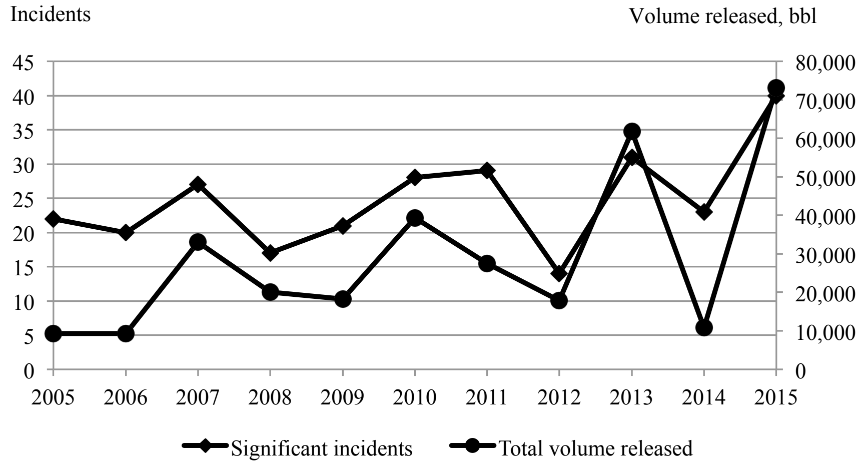

FIGURE 4-6 Significant NGL pipeline releases reported to PHMSA in the United States, 2005–2015.
NOTE: Data are from PHMSA's highly volatile liquids (HVL) incident files but exclude ammonia, refined products, and carbon dioxide pipelines.
SOURCE: PHMSA, "Pipeline Incident Flagged Files."

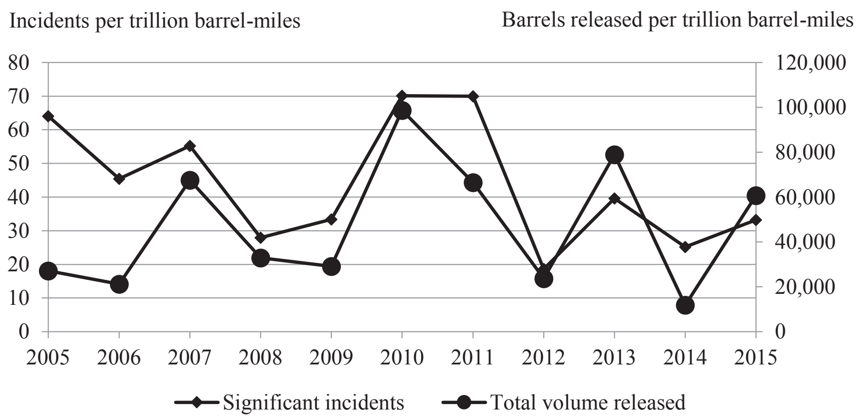

FIGURE 4-7 Significant incidents and release volumes per trillion barrel miles of NGLs transported in the United States, 2005–2015.
NOTE: Data are from PHMSA's highly volatile liquids (HVL) incident files but exclude ammonia, refined products, and carbon dioxide pipelines.
SOURCE: PHMSA, "Pipeline Incident Flagged Files."

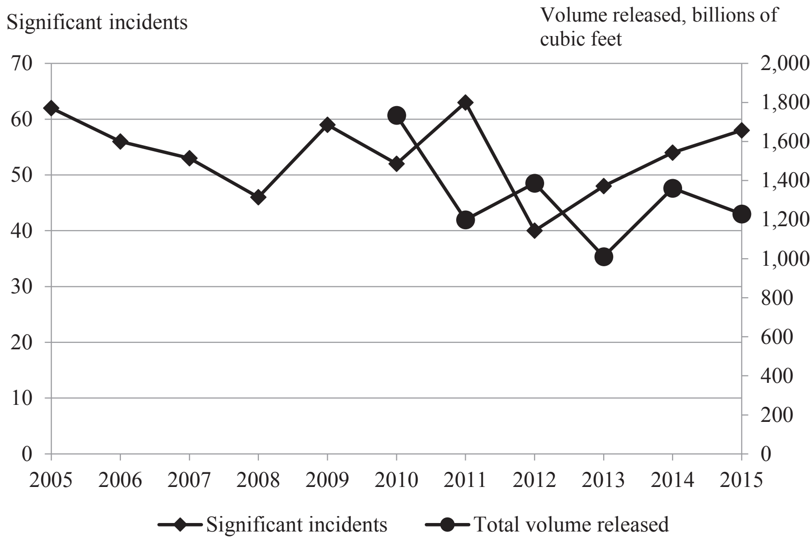

FIGURE 4-8 Significant natural gas pipeline releases reported to PHMSA in the United States, 2005–2015.
NOTE: Natural gas volumes released were not recorded before 2010.
SOURCE: PHMSA, "Pipeline Incident Flagged Files."

consistent decline in the total amount of gas released in incidents. However, when normalized for shipment volumes, there appears to have been a steady increase in the incident rate (see Figure 4-9), which can be attributed in part to a decline in the amount of natural gas shipments during that period, as discussed earlier in Chapter 3. As discussed in the next section, several large releases contributed to this pattern. For example, two incidents in Colorado and one in Texas during 2010 led to the release of more than 770,000 cubic feet of gas, and two incidents in California and Florida during 2012 led to the release of about 880,000 cubic feet.[12]

Notable Major Pipeline Incidents

Table 4-2 lists incidents of major pipeline releases involving crude oil, NGLs, and natural gas from 2010 to 2015. In addition to large release volumes, the consequences of some of these incidents include loss of life, injuries, evacuations, environmental harm, and property damage. Reported

[12] Pipeline and Hazardous Materials Safety Administration, "Pipeline Incident Flagged Files." Data are from PHMSA's HVL incident files but exclude ammonia, refined products, and carbon dioxide pipelines.

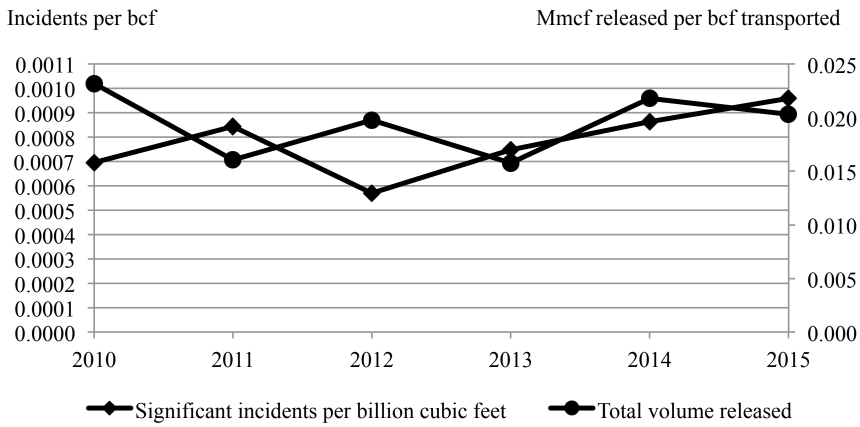

FIGURE 4-9 Significant natural gas pipeline incidents and volumes released per billion cubic feet reported to PHMSA in the United States, 2010–2015.
NOTES: Natural gas release volumes were not recorded before 2010. Normalized according to natural gas traffic volumes reported by EIA. Bcf = billions of cubic feet; mmcf = millions of cubic feet.
SOURCE: EIA, "U.S. International and Interstate Movements of Natural Gas by State," accessed November 8, 2016, http://www.eia.gov/dnav/ng/ng_move_ist_a2dcu_nus_a.htm.

proximate causes vary, but include corrosion damage, excavation damage aided by a lack of pipeline markers, and poor performance of supervisory control systems to detect and contain leaks. Many of the incidents were investigated by NTSB. In the case of the 2010 San Bruno natural gas transmission pipeline explosion, in which 8 people died and 108 homes were destroyed or damaged, NTSB concluded that the pipeline operator had not properly followed its integrity management program, as required by regulation.[13] The agency raised similar concerns after investigating the 2012 natural gas pipeline incident in Sissonville, West Virginia. The 2010 Marshall, Michigan, crude oil release was found to have been caused by corrosion fatigue cracking and made worse by the pipeline operator continuing to pump product through the ruptured line after misinterpreting pressure loss data.[14]

[13] National Transportation Safety Board, "Pacific Gas and Electric Company Natural Gas Transmission Pipeline Rupture and Fire," August 30, 2011, http://ntsb.gov/investigations/AccidentReports/Pages/PAR1101.aspx.

[14] National Transportation Safety Board, "Enbridge Incorporated Hazardous Liquid Pipeline Rupture and Release," July 10, 2012, http://ntsb.gov/investigations/AccidentReports/Pages/PAR1201.aspx.

TABLE 4-2 U.S. Crude Oil, Natural Gas, and NGL Pipeline Incidents with Severe Consequences, 2010–2015

Location	Month/Year	Product	Volume (liquids = bbl; gas = mcf)	Fatality	Injury	Fire	Evacuation	Environmental/ Property Damage
Cleburne, TX	6/2010	Natural Gas	172,000	1	6	Y	N	Y
Eagle County, CO	6/2010	Natural Gas	250,000	N	N	N	Y	N
Sealy, TX	7/2010	Natural Gas	208,458	N	1	Y	Y	Y
San Bruno, CA	9/2010	Natural Gas	47,600	8	51	Y	Y	Y
Arvin, CA	5/2012	Natural Gas	585,457	N	N	N	N	Y
Sissonville, WV	12/2012	Natural Gas	76,000	N	N	Y	Y	Y
Kit Carson, CO	12/2012	Natural Gas	313,870	N	N	N	N	N
Melbourne, FL	12/2012	Natural Gas	293,976	N	N	N	N	Y
Pond Creek, OK	2/2010	NGL	13,718	N	N	N	Y	Y
Latan, OK	2/2010	NGL	12,836	N	N	Y	N	N
Lafourche, LA	2/2013	NGL	23,702	1	N	Y	N	N
Erie, IL	8/2013	NGL	18,400	N	N	Y	Y	Y
Littleton, WV	8/2013	NGL	11,405	N	N	N	N	N
Colliers, WV	1/2015	NGL	30,565	N	N	Y	Y	Y
Jackson County, TX	1/2015	NGL	27,123	N	N	N	N	Y
Marshall, MI	7/2010	Crude Oil	20,082	N	N	N	Y	Y
Romeoville, IL	9/2010	Crude Oil	6,430	N	N	N	Y	Y
Levelland, TX	10/2010	Crude Oil	10,200	N	N	N	N	N
Iola, TX	1/2011	Crude Oil	6,911	N	N	N	N	Y
Chico, TX	6/2011	Crude Oil	12,229	N	N	N	N	N
Magnolia, AR	3/2013	Crude Oil	5,600	N	N	N	N	Y
Mountrail County, ND	9/2013	Crude Oil	20,600	N	N	N	N	Y
Mooringsport, LA	10/2014	Crude Oil	4,509	N	N	N	Y	Y

SOURCE: PHMSA, "Pipeline Incident Flagged Files."

PHMSA has sought to improve the ways that pipeline operators implement requirements for integrity management programs to prevent incidents like these. As early as 2002 when it first expanded the scope of its integrity management program regulations,[15] and again in 2016,[16] the agency has articulated the importance of continuous improvement in the risk modeling and the risk-assessment capabilities of operators. In observing a lack of progress by industry in the development of these capabilities, PHMSA proposed regulations in 2016 that would prescribe several functional goals that risk assessments should be able to achieve, including validation of risk models with historical information and the identification of interactive threats (i.e., when multiple concurrent threats act on one another) and uncertainty in the models and data.[17] To further encourage industry to make improvements along these lines, PHMSA has convened events to share best practices for risk modeling and assessment and sponsored research to provide technical assistance to the industry. The agency held a forum in 2011 on improving pipeline risk assessments and a workshop on risk-modeling methodologies in 2015.[18] It published three reports in 2016 and 2017 on pipeline risk model guidelines based on the probabilistic quantitative risk analysis approach, a risk management literature review and industry survey of risk management decision making, and a review of approaches to implementing risk-modeling and integrity-management programs.[19]

RAIL SAFETY TRENDS

Federal regulations governing hazardous materials transportation require that certain types of hazardous materials incidents be reported by the carrier to PHMSA.[20] A report must be filed if there is an unintentional release during any transportation phase, including loading and unloading, and/or a

[15] Pipeline and Hazardous Materials Safety Administration, "Pipeline Safety: Pipeline Integrity Management in High-Consequence Areas (Hazardous Liquid Operators with Less Than 500 Miles of Pipelines)," 67 FR 2136 (2002), 2143, https://primis.phmsa.dot.gov/iim/docsr/smallIMPrulefinal.pdf.

[16] Pipeline and Hazardous Materials Safety Administration, "Pipeline Safety: Safety of Gas Transmission and Gathering Pipelines," 81 FR 20722 (2016), 20763–64, https://www.regulations.gov/contentStreamer?documentId=PHMSA-2011-0023-0118&disposition=attachment&contentType=pdf.

[17] Ibid.

[18] Pipeline and Hazardous Materials Safety Administration, "PHMSA Meeting Registration and Document Commenting," *PHMSA Public Meetings and Documents*, https://primis.phmsa.dot.gov/meetings.

[19] Pipeline and Hazardous Materials Safety Administration, "Final Reports," *Research and Development Program*, https://primis.phmsa.dot.gov/matrix/FinalReports.rdm.

[20] 49 CFR 171 Subpart B—Incident Reporting, Notification, BOE Approvals and Authorization.

tank car that contains any amount of hazardous materials suffers structural damage regardless of whether there was a release. Accordingly, PHMSA's incident data files should contain records of all instances in which tank cars carrying crude oil and ethanol have experienced unintentional releases and/or been damaged during a crash, such as a derailment or yard collision. The reports contain, among other things, the quantity released, the component of the tank car that failed (e.g., tank shell, valve, bottom outlet), cause of the failure (e.g., derailment, unsecured closure, faulty fitting), tank car design type, speed of the train or car being moved, and the consequences (e.g., fire, evacuation, injuries, property damage). Incidents with serious consequences will usually be investigated by the Federal Railroad Association (FRA) and in some cases by NTSB in more detail.

Figures 4-10 and 4-11 show the total number of incidents involving tank car shipments of crude oil and ethanol reported from 2005 to 2015. Ethanol shipments were involved in 968 total incidents and crude oil shipments in 448. This sizable difference in incidents by commodity type is at least partially attributable to the fact that ethanol has been transported in large volumes by rail since about 2006, compared with crude oil's emergence as a major rail traffic segment after 2010. In both cases, however, the large majority of reported incidents is small releases caused by improperly secured closures or component failures such as a deteriorated gasket or pressure seal. They are usually detected during inspection while a tank is stationary on a siding or at a rail yard. Most involve vapor quantities or fractions of a gallon. For example, of the 427 reports of crude oil releases from stationary tanks cars, 209 had leaks of less than 1 gallon.

Even small leaks from a stationary tank car at a siding or a yard can incur costs, such as service disruptions while the car is being isolated and the leak contained. The focus here, however, is on the approximately 5 percent of incidents that occur when a tank car is damaged while moving, usually because of a derailment or a yard collision (e.g., during coupling). These incidents tend to involve larger releases and more severe consequences. From 2005 to 2015, there were 58 such incidents involving ethanol shipments and 21 involving crude oil shipments (see Figures 4-12 and 4-13 and Tables 4-3 and 4-4). These 79 incidents accounted for most of the product lost and all severe consequences such as fires, evacuations, and injuries. The 21 crude oil incidents accounted for more than 98 percent of the total 1.7 million gallons (40,400 barrels) of crude oil released unintentionally from tank cars during the period. Likewise, the 58 ethanol incidents accounted for more than 93 percent of the 2.8 million gallons (66,900 barrels) of ethanol released.

The relatively small number of incidents makes it difficult to glean patterns, such as their geographic distribution. It is notable, however, that more than half of the contiguous United States have experienced ethanol

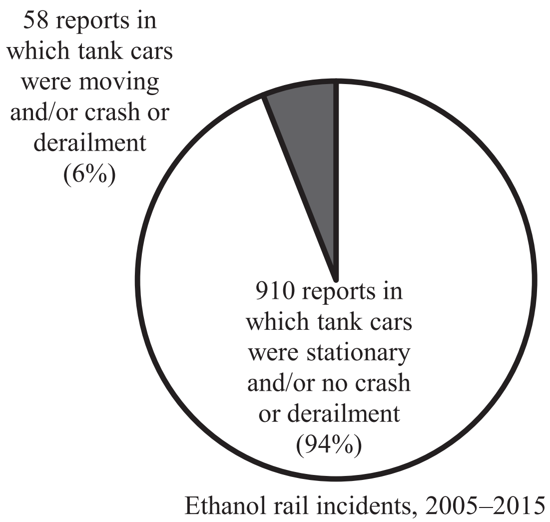

FIGURE 4-10 Reports of unintentional hazardous materials releases or damaged tank cars involving ethanol shipments by rail in the United States, 2005–2015. SOURCE: PHMSA, "Incident Statistics," accessed November 8, 2016, http://www.phmsa.dot.gov/hazmat/library/data-stats/incidents.

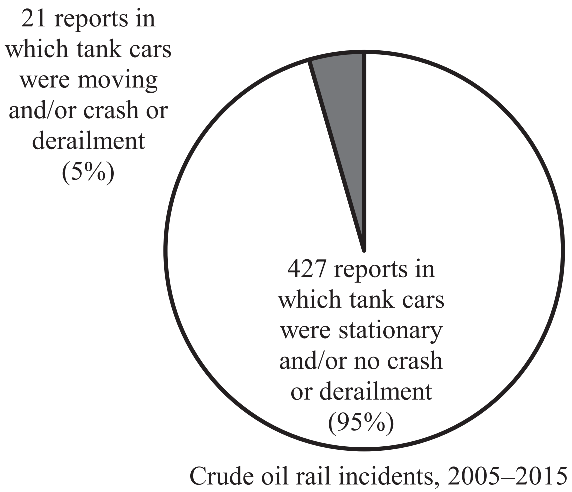

FIGURE 4-11 Reports of unintentional hazardous materials releases or damaged tank cars involving crude oil shipments by rail in the United States, 2005–2015. SOURCE: PHMSA, "Incident Statistics."

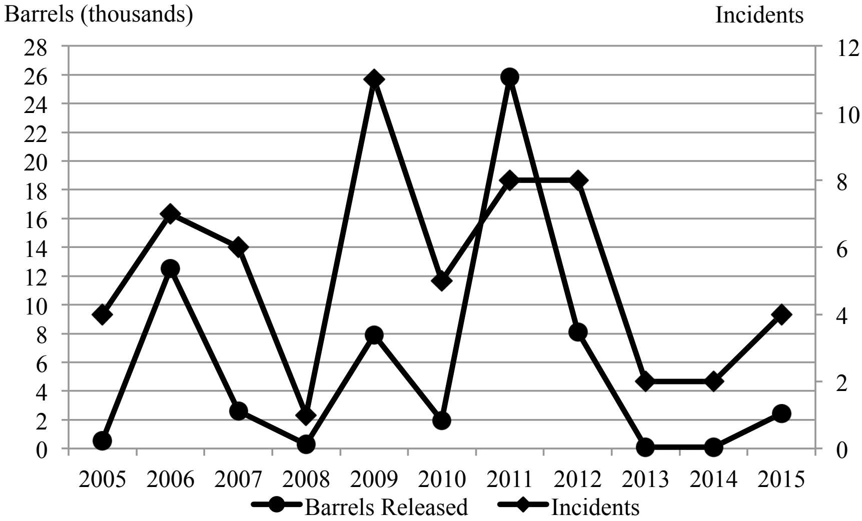

FIGURE 4-12 Ethanol tank car derailments and collisions and release quantities in the United States, 2005–2015.
SOURCE: PHMSA, "Incident Statistics."

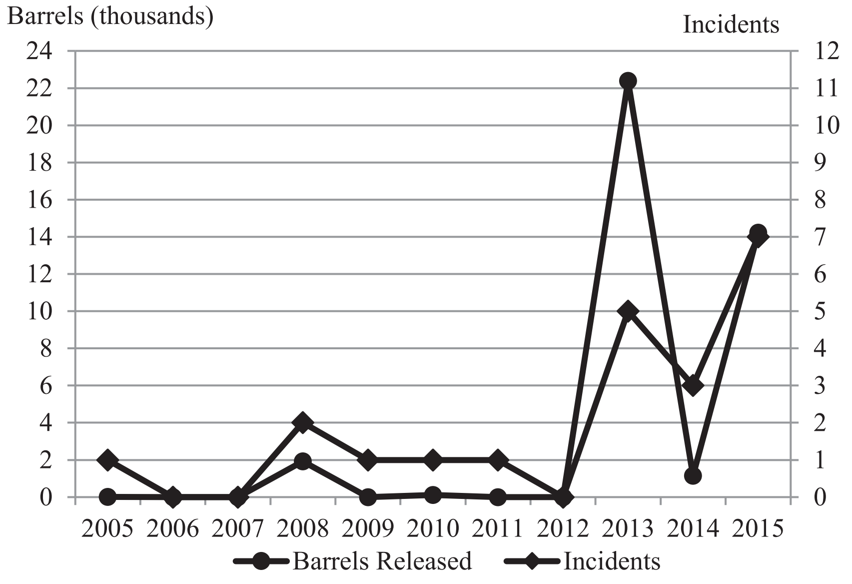

FIGURE 4-13 Crude oil tank car derailments and collisions and release quantities in the United States, 2005–2015.
SOURCE: PHMSA, "Incident Statistics."

TABLE 4-3 Tank Car Derailments and Collisions Involving the Unintentional Release of Ethanol in the United States, 2005–2015

Year	Incidents	Cars Incurring Damage or Release	Release (gallons)	Release (barrels)
2015	4	17	102,934	2,451
2014	2	2	4,025	96
2013	2	4	4,581	109
2012	8	25	340,589	8,109
2011	8	40	1,084,338	25,818
2010	5	13	81,806	1,948
2009	11	28	332,560	7,918
2008	1	1	12,447	296
2007	6	9	108,506	2,583
2006	7	27	525,223	12,505
2005	4	5	22,580	538
Total	58	171	2,619,588	62,371

SOURCE: PHMSA, "Incident Statistics."

TABLE 4-4 Tank Car Derailments and Collisions Involving the Unintentional Release of Crude Oil in the United States, 2005–2015

Year	Incidents	Cars Incurring Damage or Release	Release (gallons)	Release (barrels)
2015	7	58	598,183	14,242
2014	3	22	47,149	1,123
2013	5	47	940,457	22,392
2012	0	0	0	0
2011	1	1	1	<1
2010	1	1	4,800	114
2009	1	1	1	<1
2008	2	6	80,886	1,925
2007	0	0	0	0
2006	0	0	0	0
2005	1	1	1,500	36
Total	21	137	1,672,976	39,833

SOURCE: PHMSA, "Incident Statistics."

incidents. Because ethanol is blended in gasoline in all states, it is shipped over a larger percentage of the country's railroad network. Because shipments originate in corn-producing regions, the Midwest is the most common site of the 58 incidents, with more than one-third occurring in Illinois, Indiana, Iowa, and Ohio. As might be expected given their proximity to the Bakken formation, North Dakota and Montana have experienced the most crude oil train derailments, but otherwise there is no apparent pattern to the 21 incidents.

Notable Major Railroad Incidents

Table 4-5 lists the 20 ethanol and crude oil incidents that have had the most severe consequences of the 79, many involving fires, public evacuations, and thousands of barrels of lost product. As the timeline of incidents indicates, until 2013 nearly all large flammable liquids incidents involved ethanol shipments, including the earliest dating to October 2006, when 23 cars of an 83-car unit train derailed in New Brighton, Pennsylvania. Following an investigation of that incident, NTSB concluded the cause was a rail fracture from a defect that had gone undetected by railroad inspectors (see Table 4-5). Of the next six major ethanol derailments, from Painesville, Ohio, in October 2007 to Columbus, Ohio, in July 2012, all were determined to have been caused by track, roadbed, or structure failures, predominantly worn and broken rails.[21] Indeed, all of these notable incidents have involved derailments.

Moreover, track infrastructure failures have overwhelmingly been the cause for these derailments. A review of FRA safety data indicates that track, roadbed, and structure problems caused more than 44 percent of all reportable derailments from 2005 to 2015.[22] In the case of these severe crude oil and ethanol derailments, track flaws caused about 80 percent of the derailments. As shown in Table 4-5, 16 incidents involved track, roadbed, and structure failures, while the rest of the incidents were the result of equipment failure, human error, or causes unknown at this time. It merits noting that the incidents at Mount Carbon, West Virginia; Lynchburg, Virginia; and Mosier, Oregon, involved derailments that occurred shortly after the track was inspected, which raised questions about updated track safety regulations issued by FRA in 2014, which are discussed later in this chapter.

[21] National Transportation Safety Board, "Derailment of CN Freight Train U70691-18 with Subsequent Hazardous Materials Release and Fire, Cherry Valley, Illinois June 19, 2009," Accident Report NTSB/RAR-12/01 (Washington, D.C., February 14, 2012), https://www.ntsb.gov/investigations/AccidentReports/Pages/RAR1201.aspx.

[22] U.S. Federal Railroad Administration, "Federal Railroad Administration Office of Safety Analysis: 3.10-Accident Causes," accessed November 23, 2016, http://safetydata.fra.dot.gov/officeofsafety/publicsite/Query/inccaus.aspx.

TABLE 4-5 Notable Major Ethanol and Crude Oil Tank Car Incidents in the United States, 2005–2015

Location	Month and Year	Tank Cars Derailed	Tank Cars with Release	MPH	Product
New Brighton, PA‡	10/06	23	20	37	Ethanol
Painesville, OH†	10/07	7	4	48	Ethanol
Cherry Valley, IL*	6/09	19	15	37	Ethanol
Arcadia, OH†	2/11	31	31	46	Ethanol
Tiskilwa, IL†	10/11	10	9	34	Ethanol
Columbus, OH‡	7/12	3	3	23	Ethanol
Plevna, MT†	8/12	17	12	25	Ethanol
Lesterville, SD‡	9/15	7	3	10	Ethanol
Alma,WI[h]	11/15	15	5	26	Ethanol
Luther, OK*	8/08	8	5	34	Crude Oil
Parkers Prairie, MN‡	03/13	14	3	40	Crude Oil
Aliceville, AL†	11/13	26	25	39	Crude Oil
Casselton, ND¤	12/13	20	18	42	Crude Oil
New Augusta, MS†	01/14	15	7	47	Crude Oil
Vandergrift, PA*	2/14	19	4	31	Crude Oil
Lynchburg, VA†	4/14	17	1	24	Crude Oil
Mount Carbon, WV‡	2/15	27	20	33	Crude Oil
Galena, IL[w]	3/15	21	10	23	Crude Oil
Heimdall, ND[u]	5/15	6	5	24	Crude Oil
Culbertson, ND†	7/15	22	5	44	Crude Oil

NOTE: ‡ = internal rail defect; † = other rail defect; * = track or roadbed problem such as inadequate storm water management or wide gauge; ¤ = broken axle; [h] = human error; [w] = wheel defect; [u] = under investigation.
SOURCE: PHMSA, "Incident Statistics."

Gallons	Barrels	Fatality	Injury	Fire	Evacuation	Environmental Damage
485,278	11,554	0	0	Yes	Yes	Yes
55,200	1,314	0	0	Yes	Yes	No
323,963	7,713	1	8	Yes	Yes	No
834,840	19,877	0	0	Yes	Yes	Yes
162,000	3,857	0	0	Yes	Yes	No
54,748	1,304	0	2	Yes	Yes	Yes
245,336	5,841	0	0	Yes	No	No
49,748	1,184	0	0	Yes	No	No
20,413	486	0	0	No	Yes	Yes
80,746	1,923	0	0	Yes	Yes	No
30,000	714	0	0	No	No	Yes
455,520	10,846	0	0	Yes	No	Yes
474,936	11,308	0	0	Yes	Yes	No
90,000	2,143	0	0	No	Yes	No
10,000	238	0	0	No	Yes	Yes
29,416	700	0	0	Yes	Yes	Yes
378,034	9,001	0	1	Yes	Yes	Yes
110,543	2,632	0	0	Yes	Yes	No
98,090	2,335	0	0	Yes	Yes	No
27,201	648	0	0	No	Yes	No

Examinations of the post-crash factors that contributed to the severity of these derailments have often pointed to problems with the integrity of the tank cars used. In reporting on each of the ethanol incidents, NTSB observed that the derailed DOT-111 tank cars had exhibited poor crashworthiness and thermal resistance. In the 2006 New Brighton incident, heat from the ensuing fire caused a tank car to overpressurize and rupture. While the agency did not recommend changes to the ethanol tank car fleet following this early incident, follow-on investigations continued to point to shortcomings in the crash performance of this general service car. Of the 10 ethanol cars that derailed in Tiskilwa, Illinois, in 2011, 9 were severely damaged, with most sustaining head and shell punctures and 3 experiencing breached tanks as a result of exposure to the high temperatures of a pool fire. Following this incident, NTSB concluded that "DOT-111 tank cars are inadequately designed to prevent punctures and breaches and that catastrophic release of hazardous materials can be expected."[23] In March 2012, NTSB recommended that PHMSA require all newly manufactured and existing tank cars used for ethanol and crude oil have enhanced tank head and shell puncture–resistance systems and top fittings protection.[24]

When NTSB issued this recommendation in 2012, the use of unit trains to move crude oil had been growing dramatically. As the timelines in Table 4-5 indicate, the number of crude oil incidents began to rise as traffic volumes increased. In July 2013, the Lac-Mégantic crash occurred—a crude oil train disaster that killed 47 people. The investigations of that incident again pointed to the failings of the DOT-111 car in resisting damage; however, the 65 mph speed of the runaway train created immense crash forces. Of concern was whether the DOT-111 could resist damage at the lower speeds more commonly associated with derailments. Tables 4-6 and 4-7 show the distribution of train speeds in the crude and ethanol tank cars derailed during 2006 to 2015. Higher speed appears related to the number of cars derailed and damaged, the quantity released, and the occurrence of a fire. Uniquely contributing to this disaster, the high train speed at the time of derailment stemmed from the locomotive engineer failing to adequately apply and test the train's hand brakes when stopped and left unattended on a descending grade. However, a number of derailments during 2014 and 2015 in which tank cars sustained considerable damage occurred at relatively low speeds.

[23] National Transportation Safety Board, "Railroad Accident Brief: Tiskilwa, Illinois, October 7, 2011," Accident Brief NTSB/RAB-13/02 (Washington, D.C.), page 9, accessed September 19, 2017, https://www.ntsb.gov/investigations/AccidentReports/Reports/RAB1302.pdf.

[24] National Transportation Safety Board, "Safety Recommendation R-12-5 through R-12-8, R-07-4," March 2, 2012, https://www.ntsb.gov/safety/safety-recs/recletters/R-12-005-008.pdf.

TABLE 4-6 Ethanol Tank Car Incidents in the United States, 2005–2015

	Estimated Speed Before Derailment (mph)				
	1–10	11–20	21–30	31–40	+40
Number of Derailments	33	7	9	3	6
Cars Incurring Damage or Release	41	7	34	36	53
Release Quantity (gallons)	107,146	82,253	454,299	999,512	976,378
Release Quantity (barrels)	2,551	1,958	10,816	23,798	23,247

NOTE: Speed was reported as zero for five incidents despite all involving moving crashes or derailments. These five were not included in the table under the assumption that speed was reported incorrectly.
SOURCE: PHMSA, "Incident Statistics."

TABLE 4-7 Crude Oil Tank Car Incidents in the United States, 2005–2015

	Estimated Speed Before Derailment (mph)				
	1–10	11–20	21–30	31–40	+40
Number of Derailments	3	3	6	5	4
Cars Incurring Damage or Release	7	7	32	67	24
Release Quantity (gallons)	4,800	88,679	238,051	839,169	502,277
Release Quantity (barrels)	114	2,111	5,668	19,980	11,959

SOURCE: PHMSA, "Incident Statistics."

In the February 2015 derailment in Mount Carbon, West Virginia, all of the DOT-111 cars were compliant with an upgraded CPC-1232 industry standard, which was adopted in October 2011 for new tank cars transporting crude oil and ethanol. The CPC-1232 cars, as discussed in Chapter 3, were equipped with half-height head shields, thicker tank and head steel, fitting protection, and pressure relief devices. According to FRA's investigation, the train in the Mount Carbon incident was being operated at 33 mph, below the 50-mph maximum authorized speed.[25] The cause of the derailment was determined to be a broken rail. Twenty-seven of the tank cars carrying crude oil left the track; however, only 6 incurred enough damage to release their contents—2 sustaining punctures and 4 sustaining valve or fitting damage. The major consequences in this case occurred after the onset of a pool fire, which caused thermal tank shell failures on 13 tank cars that had otherwise survived the accident. The thermal tears caused violent

[25] U.S. Federal Railroad Administration, "Accident Findings Report for Derailment of CSX Transportation, Inc.'s Unit Crude Oil Train K08014 Transporting Crude Oil for Plains All American, Mount Carbon, West Virginia" (Washington, D.C., October 9, 2015), https://www.fra.dot.gov/eLib/Details/L17123.

fireball eruptions; the first occurring within a half hour of the derailment and the last 10 hours later. Less than a month after the Mount Carbon incident, a crude oil unit train traveling at 23 mph derailed 21 CPC-1232 tank cars in Galena, Illinois. In this case, product released from cars sustaining damaged valves and fittings ignited into a pool fire that resulted in five tank car thermal failures.

Following a review of these incidents, NTSB concluded that the CPC-1232 design was deficient for carrying flammable liquids, lacking the needed pressure-relief capacity and thermal insulation to prevent tank failures from overpressurization when exposed to a pool fire. In April 2015, the agency issued urgent recommendations calling for more robust and fire-resistant tank cars for carrying crude oil and ethanol.[26] It called for an aggressive schedule of replacing or retrofitting the DOT-111 and the CPC-1232 fleet with cars equipped with thermal insulation and higher-capacity pressure-relief devices.

Later in this chapter, a summary is provided of the key provisions of a May 2015 federal rulemaking to address safety issues arising from the increased rail movement of ethanol and crude oil by rail.[27] Regulators expect the outcome of this rulemaking, which phases out the legacy DOT-111 and CPC-1232 cars and establishes a new DOT-117 design (and retrofit version) with greater crashworthiness and thermal protection, will be fewer tank cars releasing product during derailments and fewer thermal ruptures. The continued potential for severe crashes, however, was highlighted by a June 2016 incident in Mosier, Oregon, in which four CPC-1232 tank cars were breached from a unit train carrying Bakken oil. The derailed cars lost more than 40,000 gallons of product, which ignited and required the evacuation of about 100 people. The cause of the Mosier derailment appears to have been a track failure, the persistence of which has caused NTSB to raise concern about the duration of the phase-out schedule, which extends to May 2025. Accordingly, NTSB has called on regulators to schedule intermediate milestones and progress-reporting requirements as a means of encouraging earlier tank car replacements and retrofits.

WATERWAYS SAFETY TRENDS

Like pipelines, the waterways have long transported crude oil, and to a lesser extent ethanol. Indeed, all imports of crude oil to the United States,

[26] National Transportation Safety Board, "Safety Recommendation R-15-14 Through -17," April 3, 2015, http://www.ntsb.gov/safety/safety-recs/recletters/R-15-014-017.pdf.

[27] Pipeline and Hazardous Materials Safety Association, "Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains," 89 FR 26644, 2015, https://www.gpo.gov/fdsys/pkg/FR-2015-05-08/pdf/2015-10670.pdf.

except for shipments from Canada, are transported in tanker ships. These ships are also used to transport oil from the terminus of the Trans-Alaska Pipeline to refineries in the United States. As discussed in Chapter 3, crude oil and ethanol are transported on the inland and coastal waterways primarily by tanker barge.

The U.S. Coast Guard (USCG), which is responsible for overseeing and regulating the safe operations of these vessels and movements, has established three major safety measures: the "sheen rule," designation of a responsible party, and the requirement for double-hulled vessels. Because of the sensitivity of the maritime environment, carriers are required to report any spill or discharge of petroleum and other hazardous substances to the National Response Center (NRC), which is run by USCG. Applying what is commonly known as the "sheen rule" (the Discharge of Oil regulation), the agency requires the person in charge of a vessel to report any observed sheen or discoloration on the surface of the water or that causes a sludge of emulsion to be beneath the water's surface or on the shoreline, even if the source of the discharge is not known at the time. The report must contain the location of the release, an estimate of the quantity, information about its source and cause, types of material, and data on threats posed and consequences such as injuries. NRC relays the release information in the report to a USCG or U.S Environmental Protection Agency (EPA) On-Scene Coordinator to evaluate the situation and decide whether a federal emergency response action is necessary and/or to monitor the cleanup activities of the vessel operator, designated by law as the responsible party, and the local and state governments. As the responsible party, vessel operators must make preparations along their routes to anticipate the possibility of a discharge and remediate as necessary. To prevent a recurrence of incidents such as the Exxon Valdez tanker spill and others from the late 1980s, vessels are required to be double-hulled to minimize a loss of containment.

These reforms have been credited with not only fundamentally changing the set of safety incentives that maritime carriers and shippers face but also with creating a safety culture and assurance system that is anticipatory so that safety is reasonably assured in the face of unforeseen changes in traffic levels, technology, and operating practices. The safety performance data that follow bear out the effectiveness of these reforms.

Figure 4-14 shows the total volume of releases reported by tank barges of any kind of petroleum, including crude oil and refined products, from 1995 to 2015. In most years, the total volume has not exceeded 5,000 barrels. In November 2005, a tank barge carrying 119,000 barrels of heavy crude oil from Houston, Texas, to Tampa, Florida, crashed into the remains of a pipeline service platform that was damaged during Hurricane Rita. The

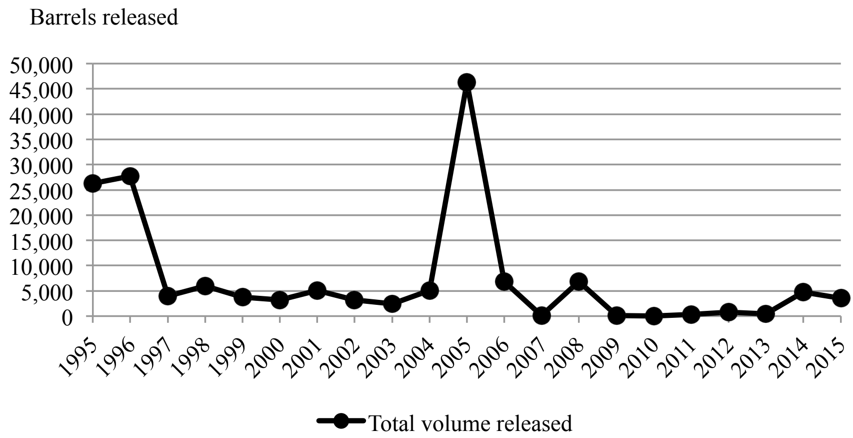

FIGURE 4-14 Petroleum oil spilled by tank barges in the United States, 1995–2015. SOURCE: American Waterways Operators and U.S. Coast Guard, "U.S. Coast Guard-American Waterways Operators Annual Safety Report: Towing Industry Safety Statistics 1994–2014," August 3, 2016, 5, http://www.americanwaterways.com/sites/default/files/USCG%20AWO%20Annual%20Safety%20Report%20August%202016.pdf.

barge discharged more than 46,000 barrels into the Gulf of Mexico.[28] Since this 2005 incident, there have been no comparable petroleum releases from vessels in U.S. waters. When normalized according to barrels of petroleum transported by water, the discharge rate has not exceed 5,000 barrels per billion barrels transported since 2005 (see Figure 4-15).

Focusing solely on crude oil discharges, the total annual discharge volume has only exceeded 25 barrels from tankers and barges combined in 2 years since the 2005 Gulf of Mexico spill, as shown in Figure 4-16. During 2013, 16 incidents were reported, for a combined discharge of 183.5 barrels. One tank barge incident, on the Mississippi River near Vicksburg, accounted for 171 of these barrels. The tank barge, with a cargo hold containing approximately 1,900 barrels of crude oil, struck a railroad bridge, causing the closing of the river during control and cleanup activities.[29]

[28] Entrix, "Tank Barge DBL 152 Incident Response Environmental Unit Report" (U.S. Coast Guard, January 2010), 2-1, https://casedocuments.darrp.noaa.gov/southeast/dbl152/pdf/5011%20DBL%20152%20Environmental%20Unit%20Report.pdf.

[29] U.S. Coast Guard, "Claim Summary/Determination," September 22, 2016, 1, https://www.uscg.mil/npfc/Claims/2016/N13011-0004%20RC%20Paid_Redacted.pdf.

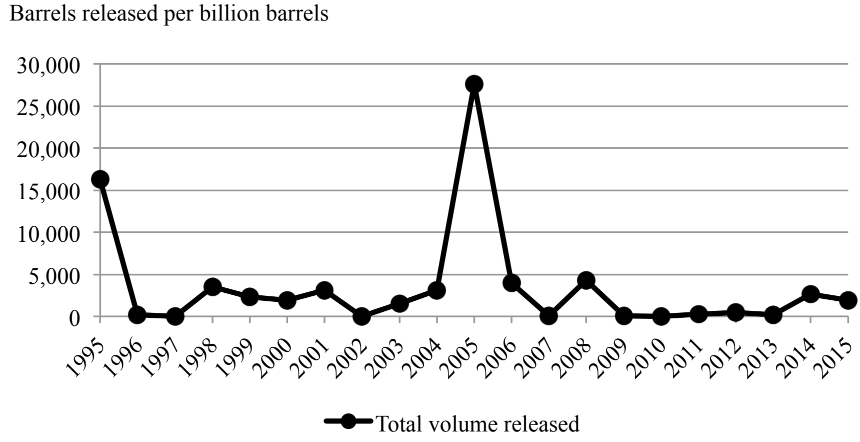

FIGURE 4-15 Discharge rate for all petroleum oil spilled by tank barges in the United States, 1995–2015.
SOURCE: American Waterways Operators and U.S. Coast Guard, "U.S. Coast Guard-American Waterways Operators Annual Safety Report: Towing Industry Safety Statistics 1994–2014," August 3, 2016, 5, http://www.americanwaterways.com/sites/default/files/USCG%20AWO%20Annual%20Safety%20Report%20August%202016.pdf.

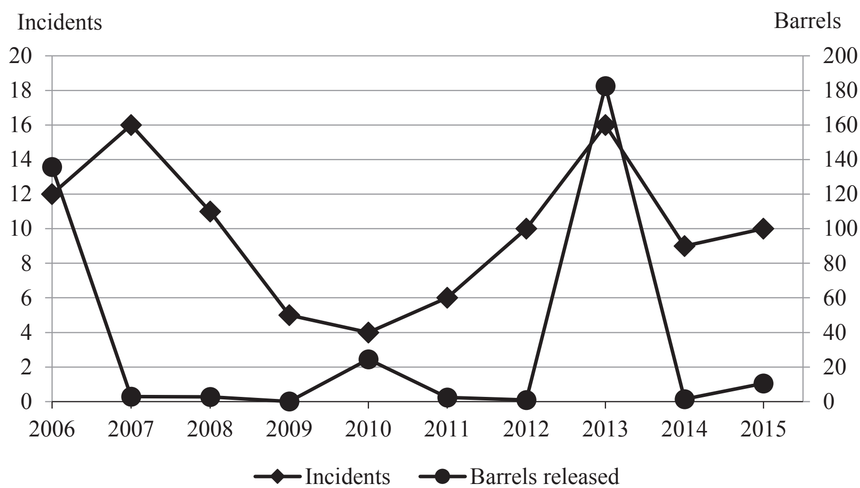

FIGURE 4-16 Crude oil discharges and volumes by tankers and barges in the United States, 2006–2015.
SOURCE: USCG, "Port State Information Exchange," *U.S. Coast Guard Maritime Information Exchange*, accessed September 19, 2017, https://cgmix.uscg.mil/PSIX/PSIXSearch.aspx.

COMPARISON OF MODAL INCIDENT DATA

Because pipelines, rail, and water are not used to transport all the commodities examined in this chapter, a comparison of incident rates and other indicators of safety performance is not always possible. Natural gas and NGL shipments (i.e., unfractionated NGLs) are transported exclusively by pipelines, making cross-modal comparisons impossible. Ethanol shippers rely almost exclusively on railroads and on barges to a much lesser extent. Unlike rail, the latter mode has no record of ethanol discharges, but its transported volumes are relatively low.

Because it is transported by all three modes in large volumes, crude oil is the only commodity that is a candidate for cross-modal safety comparisons. Tables 4-8A, 4-8B, and 4-8C show annual reports of crude oil releases and volumes from pipelines, railroads, and waterways for periods that coincide with the domestic energy revolution. It is important to note that the incident data do not take into account the severity of incidents, which limits cross-modal comparability. Comparability is limited further by differences in incident-reporting criteria. As a practical matter, it is also important to recognize that the modes are not always substitutes for one another in moving crude oil. Comparisons of the safety performance of modes when they are used differently and are not viable substitutes can have limited value for decision making.

OTHER SAFETY-RELATED EFFECTS

The safety data reviewed above are derived largely from carrier reports of hazardous materials incidents to PHMSA. It is important to keep in mind, however, that the injuries and fatalities that are the direct result of hazardous materials releases may not be the only safety-related effects of this traffic. In the case of railroads, this impact can be significant. As noted earlier, the Lac-Mégantic crash in Canada killed 47 people in 2013. While no fatalities occurred in the United States as a result of releases from derailed crude oil trains during 2005 to 2015, trains do create other safety impacts on a regular basis, most notably as a result of collisions with pedestrians on rights of way and motor vehicles at grade crossings. To the extent that the increases in crude oil moved by rail have led to more train traffic, there is a likelihood that the increase in trains has led to more of these incidents.

Based on FRA data for 2012 to 2015, the combined average risk to trespassers and grade-crossing users (including individuals later determined to have been suicidal) is 1.29 fatalities and 1.58 injuries per million train-

TABLE 4-8A Crude Oil Incidents and Releases per Traffic Volume for Pipelines, 2005–2015

Year	Shipments (barrels)	Barrels Released	Traffic (billion barrel-miles)	Incident Rate per Billion Barrel-Miles	Barrels Released per Billion Barrel-Miles
2005	3,170,890,847	101,964	1,562	0.11	65.25
2006	3,245,583,762	83,851	1,587	0.10	52.82
2007	3,361,388,084	19,787	1,442	0.11	13.72
2008	3,122,110,363	59,252	1,590	0.10	37.24
2009	3,310,023,743	24,183	1,493	0.10	16.19
2010	3,211,416,077	52,710	1,630	0.09	32.33
2011	3,570,079,712	35,276	1,674	0.09	21.06
2012	3,577,521,749	15,025	1,783	0.10	8.42
2013	3,693,147,852	43,048	1,810	0.11	23.77
2014	3,979,501,923	17,521	2,073	0.11	8.45
2015	4,647,144,132	20,668	2,361	0.11	8.75
Total, 2005–2015	38,888,808,244	473,285	19,012	0.10	24.89
Total, 2005–2009	16,209,996,799	289,037	7,677	0.10	37.65
Total, 2010–2015	22,678,811,445	184,248	11,335	0.10	16.26

SOURCE: Federal Energy Regulatory Commission; PHMSA.

TABLE 4-8B Crude Oil Incidents and Releases per Traffic Volume for Railroad Incidents, 2005–2015

Year	Shipments (barrels)	Barrels Released	Traffic (billion barrel-miles)	Incident Rate per Billion Barrel-Miles	Barrels Released per Billion Barrel-Miles
2005	1,837,500	35.81	0.60	3.32	59.38
2006	1,792,000	1.67	0.63	1.59	2.65
2007	1,564,500	0.01	0.53	1.87	0.02
2008	5,266,800	1,931.04	4.61	1.73	418.54
2009	5,625,900	0.01	4.9	0.20	0.002
2010	19,761,700	117.13	23.8	0.38	4.92
2011	50,369,200	93.53	66.5	0.50	1.41
2012	158,117,400	89.84	250.9	0.35	0.36
2013	282,192,400	22,511.50	474.5	0.25	47.44
2014	341,341,000	1,371.89	571.8	0.25	2.40
2015	283,649,800	14,244.83	468.0	0.09	30.44
Total, 2005–2015	1,151,518,200	40,397.26	1,867	0.24	21.64
Total, 2005–2009	16,086,700	1,968.54	11.32	1.15	173.90
Total, 2010–2015	1,135,431,500	38,428.72	1,855	0.23	20.71

SOURCE: Association of American Railroads; Federal Railroad Administration analysis of STB Waybill Sample data; PHMSA.

TABLE 4-8C Crude Oil Incidents and Releases per Traffic Volume for Waterways, 2006–2015

Year	Shipments (barrels)	Barrels Released	Traffic (billion barrel-miles)	Incident Rate per Billion Barrel-Miles	Barrels Released per Billion Barrel-Miles
2006	476,465,830	135.714	431.601	0.028	0.314
2007	486,322,950	2.852	452.68	0.035	0.006
2008	458,972,150	2.716	428.148	0.026	0.006
2009	434,661,080	0.0738	440.517	0.011	0.0002
2010	407,946,660	24.510	383.636	0.010	0.064
2011	402,341,100	2.364	378.308	0.016	0.006
2012	533,245,820	1.029	411.582	0.024	0.002
2013	692,604,850	182.481	498.881	0.032	0.366
2014	752,004,830	1.524	576.906	0.016	0.003
2015	747,265,830	10.548	592.233	0.017	0.018
Total, 2006–2015	5,391,831,100	363.805	4,594.494	0.022	0.079
Total, 2006–2009	1,856,422,010	141.350	1,752.950	0.025	0.081
Total, 2010–2015	3,535,409,090	222.455	2,841.550	0.019	0.078

SOURCE: U.S. Army Corps of Engineers; USCG.

miles.[30] As indicated in Table 4-8B, there were approximately 1,865 billion barrel-miles of crude oil moved by rail from 2008 to 2015. Almost all of this volume represents new railroad traffic, because before 2008 railroads moved only about 0.6 billion barrel-miles per year. If it is assumed this new traffic was moved in 100-car unit trains at 700 barrels per tank car, the result would be about 26.6 million additional train-miles during 2008 to 2015, an increase of about 0.5 percent in total freight train-miles. Based on average risks of collisions with pedestrians and motor vehicles cited above, this added traffic would be expected to lead to an additional 34 fatalities and 42 injuries on railroad rights of way and grade crossings over that same period.

These estimates are best viewed as rough approximations of the magnitude of the safety impact. It is possible that some of this crude oil traffic crowded out other rail traffic, such as movements of grain or coal, so that train-miles were not proportionally increased. In addition, some of the oil traffic could have simply led to longer trains rather than more trains. It is also conceivable that the risk of train collisions with pedestrians and vehicles does not change proportionately with the number of trains in the manner implied by the use of average annual risk factors. Nevertheless, the magnitudes of the estimates suggest that even with these uncertainties, the safety impacts are likely to be large and deserving of consideration by policy makers when interpreting and comparing the modal safety data in Tables 4-8A, 4-8B, and 4-8C.

MAJOR RAIL SAFETY INITIATIVES IN RESPONSE TO INCIDENTS

The rail, pipeline, and water modes have long been the subject of federal regulations to ensure that hazardous materials shipments are transported safely. Indeed, most public policies that are intended to ensure the safe transportation of crude oil, ethanol, and natural gas have been in place for decades, preceding the post-2005 upsurge in their traffic volumes. The safety data examined above suggest that these baseline measures have been robust. The growth in hazardous materials traffic after 2005 has not been accompanied by comparable growth in the number of hazardous materials incidents or in the number of severe incidents. Nevertheless, the safety statistics show how the location and modal distribution of incidents have changed in ways that reflect new shipping origins, destinations, and modal use patterns. These changes have prompted new policy responses,

[30] U.S. Federal Railroad Administration, "Office of Safety Analysis," *Federal Railroad Administration*, February 23, 2017, http://safetydata.fra.dot.gov/officeofsafety/default.aspx. Data were obtained through queries of Casualty Summary Tables, Suicide Casualties by State/Railroad, and Operational Data Tables.

particularly to ensure the safety of flammable liquids shipments made in tank car unit trains, which as recently as 2005 were not a consideration of rail safety regulators.[31]

In the case of rail, FRA and PHMSA have increased safety inspections and issued new regulations, emergency orders, and safety advisories targeted specifically to crude oil and ethanol traffic. They have sponsored research to gain a better understanding of the risks associated with transporting these commodities and reached out to state and local agencies to help meet their emergency response planning, information, and training needs. Some of these important safety initiatives are summarized next.

High-Hazard Flammable Trains Rule

In May 2015, FRA and PHMSA jointly issued a new set of regulations in a rulemaking titled *Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains* (HHFT).[32] The rule is intended to be comprehensive by including provisions intended to prevent tank car derailments, limit the severity of incidents when they do occur, and assist state and local agencies in planning and preparing a safer and more effective emergency response to incidents. Some of the major provisions of this rule are summarized next.

The rule contains two provisions intended to reduce the likelihood of derailments involving unit trains moving tanks cars containing crude oil or ethanol. First, railroads are required to apply a 27-factor analysis when selecting routes for these trains to travel. The 27 factors are the same ones used for routing trains containing cars loaded with poison gases (toxic-by-inhalation hazards, TIHs). These factors pertain to conditions such as the route's traffic density, maintenance, grade, and curvature that can affect the potential for a derailment. Second, the rule requires that train speeds be restricted to 50 mph in all areas, which is the same as the limit for TIH trains. While the main purpose of the speed limit is to reduce the severity of incidents, lower train speeds are also viewed as having the potential to prevent some incidents such as over-speed derailments.

Although not part of the HHFT rulemaking, in 2015 FRA also launched the Crude Oil Route Track Examination (CORTEx) program to further its goal to prevent incidents. This program concentrates increased track inspections on crude oil routes by a team of inspectors. Each round of inspections

[31] U.S. Federal Railroad Administration, "Safe Placement of Train Cars: Report to the Senate Committee on Commerce, Science, and Transportation and the House Committee on Transportation and Infrastructure" (Washington, D.C.: U.S. Department of Transportation, June 2005), https://www.fra.dot.gov/eLib/Details/L03467.

[32] Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains, p. 26645.

lasts about 2 weeks and includes an audit of the railroad's track inspection records. Afterward, regional inspectors are instructed to reinspect items that had been identified by the CORTEx team.

In addition to reducing the occurrence of incidents, several provisions in the HHFT rule are intended to reduce the severity of incidents when they do occur. A main purpose of the aforementioned 50-mph speed restriction is that it limits the kinetic energy in a crash. Indeed, the rule requires that maximum speeds be reduced from 50 mph to 40 mph in urban areas when the train contains tank cars that do not meet the rule's upgraded design standards for crash resistance.

Perhaps the most significant provision in the HHFT rule that is aimed at reducing crash incident severity is an upgraded design specification for tank cars used in crude oil and ethanol service.[33] As discussed in Chapter 3, the two main designs used for transporting these commodities have been the DOT-111 and the CPC-1232 specifications. The former is a general service nonpressure design, while the latter is a version of the same design enhanced with a stronger tank shell, added head and fittings protection, and a pressure-relief device. The 2014 HHFT rule created the new DOT-117 standard that contains several enhancements to these legacy standards that are intended to increase resistance to tank punctures (e.g., full-height head shields, thicker tank shells), reduce overpressurization from exposure to heat from fires (e.g., thermal jackets, larger pressure-relief devices), and minimize crash-related damage to top and bottom fittings (e.g., added protection for top fittings and bottom outlet valves designed to prevent unintended releases or have the handle removed before moving). The rule also includes a new specification (i.e., DOT-117R) for retrofitting DOT-111 and CPC-1232 cars to bring them closer to the DOT-117. These design changes were informed in large part by analyses of industry data on more than 47,000 tank cars damaged in incidents since the 1960s.[34] However, these data included few records of tank cars in crude oil or ethanol unit train derailments. A summary of the DOT-117/DOT-117R standards as they compare to the DOT-111 and the CPC-1232 is provided in Table 4-9.

In creating these new tank car specifications, the HHFT rule contains a design- and commodity-specific phase-out schedule for DOT-111 and

[33] Pipeline and Hazardous Materials Safety Administration, "Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains Notice of Proposed Rulemaking," 79 FR 45016 (2014), https://www.regulations.gov/contentStreamer?documentId=PHMSA-2012-0082-0180&disposition=attachment&contentType=pdf.

[34] Christopher Barkan and Todd Treichel, "Rail Transportation of Crude Oil and Ethanol" (Committee for a Study of the Domestic Transportation of Petroleum, Natural Gas, and Ethanol, Washington, D.C., May 12, 2016), 6, http://www.trb.org/PolicyStudies/CommitteeMeetings2.aspx.

TABLE 4-9 Changes to Tank Car Design in 2015 HHFT Rule

Car	Features
Legacy DOT-111 (non-jacketed or jacketed)	• 7/16″ tank shell, no jacket or • 7/16″ tank shell, jacket
CPC-1232 (non-jacketed or jacketed)	• 1/2″ tank shell, no jacket, half-height head shield, top fittings protection or • 7/16″ tank shell, jacket, full-height head shield, top fittings protection
DOT-117	• 9/16″ tank shell, jacket, full-height head shield, top fittings protection, thermal protection, top and bottom fittings protection • Retrofitted DOT-117R permits a tank shell thickness of 7/16”

CRC-1232 cars that is intended to account for differences in the relative risks of each design when transporting crude oil and ethanol. Crude oil may not be transported in any DOT-111 car starting in early 2018 or in any CPC-1232 car that lacks thermal protection starting in early 2020. Ethanol may not be transported in DOT-111 cars or in CPC-1232 cars that lack thermal protection in 2023. By mid-2025, all CPC-1232 cars are prohibited from transporting either crude oil or ethanol. It merits noting that Transport Canada announced an expedited phase-out of all DOT-111 (TC-111 in Canada) tank cars used in crude oil service by moving up the deadline to November 1, 2016.[35]

To supplement the intended safety benefits of the DOT-117 tank car specifications, the HHFT rule also includes a provision to reduce the severity of derailments through a requirement that HHFTs be equipped with one of the following advanced braking systems: distributed power or a two-way end-of-train device. The rule additionally requires that all HHFT unit trains (HHFUTs; each with 70 or more tank cars loaded with flammable liquids) be equipped with electronically controlled pneumatic (ECP) brakes by 2021.[36] The ECP brake requirement, which was advocated by NTSB,[37] seeks to limit the consequences of derailments by reducing the number of derailed cars, kinetic energy, and the potential for tanks to suffer damage and re-

[35] Progressive Railroading, “Canada to Speed up Phaseout of DOT-111s for Crude Oil Use,” *Progressive Railroading*, http://www.progressiverailroading.com/safety/news/Canada-to-speed-up-phaseout-of-DOT-111s-for-crude-oil-use--48943.

[36] HHFUTs used to transport ethanol are required to implement ECP braking by 2023.

[37] National Transportation Safety Board, “Train Braking Simulation Study” (National Transportation Safety Board, July 20, 2015), http://dms.ntsb.gov/public/55500-55999/55926/577439.pdf.

lease commodity. Seeking a stronger justification for the rule, Congress has required the Secretary of Transportation to conduct additional testing and analysis of ECP braking systems when applied to HHFUTs and to decide by the end of 2017 whether to retain the requirement. As inherently chaotic events, train derailments pose a particularly formidable challenge to test and analyze through means such as simulation and modeling. Asked to review the U.S. Department of Transportation's (U.S. DOT's) efforts, a separate National Academies of Sciences, Engineering, and Medicine committee found that the results from the modeling and simulations lacked sufficient validation to enable confident estimation of the emergency performance of ECP braking systems compared with that of pneumatic braking systems augmented with distributed power or end-of-train devices.[38] The ECP braking committee was unable to make a conclusive statement about the emergency performance of ECP brakes relative to other braking systems on the basis of the results of testing and analysis provided by U.S. DOT.

Also, to address concerns that crude oil from formations such as Bakken may be more volatile than oil from more conventional means—and thus more likely to ignite when released in an incident—the HHFT rule requires that shippers develop and document a sampling and testing program for the identification and characterization of unrefined petroleum oil shipments. Previously, shippers relied on general crude oil safety data sheets not necessarily representative of the crude oil characteristics from certain sources, such as the Bakken formation. Additionally, PHMSA has collaborated with the U.S. Department of Energy to sponsor research by Sandia National Laboratories to identify gaps in crude oil characterization and sampling methods for further research.[39] An initial finding of the Sandia research is that many factors are relevant to the flammability of crude oil in a tank car derailment, and thus concern about the characteristics of tight oil, particularly from the Bakken formation, may be too narrowly focused.[40]

Track Safety Standards

FRA issued new track inspection and maintenance regulations in 2014 that apply to hazardous materials and passenger routes. A prominent feature

[38] Transportation Research Board, "A Review of the Department of Transportation Plan for Analyzing and Testing Electronically Controlled Pneumatic Brakes; Letter Report (Phase 2)" (Washington, D.C.: Transportation Research Board, September 29, 2017), https://www.nap.edu/catalog/24903.

[39] U.S. Department of Energy, "Crude Oil Characteristics Research," *Energy.Gov,* July 9, 2015, http://energy.gov/fe/articles/crude-oil-characteristics-research.

[40] David Lord et al., "Literature Survey of Crude Oil Properties Relevant to Handling and Fire Safety in Transport" (Sandia National Laboratories [SNL-NM], Albuquerque, NM, March 2015), 83, http://www.osti.gov/scitech/biblio/1177758.

of the rule focuses on establishing a performance-based standard for the maximum allowable frequency of track service failures.[41] The regulation also sets intervals between track inspections, criteria for remedial action for defective rails, and training qualifications for rail flaw inspectors.[42]

In addition, FRA administers a program to promote implementation of innovative inspection technologies. This program—in use by most Class I railroads—allows railroads to petition to pilot the use of innovative means of nonstop continuous rail testing for inspections, such as by gage restraint measurement systems and automated track geometry vehicles.[43] Automation, for instance, has the potential to enable more frequent inspections than required by current regulation, which would have the side benefit of enabling the prioritized reallocation of railroad inspection personnel to the routes frequently traversed by unit trains moving large quantities of hazardous energy liquids. In briefings to the committee, one railroad reported that the use of automated track inspection vehicles had increased its inspection capability as measured in miles of track from 91,000 miles in 2014 to approaching 240,000 miles by the end of 2016.

Train Securement

The inadequate application of hand brakes on a crude oil unit train stopped overnight en route to Lac-Mégantic allowed the equipment to roll down the track about 7 miles before derailing in town. As one of the causal factors involved in the derailment of the runaway train, in August 2015, FRA issued a rule, *Securement of Unattended Equipment*, to regulate the securement of unattended equipment to mitigate this risk unique among other recent crude oil derailments.[44] This rule requires hand brakes or other mechanical securement devices to be sufficient to hold the equipment, as well as that the controlling locomotive hauling any hazardous materials be locked when stopped and unattended outside of a yard.

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[41] U.S. Federal Railroad Administration, "Track Safety Standards: Improving Rail Integrity," 49 CFR 213 (2014), https://www.fra.dot.gov/Elib/Document/3546. The performance standard requires 0.09 or fewer service failures per year per mile of track for hazardous materials routes or 0.08 or fewer service failures per year per mile of track for routes with hazardous materials and passengers sharing a route (p. 4234).

[42] Ibid., p. 4248. The rulemaking's discussion about setting inspection intervals does not provide an obvious technical basis for setting 30 million gross tons as the standard as opposed to the previous standard of 40 million gross tons or some alternative figure.

[43] Karl Alexy, Director, Office of Safety Analysis, FRA, in discussion with project staff, October 6, 2016. The program allows railroads to pilot nonstop continuous rail-testing processes in accordance with 49 CFR Parts 211 and 213.

[44] U.S. Federal Railroad Administration, "Securement of Unattended Equipment," 49 CFR 232 (2015), https://www.regulations.gov/contentStreamer?documentId=FRA-2014-0032-0012&disposition=attachment&contentType=pdf.

MEASURES TO AID EMERGENCY PREPAREDNESS AND RESPONSE

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Oil Pollution Act of 1990 (OPA 1990) form the basis for regulations issued by EPA, FRA, PHMSA, and USCG governing emergency preparedness and response to spills of oil and other hazardous materials from transportation. Among other things, the regulations define agency and industry roles in national and regional response teams and establish the unified command structure across agencies and the responsible party.

An important element of this contingency planning is the National Response System, which is activated by the report of an incident to USCG's NRC. Figure 4-17 lists the various entities that coordinate within this system, the relevant mode, and their role in preparedness or response.

The details of these national planning and preparedness programs are too complex to present here. It merits noting, however, that special regulatory provisions deal with the concerns associated with oil discharges into water. USCG, for instance, requires waterways operators to develop response plans, and PHMSA requires pipeline operators to do the same.

Governmental	Private Sector / Trade Associations	Nongovernmental Organizations
• U.S. Environmental Protection Agency (EPA) *†(p)(r) • U.S. Coast Guard (USCG) *†(p)(w) • Pipeline and Hazardous Materials Safety Administration (PHMSA) *†(p)(r) • Federal Railroad Administration (FRA) *†(r) • Federal Emergency Management Agency (FEMA) † • National Oceanic and Atmospheric Administration (NOAA) *†(p)(r)(w) • State Emergency Response Commissions (SERCs) *(p)(r)(w) • Local Emergency Planning Committees (LEPCs) *†(p)(r)(w) • State, tribal, and local responders (SEMAs; e.g., fire and rescue and police departments) *†(p)(r)(w)	• Association of American Railroads (AAR) *(r) • American Waterways Operators (AWO) *(w) • American Oil Pipe Lines (AOPL) *(p) • American Petroleum Institute (API) *(p)(r) • Interstate Natural Gas Association of America (INGAA) *(p) • Renewable Fuels Association (RFA) *(r)(w) • Oil Spill Response Organizations (various) *†(p)(r)(w)	• CHEMTREC (CHEMical TRansportation Emergency Center) †(p)(r)(w) • International Association of Fire Chiefs (IAFC) *†(p)(r)(w) • National Association of SARA Title III Program Officials (NASTTPO) *(p)(r)(w) • National Association of State Fire Marshals (NASFM) *(p) • National Fire Protection Association (NFPA) *†(p)(r)(w) • TRANSCAER (TRANSportation Community Awareness and Emergency Response) *(r)(p)

FIGURE 4-17 Primary domestic governmental, private sector, and nongovernmental organizations involved in the National Response System as it relates to long-distance crude oil, natural gas, and ethanol shipments.
NOTE: Involved with pipelines = (p); railroads = (r); waterways = (w); preparedness = *; response = †.

The planning requirement entails documenting that adequate resources and expertise as necessary are available to mitigate and recover from a worst-case oil discharge into water. In the case of waterways, these plans usually include oil spill trajectory modeling. These oil spill dispersion models enable response organizations to more effectively anticipate where to marshal skimmers and booms to protect the environment and recover crude oil.[45] While railroads are not subject to similar spill planning regulation, PHMSA proposed a new rule in July 2016, as summarized in Box 4-1, that would introduce such requirements for this mode.

This proposed HHFT rule included two additional provisions intended to improve the preparedness and procedures for emergency responses to rail incidents involving crude oil. First, railroads would be required to provide state and tribal agencies with a point of contact for HHFT shipment information, similar to the provision for TIH shipments. Second, the rule would make permanent the May 2014 emergency order that required railroads to inform State Emergency Planning Commissions about any single train carrying 1 million or more gallons of Bakken crude oil. The notification must include information on routes, shipment frequencies, and points of contact.[46]

The information-sharing policy in the May 2014 emergency order was apparently developed without consultation with state and tribal authorities responsible for emergency response preparation. In a letter to PHMSA, the National Association of SARA Title III Program Officials (NASTTPO) expressed concern about the inadequacies of information sharing by rail carriers pertinent to HHFT traffic. The letter maintained that state officials were not being provided timely commodity flow information, contact information for railroad hazardous materials managers, and information about railroad emergency preparedness plans and response capabilities.[47] To the extent that railroads shared information, NASTTPO claimed that state officials were often hampered in their dissemination of the information to local emergency responders because of uncertainty about the sensitivity of the information and the receipt of redacted documents.[48] In some cases, railroads shared information with state fusion centers, which are law

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[45] The use of oil spill trajectory modeling was prompted by the 1976 spill by the Argo Merchant off the coast of Nantucket, Massachusetts.

[46] In July 2016, PHMSA proposed a rule that would expand the Bakken crude oil notification requirement to cover all HHFTs.

[47] National Association of SARA Title III Program Officials, "Hazardous Materials: Oil Spill Response Plans for High-Hazard Flammable Trains," September 20, 2014, 1, https://www.regulations.gov/contentStreamer?documentId=PHMSA-2014-0105-0206&attachmentNumber=1&disposition=attachment&contentType=pdf.

[48] Government Accountability Office, "Emergency Responders Receive Support, but DOT Could Improve Oversight of Information Sharing," 35, http://www.gao.gov/assets/690/681123.pdf.

Box 4-1
Oil Spill Response Plans for High-Hazard Flammable Trains Notice of Proposed Rulemaking

Under current regulations, nearly all shipments of oil by rail need a basic oil spill response plan (OSRP), an internal document identifying the means of and personnel and equipment available for response to a discharge. This proposal by PHMSA and FRA would go beyond that for HHFT and accomplish two main purposes:

Comprehensive OSRPs: Railroads would develop these plans for FRA approval consistent with federal guidance on spill response and planning to ensure the capacity to respond to and remove a worst-case discharge, accounting for at least 300,000 gallons of petroleum oil. Although the OPA 1990 framework omits ethanol, the proposed rule would include denatured alcohol fuel in a concentration of as little as 10 percent petroleum oil. The proposed rule would bring rail shipments into alignment with the comprehensive oil spill response plan requirements established under OPA 1990.

Petroleum Oil Testing: It would allow an American Society for Testing and Materials (ASTM) standard for determining a product's initial boiling point to be used to test petroleum oil that more accurately measures more volatile components in crude oil (i.e., the "light ends"). Although this provision would not incorporate the American Petroleum Institute's recommended practice for testing of petroleum oil for railroad tank cars, the addition of the ASTM initial boiling point test would bring regulation and industry practice closer.

enforcement bodies that do not have strong ties to state and local authorities responsible for emergency response planning and preparations.

In most cases, local and state agencies are first on the scene for a pipeline rupture or train derailment. PHMSA provides grants to state and local authorities to develop and test emergency response plans and to train firefighters and police on response methods and practices. PHMSA has created two new programs to deliver training to responders to crude oil and ethanol transportation incidents. The agency's Assistance for Local Emergency Response Training grant programs target training of emergency responders, with a focus on rural and volunteer responders, whose increased participation in these training activities is a priority for policy makers and industry. The Transportation Rail Incident Preparedness and Response program provides train-the-trainer resources and distributes information online to the emergency response community on crude oil properties and recommended response practices such as hazard assessment, risk evaluation, and choice of protective clothing and equipment.

Shippers and carriers of crude oil and ethanol have also taken steps to improve the training of responders. A notable example is the railroad- and shipper-sponsored TRANSCAER program,[49] which is dedicated to improving understanding of and response capabilities for hazardous materials transportation incidents. Between 2014 and 2015, TRANSCAER provided training for more than 100,000 responders.[50] As rail shipments of ethanol and crude oil increased, TRANSCAER increased its focus on these flammable liquids. For example, the program partnered with the American Petroleum Institute to create a crude-by-rail safety course that has been presented at national, state, and local hazardous materials and emergency response conferences.

To further assist with this response, PHMSA publishes the *Emergency Response Guidebook* (including a version for mobile devices),[51] which provides initial response guidance on the hazards involved, actions to be taken, and public protection options. To ensure that first responders have shipment hazard information at the scene of incidents, PHMSA requires that hazardous shipments be accompanied by shipping papers that describe the material and its hazards and provide the shipper's emergency contact information. These papers usually reference the American Chemistry Council's CHEMTREC,[52] a 24-hour hotline for emergency responders to obtain information about chemicals and hazardous materials.

Most railroads have standardized their shipping papers to report the train position of each car carrying hazardous material, and they typically designate a single point of contact for routing decisions so that state and regional fusion centers and other officials are aware of the routes used to transport hazardous materials. The Association of American Railroads (AAR) assisted in the development of the mobile app AskRail, which provides details on a train's consist and links the listed cargo to response information from the *Emergency Response Guidebook* to enable faster decision making on-scene (see Figure 4-18).[53] AAR released AskRail in late 2014.

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[49] TRANSportation Community Awareness and Emergency Response.

[50] Frank Reiner, "TRANSCAER: Assisting Communities to Prepare for and Respond to Possible Hazardous Material Transportation Incidents" (Committee for a Study of the Domestic Transportation of Petroleum, Natural Gas, and Ethanol, Washington, D.C., February 5, 2016), 6, http://www.trb.org/PolicyStudies/CommitteeMeetings2.aspx. In 2015, TRANSCAER programs trained 52,474 responders in addition to the nearly 55,000 trained in 2014. (https://www.transcaer.com/docs/general/TRANSCAER-FactSheet-5.pdf).

[51] Pipeline and Hazardous Materials Safety Administration, "2016 Emergency Response Guidebook" (U.S. Department of Transportation, 2016), http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/Hazmat/ERG2016.pdf.

[52] CHEMical TRansportation Emergency Center.

[53] Bob Fronczak, "Rail Transport of Petroleum, Natural Gas and Ethanol" (Committee for a Study of the Domestic Transportation of Petroleum, Natural Gas, and Ethanol, Washington, D.C., February 5, 2016), 26.

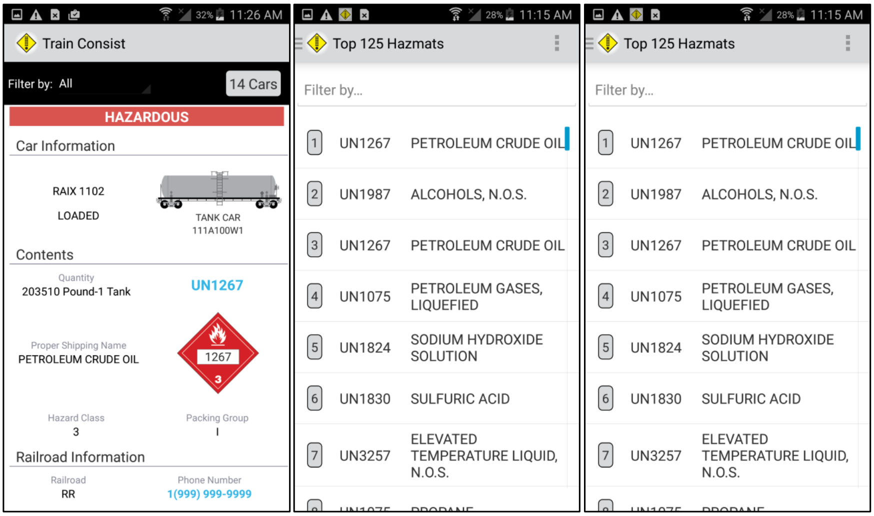

FIGURE 4-18 AAR's AskRail app screenshots for train consist and tank car details, hazardous materials identification, and response guidance resources (left to right).

Despite these efforts, first responders encounter difficulty acquiring the necessary training to manage incidents involving tank car unit trains. The time commitment needed for training and exercises can limit participation, especially for volunteer firefighters. According to a survey of 23 counties conducted by the U.S. Government Accountability Office (GAO), many first responders, including a majority of volunteer firefighters in rural areas, cited the need to take unpaid leave from work to attend training sessions.[54] Other reasons given for not taking advantage of training opportunities include the difficulty that both volunteer and professional units face in filling the positions of responders who are away at training and obtaining permission for leave from regular duties and traveling outside the local community. While most of the 23 counties surveyed by GAO reported that their first responders had the basic competencies needed to identify hazardous cargoes and notify appropriate parties in the event of an incident, 17 reported that less than 60 percent of their personnel had more advanced levels of response expertise and training.[55]

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[54] Government Accountability Office, "Emergency Responders Receive Support, but DOT Could Improve Oversight of Information Sharing," 17.
[55] Ibid., p. 15.

5

Summary Observations and Recommendations

This report reviews the response of the U.S. long-distance transportation sector to the sharp increase in the domestic production of crude oil, ethanol, and natural gas over the past decade. The demands faced by the nation's inland pipeline, rail, and barge operators to move these new energy supplies economically and safely from new origins, across new transportation routes, and by new means of conveyance had been largely unexpected. To the credit of these operators, as well as the safety regulators who oversee them, the vast majority of these domestic supplies has been transported without incident, enabling the country to capitalize on its new energy resources and to reduce imported energy and the safety risks associated with its transportation.

When this study commenced in late 2015, a national debate was under way about whether the domestic energy revolution was creating demands on the transportation system that would sacrifice safety. Railroad tank cars and waterborne tank barges were hauling oil and fuel ethanol in increasingly larger quantities and over longer distances, often on routes passing through communities that had little, if any, experience with regular and large quantities of flammable liquids traffic. Some high-profile incidents had occurred, and there was skepticism about whether more pipelines would be built to provide a safer means of transportation, in part because of highly publicized opposition to new pipelines on grounds that their safety could not be assured.

In retrospect, skepticism about the ability of the pipeline sector to respond to an increasing and changing geographic demand for the movement of oil and gas was unwarranted. The sector has attracted investment, extending the country's pipeline capacity in a relatively short period for such an infrastructure-intensive mode. Meanwhile, the domestic energy revolution has taken new turns in response to volatility in oil and natural gas prices, which has led to marked reductions in the demand for the transportation of these energy liquids and gases by rail and by barge. Even the demand for transporting ethanol, which is met largely by railroads, has passed from a period of growth to one of stability as ethanol production has approached the levels targeted by federal policy.

As pipeline capacity has grown and the fundamentals of the country's energy markets have changed, trains and barges continue to transport crude oil and ethanol but in volumes that are down markedly since 2014. In this short time, the transportation sector has once again had to adapt to unforeseen conditions, demonstrating its robustness and flexibility in the face of the fast-changing domestic energy landscape.

The transformation of the country's energy markets is still playing out, and therefore future demands on the transportation system remain unclear. Trying to predict the safety implications of these demands is therefore tantamount to chasing a moving target, bound to result in a report whose content is more retrospective than prospective. Indeed, this report focuses largely on safety issues that were prominent during the period when the transportation sector was responding to the fast-increasing demand for the movement of energy liquids and gases and when government safety regulators were trying to catch up. Nevertheless, such a retrospective review can be important because of the insights it can provide for recognizing and responding in a faster and more effective manner to future changes in the demand for energy transportation and associated safety risks.

In sponsoring this study, the Transportation Research Board (TRB) Executive Committee requested a review and comparison of how the country's three major long-distance modes—pipelines, railroads, and barges—have fared in safely transporting the new traffic from the domestic energy revolution. Their respective safety performance over the past decade can be gauged to a limited degree by examining trends in unintended releases of oil, gas, and ethanol relative to the volume of these products transported. While data of this kind are provided in this report, they are poorly suited to making cross-modal comparisons of safety performance because of modal differences in incident-reporting criteria; the difficulty of representing rare, high-consequence events in statistical comparisons; and the potential for some of the new traffic to create second-order safety risks, such as the possibility of the new energy trains being involved in rail-highway grade-crossing accidents. Moreover, cross-modal safety comparisons can have questionable purpose for decision making in cases when the modes are not viable alternatives. For instance, statistics suggesting that one mode is safer than another are immaterial if traffic volumes are too low to make investing in the seemingly safer mode economical.

Although there is limited value in judging the relative safety performance of pipelines, railroads, and barges using available incident data, a number of insights can be gleaned from comparing the safety-assurance systems of the three modes. Pipelines and barges have accommodated major portions of the growth in domestic energy liquids and gases, and they have done so without creating major new safety concerns and within the basic framework of their longstanding regulatory and safety-assurance systems. Special attention is given in this report to the new regulations and other policies put in place to assure the safety of rail shipments of crude oil and ethanol, mainly because this traffic did not exist before the domestic energy revolution and has created several new safety concerns.

The study committee is charged with making recommendations, as needed, on policies that can help reduce the likelihood of future incidents involving the transportation of these domestic energy supplies and to ensure an effective emergency response when incidents do occur. In responding to the domestic energy revolution, the nation's rail, pipeline, and water transportation modes have demonstrated a high degree of innovation and adaptability, but with safety-assurance systems that have been challenged at times, particularly in the case of rail. The experience of the waterways, however, shows how safety can be assured when new traffic demands arise unexpectedly; in this case by a concerted strategy, put in place over the last three decades, to create a more robust and anticipatory safety assurance system. Based on information presented in this report, the committee offers its overarching observations on how the three modes, their safety assurance systems, and the emergency preparedness community have fared in responding to the challenges and demands of the domestic energy revolution. In light of these observations, several recommendations are made to strengthen aspects of this response.

OBSERVATIONS

Expansion of Oil and Gas Pipelines Will Require Safety Vigilance

Pipelines have always transported a large majority of the country's domestic and imported crude oil and natural gas, as this mode, more than any other, is dedicated almost exclusively to the transport of hazardous liquids and gases. Although pipelines are not used to any significant degree to transport ethanol, pipeline operators have a high degree of familiarity with transporting oil and gas. Large investments have been made in new oil and gas pipeline capacity over the past decade. Oil transmission pipeline mileage grew by more than 40 percent between 2010 and 2016 despite volatility in oil prices and some high-visibility pipeline routing and construction permitting controversies.

The committee did not find evidence that pipelines have encountered special safety challenges in accommodating the new demands of the growing domestic energy supply. The pipeline incident rate has been generally stable for hazardous liquids and gas shipments, with year-to-year fluctuations in total release volumes affected mainly by the periodic occurrence of high-consequence incidents that are sufficiently rare to limit judgments about changes in their underlying risk. Nevertheless, substantially more pipeline mileage and higher traffic volumes can be expected to result in more pipeline releases over time, simply because of the increase in exposure. The safety impact, however, is likely to depend on the extent to which new pipeline technologies, leak-monitoring systems, and more vigilant and capable integrity management programs are effective in protecting both the newer pipelines and the older ones that connect to them.

While no new safety problems have emerged as a result of the increased use of pipelines in transporting the larger volumes of domestic oil and gas, the potential for adverse safety effects from changes to the pipeline network will require careful monitoring. This need for monitoring was evident from 2008 through 2010 when Pipeline and Hazardous Materials Safety Administration (PHMSA) inspectors identified urgent pipeline construction issues, which over time would have likely affected pipeline integrity. Time-dependent failure mechanisms such as corrosion and cracking, as well as outside-force damage, will undoubtedly lead to releases in some of the newer pipelines as time passes, requiring vigilance in leak monitoring, maintenance, and integrity management, as well as an effective emergency response capacity. Where the increase in domestic supplies of crude oil and natural gas are being transported in pipelines that have undergone flow reversals or been repurposed from carrying other commodities, an inventory of these lines may be warranted to monitor for potential problems associated with changes in their stress and operating profiles.

Marine Transportation System Offers a Model for Robust Safety Assurance

Tank barges have a long history of transporting crude oil and comparatively small volumes of ethanol and natural gas liquids (NGLs). Nevertheless, crude oil traffic moved by tank barge grew at a rapid pace after 2010 as hydraulic fracturing activity increased to boost demand for crude oil transportation on the inland and intracoastal waterways. Although the increase in barge movements of the domestic oil supply has not attracted much public or policy maker attention, the traffic volumes exceed those of rail, particularly because of the large quantities transported along the Gulf Coast.

The safety record of energy liquids movements by barge has been exemplary. There are no reports of ethanol or NGL releases from tank barges over the past 10 years and rare reports of crude oil releases. The highly sensitive nature of the maritime environment has long demanded vigilance in preventing, containing, and mitigating oil releases from tank barges. Some 30 years ago, however, a series of catastrophic, high-profile oil spills from tanker vessels and tank barges caused the federal government to revamp the safety-assurance system in ways that have fundamentally altered the industry's safety profile. In addition to requiring the use of double-hulled tankers and tank barges for shipping oil and refined products, several new statutory and regulatory requirements created a safety culture that has proven to be robust, enabling the marine transport industry to safely accommodate unanticipated fluctuations in the demand for oil and other energy liquids transportation. These reforms included the clear designation of the vessel operator as the responsible party for spills, requirements for operators to make preparations for emergency response over the length of the transportation route, and requirements for operators to immediately notify the U.S. Coast Guard of any oil discharged into water regardless of volume and including any sheens observed that may have been caused by other parties.

These reforms have been credited with not only fundamentally changing the set of safety incentives that maritime carriers and shippers face but also with improving the industry's safety culture. An aim was to create a safety-assurance system that would be anticipatory so that safety would be reasonably assured in the face of unforeseen changes in demand, technology, and operating practices. As discussed next, the railroads were in a much different position when the domestic energy revolution commenced. Unlike the waterways, the railroads had virtually no experience transporting large volumes of crude oil and ethanol. The industry and regulators were compelled to react to incidents and the new safety issues they presented. As these safety issues have become better understood, and the demand for rail transportation of crude oil has slowed, the challenge for the rail industry and regulators is to develop a safety assurance system that has a high degree of robustness like that of the maritime sector.

Railroads Have an Opportunity to Create a More Robust Safety Assurance System

Railroads had little experience carrying ethanol and crude oil in large quantities until after 2005, when this traffic increased sharply in response to public policies to promote fuel ethanol and to new supplies of domestic crude oil produced from hydraulic fracturing in areas lacking sufficient pipeline takeaway capacity. Railroads responded by transporting these flammable liquids in tank car unit trains, despite limited experience transporting hazardous materials in such trainload volumes, an absence of tank cars designed specifically to carry flammable liquids, and many oil and ethanol shippers who lacked experience preparing flammable liquids shipments for long-haul movement by rail. It is notable that unlike in the pipeline and marine transportation sectors, in which the carriers have primary responsibility for all major factors affecting safety, railroads share this responsibility with shippers who own or lease, load, and secure the tank cars used to transport flammable liquids by rail.

In response to derailments of trains carrying ethanol and crude oil, the initial focus of the industry and regulators was on reducing the severity of incidents by making the tank cars that carry these flammable liquids more crashworthy and resistant to thermal failure. The new tank car design specifications developed to improve crashworthiness and thermal resistance were informed largely by the historical performance of tank cars that derailed in mixed-car trains, as opposed to unit trains. Until recently, there has simply not been enough experience with tank car unit trains to know how the dynamics of their derailments, which are more likely to involve multiple tank cars, compare with the dynamics of tank cars that have derailed in mixed-car trains. The limited (less than a decade) experience with flammable liquids unit trains suggests the high kinetic energy of the derailments has been a factor in the ignition of released product, more so than the specific volatility characteristics of the product being transported, such as its vapor pressure. However, there has been limited modeling of derailment kinetic energy that results in the conversion of thermal energy associated with multitank car derailments.

As the tank cars compliant with the new design specifications are being phased in, tank cars built to the older specifications that are less crashworthy and less resistant to thermal failures may continue to be used for flammable liquids traffic for a few more years. Preventing the derailment of these cars is therefore an imperative. Post-incident investigations of severe flammable liquids train derailments indicate track wear and defects are common causal factors. New regulations that establish maximum failure rates per track mile are intended to be performance based so as to encourage innovation in the inspection and repair of defects. Questions remain, however, about the technical basis for the allowable failure rate, the prioritization that should be given to repairing specific types of defects, and whether these allowable rates and repair priorities should be adjusted for routes with significant crude oil and ethanol traffic. Likewise, questions remain about the technical basis for regulatory requirements that establish maximum speed limits for this traffic, which were established based on speed limits imposed on other types of hazardous materials that are seldom transported in unit trains.

Emergency Response Preparedness Has Improved But with Geographic Variability

The emergency response community has had longstanding familiarity with energy liquids being transported by pipeline and waterways. Because unit trains of crude oil and ethanol are a relatively new phenomenon, many of the communities traversed by this traffic had no familiarity with responding to incidents involving trainload shipments of these flammable liquids. Preparedness for incidents involving this traffic has improved as knowledge of crude oil and ethanol behavior in derailments has grown and as emergency response procedures, resources, and information have improved, aided by grants, research, training, and educational efforts of industry and government safety agencies. Transportation operators have strengthened their connections with state and local officials, developed new communications tools to aid emergency response, and increased their offerings of emergency response training.

Despite these important developments of emergency response procedures and training programs, opportunities for improvement remain. Industry and government authorities face a continuing challenge in ensuring that these procedures are widely known and that training opportunities are exploited, especially among rural communities that are served by volunteer fire departments. Not only are clear guidelines lacking on the kinds of traffic data that carriers should be providing state and local agencies to prepare for energy liquids and gas transportation emergencies, but the recipient agencies differ so much from state to state that it unclear if this information is being transmitted to those who need it.

RECOMMENDATIONS

A decade after the start of the domestic energy revolution, it is not possible to say definitively that the impacts on the transportation sector have stabilized or temporarily reached a steady state. However, as the pace of change has slowed, now is an opportune time to take a more strategic look at the functioning and performance of each mode's safety assurance systems with an eye to their future ability to respond effectively to unanticipated safety developments.

The committee recommends that the Pipeline and Hazardous Materials and Safety Administration (PHMSA) undertake a comprehensive review of the successes and failures during the past decade in responding promptly and effectively to the transportation safety challenges presented by the domestic energy revolution for the purpose of informing the development of more anticipatory and robust safety assurance systems, including regulatory approaches. It is the committee's view that such a retrospective assessment will provide insight into requirements and practices that have worked well in ensuring the safety of some modes and that may be candidates for application in others. By way of example, PHMSA could examine the oil spill dispersion models that currently inform the emergency response plans of tank barge operators to determine whether similar modeling may be applicable in cases where crude oil trains and pipelines traverse highly sensitive environmental areas.

The general goal should be to develop a more forward-looking and anticipatory approach to safety assurance. To this end, **the committee recommends that PHMSA periodically consult with industry on developments impacting energy liquids and gas transportation and report annually on steps that are being taken to monitor and assess the risk implications of such developments.** In 2005, for instance, it should have been evident that ethanol movements by train were about to grow substantially in response to the federal Renewable Fuel Standard. In keeping abreast of such developments, PHMSA will be in a better position to collect the information and undertake the analyses that are needed to assess potential risks and to begin managing them in ways that will lessen the potential for harm to the public, environment, and emergency response community.

PHMSA's approach to risk monitoring and control should have a strong data and analytical basis. To this end, **the committee recommends that PHMSA evaluate the utility of existing incident- and traffic-reporting data for the purpose of identifying and assessing public safety and environmental risks associated with transporting energy liquids and gases, determine whether new and improved incident- and traffic-reporting systems are needed, and ensure that these data and risk metrics are being shared with state emergency preparedness agencies and used by industry for safety assurance purposes.** A relevant example of where such metrics can be used is in monitoring and assessing the risks associated with pipelines that have been converted for different commodities or had their flow directions reversed.

To develop such metrics, regulators would benefit from more uniform sets of data on incidents and traffic across modes. Not only are such data necessary to enable effective monitoring of the safety performance of the different modes when transporting energy liquids and gases, but also for allocating public funds for emergency response preparation. Accordingly, **the committee recommends that PHMSA consult shippers and carriers on the kinds of data that are available and needed to improve incident- and traffic-reporting systems for the purpose of developing risk metrics—in that, indicators to assist in setting safety policies—and consult with state emergency preparedness agencies on opportunities for presenting and sharing these data and metrics with local communities and their emergency responders.**

An analytical approach to safety assurance will require the use of more quantitative tools for risk analysis by regulators and industry. **The commit-**

tee recommends that PHMSA and the modal safety regulators encourage pipeline, barge, and rail carriers to make greater use of quantitative risk analysis tools to inform decisions about the routing of energy liquids and gases and about priorities for maintenance and integrity management of the equipment and infrastructure used. A candidate application for such tools is for assessing the risks associated with standards for maintenance of track traversed by unit trains of energy liquids and pipeline flow reversals and conversions.

Another early candidate for the use of these quantitative tools is to assess and seek to strengthen the analytic basis for the multifactor train-routing criteria and train speed restrictions in the high-hazard flammable trains (HHFT) rule. Indeed, **the committee recommends that PHMSA and the Federal Railroad Administration (FRA) regularly and systematically assess the risk-reducing effects of the HHFT rule, perhaps starting with a review of the crash and thermal performance of the new DOT-117 tank car designs.** As these new tank cars enter the fleet in larger numbers, their safety record will become observable, allowing for assessments of how design features that were informed by past tank car crashes are faring in the newer environment of flammable liquids unit train service.

PHMSA and FRA upgraded the crashworthiness and thermal resistance of tank cars used in flammable liquids service out of a recognition that derailments will occur. Of course, the upgrades will not prevent all flammable liquids releases from tank car derailments, and the risk of release remains higher for crashes involving the older designs being phased out for flammable liquids service. Under these circumstances, the prevention of derailments remains a safety imperative. **To obtain a more comprehensive understanding of the full array of factors that can give rise to and affect the severity of flammable liquids train crashes, the committee recommends that FRA and PHMSA seek to model these factors systematically, giving attention, for instance, to the propagation of internal rail defects and the kinetics that arise from multicar derailments.**

This deeper understanding of crash-causation factors will, among other things, inform railroad track inspection programs. Ensuring that these programs spot track defects that can lead to failures is essential to ensuring the safe operation of flammable liquids unit trains. To strengthen these programs, **the committee recommends that FRA enable and incentivize more frequent and comprehensive inspections of rail routes with regular energy liquids traffic, particularly by enabling railroads to exploit new inspection capabilities made possible by advances in sensor, high-resolution imaging, and autonomous systems technologies.**

Finally, it is necessary to presume that failures of energy liquids and gas pipelines, trains, and barges will occur, and that emergency responders will be called to the scene to contain and mitigate their consequences.

Because the domestic energy revolution has led to the opening of many new energy transportation routes, some of these incidents will occur in communities with limited relevant emergency response experience. **The committee recommends that PHMSA make a concerted effort to ensure that federal emergency preparedness grants are being used to meet the planning, training, and resource needs of communities that are facing new and unfamiliar risks as a result of the changes that have occurred in the routing and volume of energy liquids and gas shipments. As a starting point, PHMSA should review the extent to which emergency responders in these communities, especially in rural areas, are taking advantage of relevant government and industry response training opportunities, and then use this information to tailor programs that will enable and incentivize higher levels of participation.**

CONCLUDING COMMENTS

The committee believes, as reflected in the actions recommended above, that industry and regulators should strive to make the safety assurance system for energy liquids and natural gas transportation more anticipatory, responsive, and risk informed. Based on its review of responses to the safety challenges arising from the domestic energy revolution, the committee is optimistic about the ability of industry and government to achieve such an outcome, especially through more collaboration. Working together, industry, regulators, and the emergency response community will be in a better position to reduce the occurrence and the severity of incidents involving transportation of energy liquids and natural gas. To do so, however, they will need to share information and develop more robust risk analytics, create and apply incentives to further the use of automation and other technological innovations for monitoring the safe operation and the condition of equipment and infrastructure, and regularly review the effectiveness of safety regulations. The actions recommended in this report represent first steps in meeting these needs.

Appendix

Agendas

Committee for a Study of Domestic Transportation of Petroleum, Natural Gas, and Ethanol

First Meeting
February 4–5, 2016
Washington, D.C.

February 4

10:30 a.m. Briefing on study charge
VADM Paul G. Gaffney II, *Chair*

10:45 a.m. A review of hazardous materials safety regulations and data by responsible federal agencies
Jeff Wiese, Associate Administrator for Pipeline Safety, Pipeline and Hazardous Materials Safety Administration (PHMSA)
Karl Alexy, Director, Office of Safety Analysis, Federal Railroad Administration (FRA)
CAPT Benjamin Hawkins, Chief, Office of Design and Engineering Standards, U.S. Coast Guard
Lad Falat, Director of Engineering and Research, Office of Hazardous Materials Safety, PHMSA
Paul Stancil, Hazardous Materials Investigator, National Transportation Safety Board

1:15 p.m. Presentations on industry standards and practices involved in transmission and production of crude oil, natural gas, and ethanol

- Terry Boss, Senior Vice President of Environment for Safety and Operations, Interstate Natural Gas Association of America
- Caitlyn Stewart, Senior Manager, Regulatory Affairs, American Waterways Operators
- Robert Fronczak, Assistant Vice President for Environment and Hazmat, Association of American Railroads (AAR)
- Robin Rorick, Group Director of Midstream and Industry Operations, American Petroleum Institute
- Kelly Davis, Director of Regulatory Affairs, Renewable Fuels Association

3:15 p.m. An overview of energy transportation trends by federal statistical agencies

- Arup Malik, Operations Research Analyst, Office of Petroleum, Natural Gas, and Biofuels Analysis, U.S. Energy Information Administration
- Ron Duych, Senior Transportation Specialist, Bureau of Transportation Statistics
- Karen McClure, Industry Economist, FRA

4:30 p.m. Adjournment

February 5

9:00 a.m. An overview of operations, challenges, and trends in the emergency preparedness and response community

- David Willauer, Chair, Transportation Research Board Transportation of Hazardous Materials Subcommittee on Crude Oil Transportation
- Rick Edinger, Hazmat Committee Vice Chair, International Association of Fire Chiefs
- Frank Reiner, Chairman of the National TRANSCAER Task Group, TRANSCAER

10:45 a.m. Adjournment

Second Meeting
May 12, 2016
Washington, D.C.

10:40 a.m. An overview of how domestic energy markets have been changing, future trends, and the implications for shipping energy commodities?
E. Russell Braziel, President and CEO, RBN Energy

1:15 p.m. A review of the properties of crude oil shipments and the environmental impacts of releases
Anay Luketa, Principal Member of Technical Staff, Fire Science and Technology Department, Sandia National Laboratories
Debbie French McCay, Principal, Applied Science Associates (RPA ASA)

3:00 p.m. Challenges and responses in safety assurance of crude oil and ethanol shipments at midstream terminals and by railroad tank car
Peter Lidiak, Vice President of Government Affairs, International Liquid Terminals Association
Todd Treichel, Director, Railway Supply Institute-AAR Railroad Tank Car Safety Research and Test Project
Christopher Barkan, Professor and Executive Director, Rail Transportation and Engineering Center (RAILTEC), University of Illinois at Urbana-Champaign

4:30 p.m. Adjournment

Subcommittee Meeting
June 2, 2016
Houston, Texas

8:00 a.m. Overview of midstream energy liquid and gas pipeline operations, control room procedures, emergency preparedness and response by Kinder Morgan staff
Gary Buchler, Chief Operating Officer
James Holland, Vice President, Technical Services
Mark Jensen, Director, Products Movement
Elizabeth Oakley, Manager, Control Center
Nancy Barton, Director, Natural Gas Compliance/Pipeline Management
Ray Miller, Vice President, Pipeline Management

12:30 p.m. Overview of inland and coastal barge operations in long-distance hauling of crude oil, mariner training, and emergency preparedness and response by Kirby Corporation staff

James Farley, Vice President, Industry Relations
Jim Guidry, Executive Vice President, Vessel Operations, Inland and Offshore Marine Groups
Matt Woodruff, Director, Public and Government Affairs
Christian O'Neil, Executive Vice President and Chief Operating Officer, Marine Transportation Group

5:00 p.m. Demonstration of barge operator training using immersive simulators

Stephen Polk, Director, Seamen's Church Institute Center for Maritime Education

June 3, 2016
Fort Worth, Texas

11:00 a.m. Overview of railroad operations, control room, inspection technologies, and hazardous materials handling by BNSF Railway staff

Ryan Ringelman, General Director, System Safety
Frank Moffitt, General Director, Maintenance Planning
Sean Hill, Director, Transportation Support
Ryan Miller, General Director, Cars
Pat Brady, General Director, Hazardous Material

Study Committee Biographical Information

Paul G. Gaffney II (NAE), *Chair*, retired in 2013 as President of Monmouth University and is now President *Emeritus*. He continues to serve as Policy Fellow in the university's Urban Coast Institute. As a Vice Admiral in the U.S. Navy, he served as President of the National Defense University, as well as the Chief of Naval Research. He was appointed Commissioner on the U.S. Ocean Policy Commission; serving for its full term from 2001 to 2004. His naval career spanned more than 30 years, including duty at sea, overseas, and ashore in executive and command positions. He has been recognized with a number of military decorations and the Naval War College's J. William Middendorf Prize for Strategic Research. He chaired the federal Ocean Research/Resources Advisory Panel and was the inaugural chair of the federal Ocean Exploration Advisory Board (2014–2017). He is a director of Diamond Offshore Drilling, Inc. He has served on several National Academies committees, including Chair of the Board on Energy and Environmental Studies Marine and Hydrokinetic Energy Technology Assessment Committee and member of the Ocean Studies Board. He is a member of the National Academies of Sciences, Engineering, and Medicine's Gulf Research Program Advisory Board and chairs its Gulf of Mexico Loop Current Study. He co-chaired the National Oceanic and Atmospheric Administration's Decadal Ocean Exploration Study. He was elected to the National Academy of Engineering in 2010. He graduated from the U.S. Naval Academy in 1968, and completed a year as a student and advanced research fellow at the Naval War College, graduating with highest distinction. He earned a master's degree in ocean engineering from Catholic University of America and an M.B.A. from Jacksonville University.

Monica M. H. Blaney is Chief, Risk Evaluation in the Research, Evaluation, and Systems branch of the Transport Dangerous Goods (TDG) Directorate of Transport Canada. The branch makes recommendations and implements decisions and directives to minimize the adverse effects of accidental losses to people, property, and the environment associated with the transportation of dangerous goods. The branch applies risk-management techniques in a regulatory framework targeted toward a highly diverse and competitive sector of the Canadian transportation system. Previously, she led the Asia-Pacific Gateway and Corridor Initiative and Western Canada portfolio for transportation infrastructure and freight systems analyses. She has also been tasked with working with the U.S. Federal Highway Administration on freight transportation data collaboration. Previously, she was manager for rail/intermodal/marine at Alberta Infrastructure and Transportation's Strategic Policy Branch. In this position, she was responsible for advising on policy matters related to the freight transportation system. Before entering public service, she worked for Canadian National Railway, where she held numerous positions related to marketing, planning, and operations. She has served as principal investigator for studies sponsored by the Transportation Research Board's National Cooperative Freight Research Program. She earned a B.Sc. in statistics and a B.Sc. in agriculture from the University of Manitoba and an M.B.A. in maritime and logistics management from the University of Tasmania.

Guy F. Caruso is Senior Adviser to the Energy and National Security Program at the Center for Strategic and International Studies (CSIS). Before joining CSIS, he served as Administrator of the U.S. Energy Information Administration (EIA) from July 2002 to September 2008. He joined the U.S. Department of Energy (DOE) as a Senior Energy Economist in the Office of International Affairs, rising to Director of the Office of Market Analysis. Previously, he worked for the Central Intelligence Agency as an International Energy Economist in the Office of Economic Research. He was Director of the National Energy Strategy project for the U.S. Energy Association. He has also worked at the International Energy Agency, first as Head of the Oil Industry Division, and later as Director of the Office of Nonmember Countries. In 2008, he was awarded the French National Order of Merit. He holds a B.S. in business administration and an M.S. in economics from the University of Connecticut, as well as an M.P.A. from Harvard University.

Edward R. Chapman retired in 2015 from his position as Director for Hazardous Materials at BNSF Railway, where he worked for 37 years. At BNSF, he led the railroad's activities aimed at reducing railroad and shipper-caused commodity releases, including programs to train state and local first responders to hazardous materials incidents. He has been certified as a corporate hazardous materials responder since 1988. In 2014, he received the Association of American Railroads' Holden-Proefrock Award in recognition of his contributions to railroad hazardous material safety. He is a past chairman and remains a member of the Transportation Community Awareness and Emergency Response Task Group, an industry program that aids community preparedness planning and coordinates the development of programs and training for local emergency responders. He has been a member of several Transportation Research Board committees, including the Committee for a Study of the Feasibility of a Hazardous Materials Transportation Cooperative Research Program and the Committee for the Assessment of a National Hazardous Materials Shipments Identification System. He earned a B.S. in industrial engineering from Texas A&M University.

Robert J. Chipkevich is Principal of Chipkevich Safety Consulting Group, a transportation safety consultancy. He retired in 2010 from the National Transportation Safety Board (NTSB) after more than 25 years of service. He headed NTSB's hazardous materials accident investigation program for 20 years, the pipeline accident investigation program for 15 years, and the railroad accident investigation program for 9 years. As the Director for Accident Investigations, he assessed hundreds of transportation accidents each year and launched investigation teams to the most serious accidents. While at NTSB, he investigated on-scene many of the most serious hazardous material accidents in the United States across all modes of transportation. He testified before U.S. Congress more than a dozen times on transportation safety issues. Before becoming a Director at NTSB, he worked for the Federal Highway Administration in Boise, Idaho, and served as Assistant Director of the Motor Carrier Division, Tennessee Public Service Commission in Nashville. He has served on numerous transportation safety committees, including the Federal Railroad Administration Railroad Safety Advisory Committee, the National Association of State Fire Marshals Pipeline Safety Committee, the Flight Safety Foundation, the American Lifelines Alliance, and the Association of American Railroads Tank Car Committee. He earned a B.S. in business with a major in transportation from the University of Tennessee.

Joseph W. Martinelli is Founder of PiPRO, a consultancy serving pipeline industry clients through risk management, incident response, and business management. He retired as President of Chevron Pipe Line Company after nearly five decades of work in the petroleum industry. He has held executive positions in the areas of oil exploration and production as well as pipeline operation. He has also served in senior management positions at Gulf Oil Exploration Corporation. During his career, he was a member of a number of industry organizations and boards, including those of the Association of

Oil Pipelines and the American Petroleum Institute. He was Program Chair for pipeline executive seminars at the Northwestern University Transportation Center. He is a charter member of the National Academy of Construction. The National Institute of Standards and Technology selected him as a Baldrige Examiner. He earned a B.S. in petroleum engineering and an M.B.A. from the University of Pittsburgh.

Ali Mosleh (NAE) is Distinguished Professor and holder of the Evelyn Knight Chair in Engineering at the University of California, Los Angeles. Previously, he was the Nicole J. Kim Eminent Professor of Engineering and the Director of the Center for Risk and Reliability at the University of Maryland. His areas of expertise are Bayesian methods for data analysis, common cause failure analysis, modeling of the impact of organizational factors on system reliability, dynamic accident simulation and probabilistic risk assessment, and space systems risk analysis. He has led many studies on the risk and safety of complex systems, such as space missions, nuclear power plants, commercial aviation, communication networks, and health care systems. He was elected to the National Academy of Engineering in 2010. He has served on several National Research Council committees, including the Committees on Alaska's Oil and Gas Pipeline Infrastructure and on Risk of Vessel Accidents and Spills in the Aleutian Islands. He currently serves on the Transportation Research Board Marine Board. He earned a B.S. in physics from Sharif University of Technology and an M.S. and a Ph.D. in nuclear science and engineering from the University of California, Los Angeles.

Tonya Ngotel is Director of Exercise Programs, Center for Preparedness Education at the College of Public Health, University of Nebraska Medical Center. Previously, she served as Coordinator for the State Emergency Response Commission (SERC) for Nebraska, where she was responsible for overseeing the day-to-day operations of SERC, as well as the establishment of its plans, policies, and procedures. Her duties included communicating critical information to first responders across the state. She has represented the national hazardous materials planning community as President of the National Association of SARA Title III Program Officials (NASTTPO) since 2012. Her position at NASTTPO requires interacting with regional and national-level executives and senior government officials pertaining to the transportation and storage of hazardous materials. She serves on various advisory councils and working groups of the U.S. Environmental Protection Agency, the Federal Emergency Management Agency, and the Executive Office of the President. She earned a B.A. in human resources and psychology from Doane College.

Gregory G. Noll is Program Manager for the South Central Task Force, an eight-county, all-hazards emergency preparedness organization in south-central Pennsylvania. He is also Senior Partner at Hildebrand Noll Associates, a consulting firm specializing in emergency planning, response, and incident-management issues. He is the past co-chair and current member of the InterAgency Board Training and Exercises SubGroup. He has received several national-level awards, including the 2011 John M. Eversole Lifetime Achievement Award by the International Association of Fire Chiefs (IAFC), which is the highest award given by the IAFC Hazardous Materials Committee. He is a Certified Safety Professional and a Certified Emergency Manager, and has been involved in several national emergency response initiatives, including chair of the National Fire Protection Association's Technical Committee on Hazardous Materials Response Personnel. He earned a B.A. in business administration and management from Kutztown State College and an M.A. in public administration from Iowa State University.

Craig E. Philip (NAE) is Research Professor of Civil and Environmental Engineering and Director of the Center for Transportation and Operational Resilience (VECTOR) at Vanderbilt University. From 1993 to 2014, he served as President and CEO of Ingram Barge Company. He began his career at Consolidated Rail Corporation and later served with Southern Pacific Railroad, where he was Vice President of its Intermodal Division. He has been actively engaged in transportation and logistics industry leadership, serving as chairman of the American Waterways Operators, the National Waterways Conference, and the U.S. Chamber of Commerce's Transportation and Infrastructure Committee. He was a member of the Transportation Research Board's Executive Committee, and is currently a member of the Marine Board. He served as a U.S. Commissioner of the World Association for Waterborne Transport Infrastructure and on the U.S. Department of Transportation's National Freight Advisory Committee. He serves on the boards of the ArcBest Corporation, Seamen's Church Institute, Red Cross of Tennessee, and Nashville Civic Design Center. In 2010, he was designated a Distinguished Diplomate in the Academy of Coastal, Ocean, Port, and Navigation Engineers. He was elected to the National Academy of Engineering in 2014. He earned a B.S. in civil engineering from Princeton University and a Ph.D. in civil engineering from the Massachusetts Institute of Technology.

Ian P. Savage is Professor of Instruction in the Department of Economics and Transportation Center, Northwestern University, where he has worked since 1986. He is Associate Chair of the Department of Economics and has served as Associate Director of the Transportation Center. His research has centered on urban public transportation and transportation safety. He has conducted research into safety performance and the effectiveness of safety regulations in most modes of transportation with particular emphasis on the trucking and railroad industries, as well as a study of double-hulled tankers. He has served on the organizing committees of local, national, and international professional organizations. He was a member of the Transportation Research Board (TRB) Committee for Review of the Federal Railroad Administration Research, Development, and Demonstration Programs, and is currently a member of the TRB Standing Committee on Highway/Rail Grade Crossings. He earned a B.A. in economics from the University of Sheffield and a Ph.D. from the School of Economic Studies and Institute for Transport Studies at the University of Leeds.

Katherine F. Turnbull is Associate Director of the Transportation Institute of the Texas A&M University System. She is head of the System Planning, Policy, and Environment Research Group, responsible for managing programs in College Station, Arlington, and Austin with 180 employees and an annual research budget of approximately $10 million. In addition, she is a Visiting Assistant Professor in the Department of Landscape Architecture and Urban Planning. Her research focuses on transportation planning and intelligent transportation systems. She is currently the principal investigator for a study examining the impact of the energy sector (i.e., oil, gas, wind, crude by rail, and coal) on the transportation systems of eight states. She is active in the Transportation Research Board and the Institute of Transportation Engineers (ITE). She served as Chair of the TRB HOV Committee for 6 years and currently chairs ITE's Transit Council. She is also a member of the Intelligent Transportation Society of America Coordinating Council. She earned a B.S. in political science and history from the University of Minnesota, an M.S. in urban affairs from the University of Wisconsin, and a Ph.D. in urban and regional science from Texas A&M University.